Evaluation and Improvement of the Residential Energy Hub Management System

by

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AUTHOR'S DECLARATION

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.

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Abstract

Energy consumption in the residential sector of Ontario is expected to grow by 15%, most of which is expected to be from electricity use, with an annual average growth rate of 0.9% between 2010 and 2020. With Ontario government's Integrated Power System Plan (IPSP) recommending phasing out coal fired generators by 2014, the execution of Conservation and Demand Management and Demand Response programs can have significant impact on reducing power consumption and peak demand in the province. Electricity generation, especially from fossil fuel, contributes 18% of total green house gas (GHG) emissions in Ontario. With climate change effects being attributed to GHG emissions and environmental regulations, it is necessary to reduce GHG emissions from power generation sector. In this context, the current Energy Hub Management System project, of which the work presented here is a part, may lead to the reduction of electricity power demand and GHG emissions in Ontario.

This thesis presents the validation of Energy Hub Management System (EHMS) residential sector model. Performances of individual appliances and the results obtained from various case-studies considering the EHMS model are compared with respect to a base case representing a typical residential customer. The case-studies are carefully developed to demonstrate the capability of the EHMS model to generate optimum operational schedules to minimize energy costs, energy consumption and emissions based on user defined constraints and preferences. Furthermore, a forecasting methodology based on single variable econometric time series is developed to estimate day-ahead CO_2 emissions from Ontario's power generation sector. The forecasted emissions profile is integrated into the EHMS model to optimize a residential customer's contribution to CO_2 emissions in Ontario.

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List of Abbreviations

AC	Air Conditioning
CDM	Conservation and Demand Management
DR	Demand Response
DRY	Dryer
DW	Dishwasher
$EHMS$	Energy Hub Management System
ESD	Energy Storage Device
FRP	Flat Rate Pricing
FR	Fridge
GHG	Green House Gas
H	Heating
$HOEP$	Hourly Ontario Electricity Price
$IESO$	Independent Electricity System Operator
IL	Illumination Level
LDC	Local Distribution Company
LI	Lighting
OEB	Ontario Energy Board
OPA	Ontario Power Authority
$Ppump$	Pool pump
RTP	Real Time Pricing
SCC	Social Cost of Carbon (dioxide emissions)
Stv	Stove
TOU	Time of Use
TWH	Tub Water Heater
W	Washer
WH	Water Heater

Nomenclature

$X_{j,k}$	Historical value of Ontario market demand at k^{th} hour of j^{th} day (MW)
$\hat{X}_k$	Day-ahead value of Ontario's market demand at k^{th} hour (MW)
$\bar{X}_k$	Mean of n demand observations corresponding to hour k (MW)
$\hat{Y}_{k,p}$	Forecasted value of generation from power plants (coal or gas) at k^{th} hour (MW)
$Y_{j,k,p}$	Historical value of power output from power plants (coal or gas) at k^{th} hour of j^{th} day (MW)
$\bar{Y}_{k,p}$	Mean of n generation output from coal/gas units at hour k (MW)
k	Hour of the day
j	No. of days
n	No. of observations corresponding to each hour k
p	Index for coal or gas
E_k	Forecasted CO_2 emissions at k^{th} hour in tonne/hr
R_c	Rate of CO_2 emissions from coal-fired plants = 1.0201 tonne/MWh
R_g	Rate of CO_2 emissions from gas-fired plants = 0.5148 tonne/MWh
Pc_k	Forecasted generation of coal-fired plants at k^{th} hour (MW)
Pg_k	Forecasted generation of gas-fired plants at k^{th} hour in (MW)
CE_k	Hourly average cost of emissions (cents/kWh)
$RMSE(t)$	Root Mean Square Error of the relative errors during hour t
N	Number of forecasted values of each hour
Y_k^*	Forecasted value of observation
Y_k	Observed value of observation k
J	Objective function
T	Time schedule set in which appliance i operates {1:96}
T'	Time schedule set in which appliance i operates {1:192}
i	Index of appliances

t	Index of time
$S_i(t)$	Binary decision variable for appliance i ON/OFF status at time $t \in T$
$S'_i(t)$	Binary decision variable for appliance i ON/OFF status at time $t \in T'$
$C(t)$	Cost of electricity at time t
A	Set of appliances including $AC, TWH, Stv, Ppump, DW, W, DRY$
P_i	Rated power of appliance i
C_{ESD}	Revenue rate from ESD
$CG(t)$	Cost of natural gas at time t
$CE(t)$	Hourly average emission cost at time t
HR_i	Heat rate of appliance i
w_1	Weight attached to customer's total energy cost
w_2	Weight attached to customer's total energy consumption
w_3	Weight attached to customer's total emissions cost
$U_i(t)$	Binary start up dummy variable for appliance i at time t
$D_i(t)$	Binary shutdown dummy variable for appliance i at time t
$\theta_i(t)$	Temperature of i appliance at time t
θ_i^{up}	Upper limit of temperature of appliance i
θ_i^{low}	Lower limit of temperature of appliance i
$\Delta T^{up}(t)$	Upper temperature deviation from set point at time t
$\Delta T^{low}(t)$	Lower temperature deviation from set point at time t
$\theta_{set,i}(t)$	Temperature set point of appliance i at time t
$IL(t)$	Illumination level of the house at time t
$ESL(t)$	Energy storage level at time t
$AL(t)$	Activity level at time t
$AL_i(t)$	Activity level of appliance i at time t
$HWU(t)$	Average hourly hot water use at time t

MUT_i	Minimum up time of appliance i
MDT_i	Minimum down time of appliance i
$MSOT_i$	Maximum successive operation time of appliance i
EOT_i	Earliest operation time of appliance i
LOT_i	Late operation time of appliance i
ROT_i	Numbers of ON decisions of appliance i
MAT_{GAP}	Maximum time gap
$IL_{out}(t)$	Illumination of the house due to outdoor source (sun light) at time t
$IL_{req}(t)$	Required illumination at time t
$ESL_{ESD}(t)$	Battery storage level at time t
ESL_{ESD}^{min}	Minimum energy storage level of the ESD
ESL_{ESD}^{max}	Maximum energy storage level of the ESD
$Discharg_{ESD}$	Amount of power that ESD system injects into the grid per 15 minute interval
$Charge_{ESD}(t)$	Charged energy into the ESD at time t
LPN	Large positive number
β_i	Beta parameter of appliance i
α_i	Alpha parameter of appliance i
γ_i	Gamma parameter of appliance i

Chapter 1
Introduction

1.1 Motivation

According to the Government of Ontario's Supply Mix Directive dated June, 2006 [1], and subsequently the Integrated Power System Plan (IPSP) of Ontario Power Authority (OPA) [2], execution of a Conservation and Demand Management (CDM) program is required as a priority in order to reduce the peak demand by 1,350 MW by 2010 and by another 3,600 MW by 2025, since with anticipated increase in natural gas and electricity demand the residential sector in Ontario will be accounting for considerable amount of energy consumption. Thus, energy consumption in the residential sector of Ontario is expected to grow by 14.8%, most of which is expected to be from electricity use, with an annual average growth rate of 0.9% between 2010 and 2020 [3]. Natural gas demand is expected to remain prevalent in homes, followed by electricity until 2020 as shown in Table 1-1, the growth in electricity consumption reflects the expected penetration of air conditioner, appliances and other electronic devices. At the same time Ontario government's IPSP recommends phasing out of its coal fired generators by 2014. Therefore implementing CDM and Demand Response (DR) can have significant impact on reducing power consumption and peak demand.

Table 1-1: Energy demand (in PJ) by end use residential sector in Ontario [3].

	1990	1995	2000	2005	2010	2015	2020
Natural Gas	252.3	318.1	315.3	325.7	340.1	355.3	371
Electricity	163	150.5	153.7	164.1	177.2	190	201.8
Coal	0	0	0	0	0	0	0
Renewable Energy	16.2	18.4	17.6	18.7	18.4	18.5	18.9

Emissions in Ontario mainly come from fossil fuel consumption in transportation, heating and electricity generation. Figure 1-1 illustrates the current and forecasted Green House Gas (GHG) emissions in Ontario if no emissions mitigation action is taken by government [4]. As inscribed in the Copenhagen Accord, Canada has committed to reducing GHG emissions by 17% below its 2005 levels, by 2020 [5]. Ontario is committed to reduce its GHG emissions 6% below 1990 level by 2014. To achieve these targets, Ontario needs to succeed in emissions reductions in every energy sector.

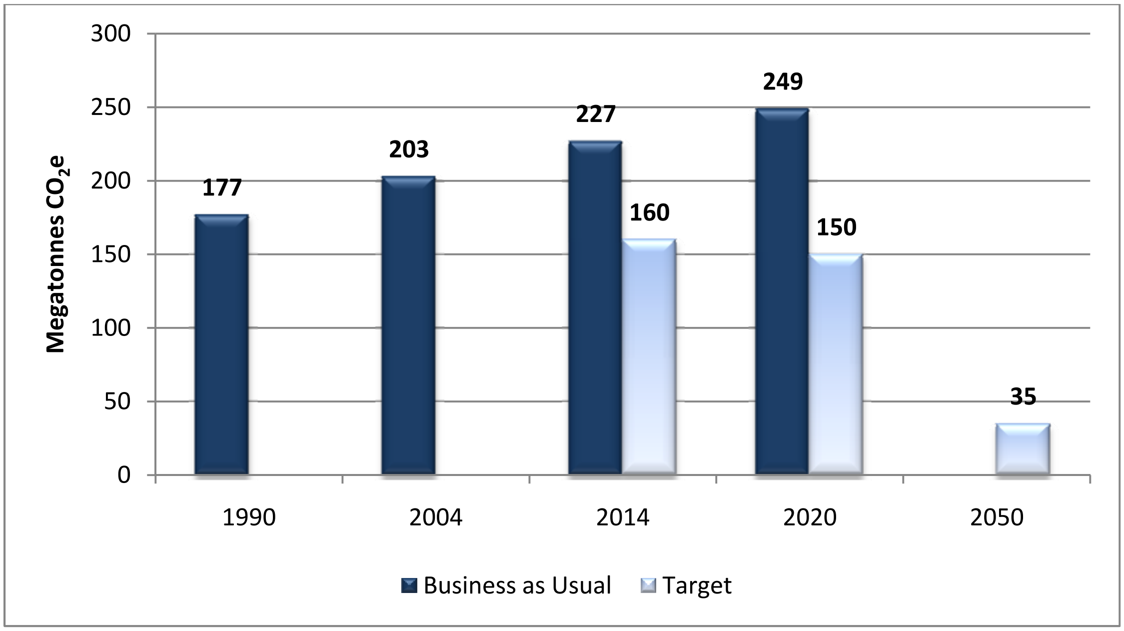

Figure 1-1: GHG trajectory for Ontario from 1990 to 2010 (without government actions) and targets [4].

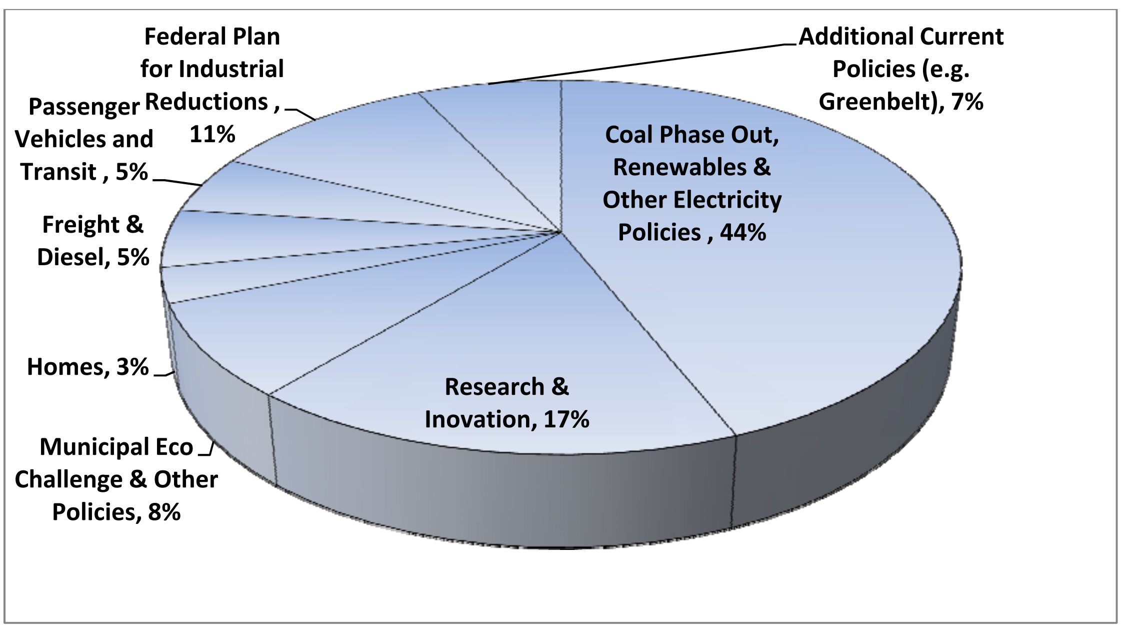

Figure 1-2: Prospective emissions reductions from sectors to be achieved by 2014 [4].

Figure 1-2 depicts prospective emissions reductions, from sectors, that can be achieved in Ontario by 2014 based on current and new policies [4]. It is seen that 44% of the emissions reduction can be achieved by phasing out coal based generation and other electricity policies such as CDM and DR.

Since the existing policies and programs, as stated in [6], includes electricity conservation measures, phasing out coal while encouraging renewable electricity generation and CDM programs will result in reduced GHG emissions in Ontario.

1.2 Energy Hub Management System

An energy hub in the system is any location where energy system activities such as energy production, storage and consumption of different energy carriers take place (e.g. a house, office, farm or manufacturing facility). The proposed structure of an Energy Hub Management System (EHMS) comprises a macro energy hub and a micro energy hub [8]. The macro hub is envisaged to receive data from the external environment (i.e. electricity process, market demand and weather forecasts) and also from the micro hubs. The micro hub will monitor and control the local devices and send relevant data to the macro hub. The proposed mathematical model in [8] is focused on a residential micro hub with the objective to optimize the energy cost, energy consumption or emissions depending upon customers' choice of operation. At the macro hub level, the mathematical model would ideally incorporate several such micro hubs receiving information from utilities and micro hubs.

Figure 1-3 shows the overall schematic of an EHMS illustrating the interactions of macro hub and micro hubs, with system data and associated information exchange between them. A typical macro hub will comprise of several micro hubs which would communicate with the macro hub regarding their energy usage and control decisions. Figure 1-3 also shows that there are four categories of macro hubs, namely residential, commercial/institutional, agricultural and industrial having similar measures for data and information exchange.

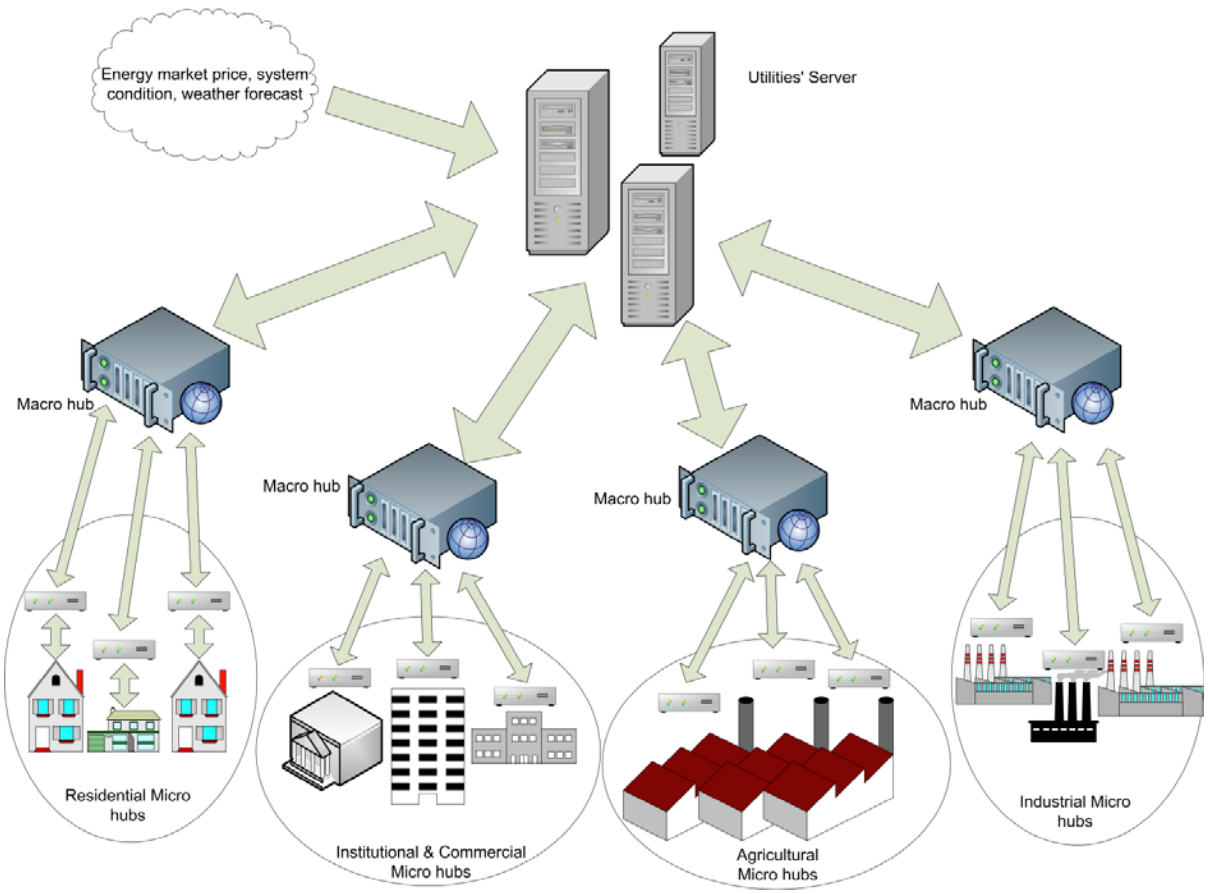

Figure 1-3: Overall schematic of EHMS (used with permission from [8]).

Figure 1-4 represents the structure of a residential micro energy hub system. This figure illustrates two-way communication between the micro hub and various appliances, the energy production system, energy storage system and smart meter. The proposed mathematical model in [8] and associated optimization solver will reside in the micro-hub controller.

This thesis focuses on the improvement and validation of residential energy micro-hub system proposed in [8] and, revised and improved in [9], in a realistic household environment.

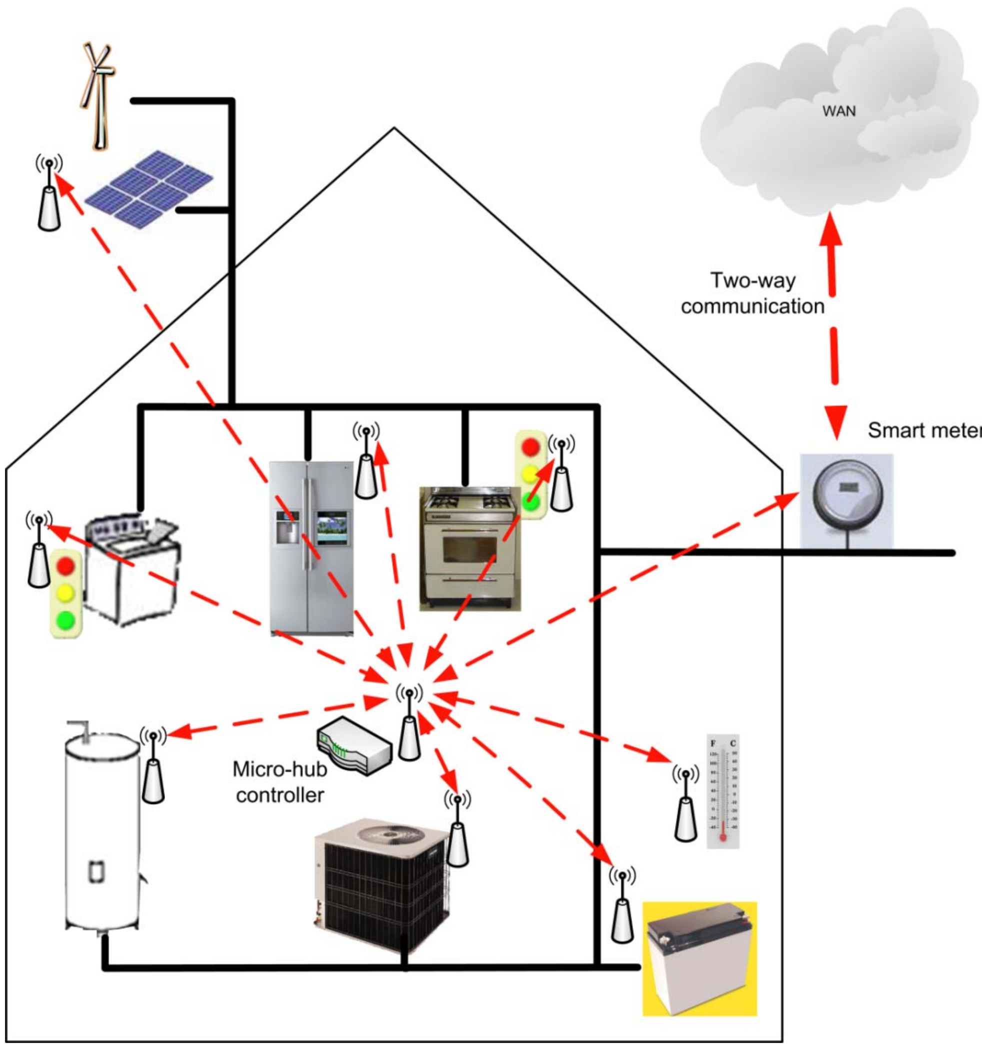

Figure 1-4: Residential micro energy hub structure (used with permission from [8]).

1.3 Conservation, Demand Management and Demand Response

In Ontario, energy conservation and load management is referred to as CDM, which encompasses less use of energy, replacing low-energy consuming appliances, modifying the time when energy is used, fuel switching and reducing load on the grid by generating power from renewable resources. The six CDM objectives, i.e. peak clipping, valley filling, load shifting, strategic conservation, strategic load growth and flexible load shapes, can be achieved through energy efficiency and DR programs [7].

Energy efficiency programs focus on reducing overall energy use by transition to energy-efficient technologies. These programs encourage users to implement energy efficient appliances, efficient building designs and advanced heat recovery systems.

DR is defined in [10] as "the changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized". Figure 1-5 shows the CDM programs that focus on DR. DR programs make use of dynamic pricing and requires advanced metering infrastructure to support them. DR primarily involves the switching of loads during periods of peak demand or when load is approaching the available generation capacity. Efficient application of DR programs require advanced metering infrastructure.

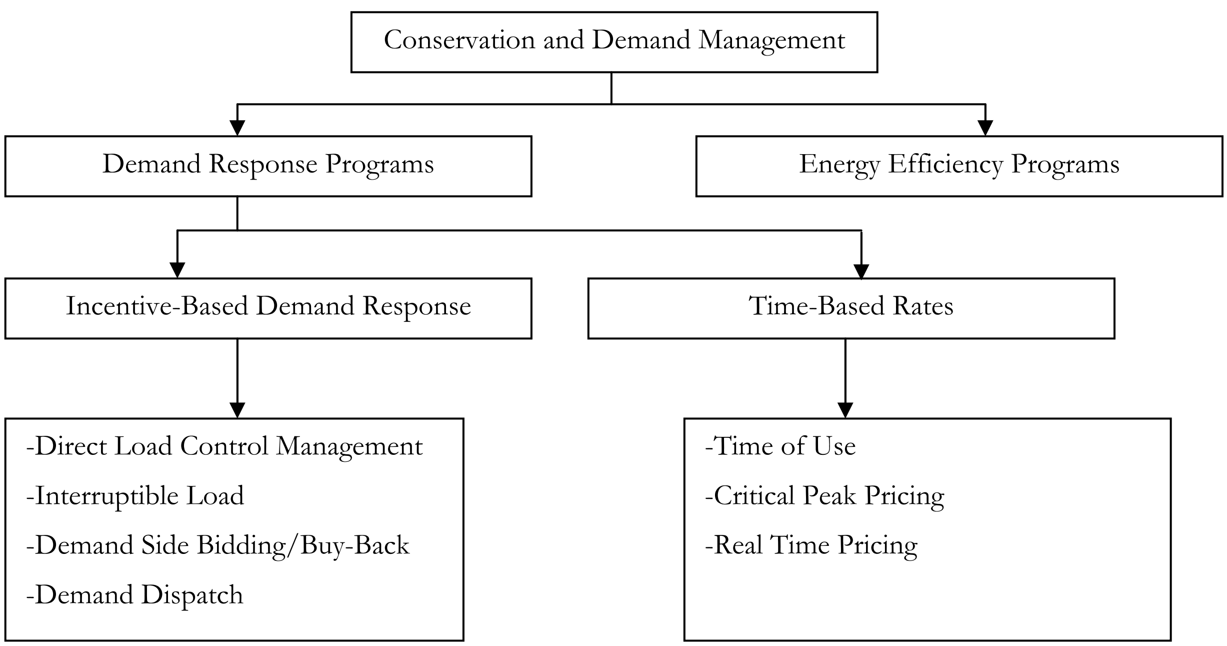

Figure 1-5: CDM programs focused on DR [7].

Demand dispatch is an approach similar to DR, i.e. shedding load as needed, but unlike DR, demand dispatch can be used at all times to support the operation of the grid [11]. With the increasing penetration of intermittent renewable generation into Ontario's electricity system, demand dispatch is likely to play an important role. With more and more addition of non-dispatchable renewable generation into the grid it will become increasingly difficult for the dispatchable generators (such as gas and coal) to ramp up and follow the load and, therefore, demand dispatch can be implemented by enabling direct control of loads.

The OPA has initiated various DR programs in Ontario which include the DR1, DR2, DR3 and Peak Saver/Residential and Small Commercial DR programs in various Local Distribution Companies (LDCs) such as Milton Hydro. The DR1, DR2 and DR3 programs of OPA are briefly described next [12]:

DR1: Encourages short-term demand response capacity in response to Independent Electricity System Operator's (IESO) 3-Hour ahead Pre-Dispatch Price signal in the electricity market. This is a voluntary program, designed for participation by consumers who can choose to curtail load, or not, in response to economic signals, primarily using existing equipment and processes. Participants offer their own "strike price" on a monthly basis, at which they are willing to curtail load. The participant's strike price must be higher than the minimum Floor Strike Price for the month, specified by OPA.

DR2: Load shift program with contractual obligations. In this program, participants agree to reduce a pre-determined amount of load for at least four consecutive hours up to 12 hours during on-peak period and increase load during off-peak period. Revenue rates vary from $8 to $100/hr depending upon different seasons.

DR3: Contractual load shedding program in which participants are required to reduce 5 MW of their demand. Participants provide the available hours (100 or 200 hours/year) for which they agree for load curtailment and hence are get paid by OPA for the load reduction.

Natural Resources Canada (NRCan) is carrying out projects to make it easier for the commercial buildings to participate DR Programs. NRCan's CANMET Energy Technology Centre at Varennes, is conducting research on energy management and demand responsive control strategies in commercial buildings [13].

1.4 Overview of Ontario's Residential Sector Energy Consumption

The distribution of residential electrical energy use in Ontario is shown in Figure 1-6 [14]. As seen in this figure, residential heating (30%) is the most significant contributor to electricity consumption in Ontario homes, followed by air-conditioning (space cooling) and lighting loads, which are 14% and

13% respectively. Appliances like dishwasher and cloth washer loads contribute only 0.5% each to the total electrical energy usage; however, these loads have high power ratings that appear during a short period of time and, therefore, these loads contribute to increase in peak demand if not scheduled appropriately. Similarly, if CDM and DR programs are implemented in the residential sector, then there is a possibility that as soon as a peak-price period is avoided, a number of appliances will be turning on simultaneously which may produce an instantaneous burden and a sudden surge in power demand may affect the distribution system.

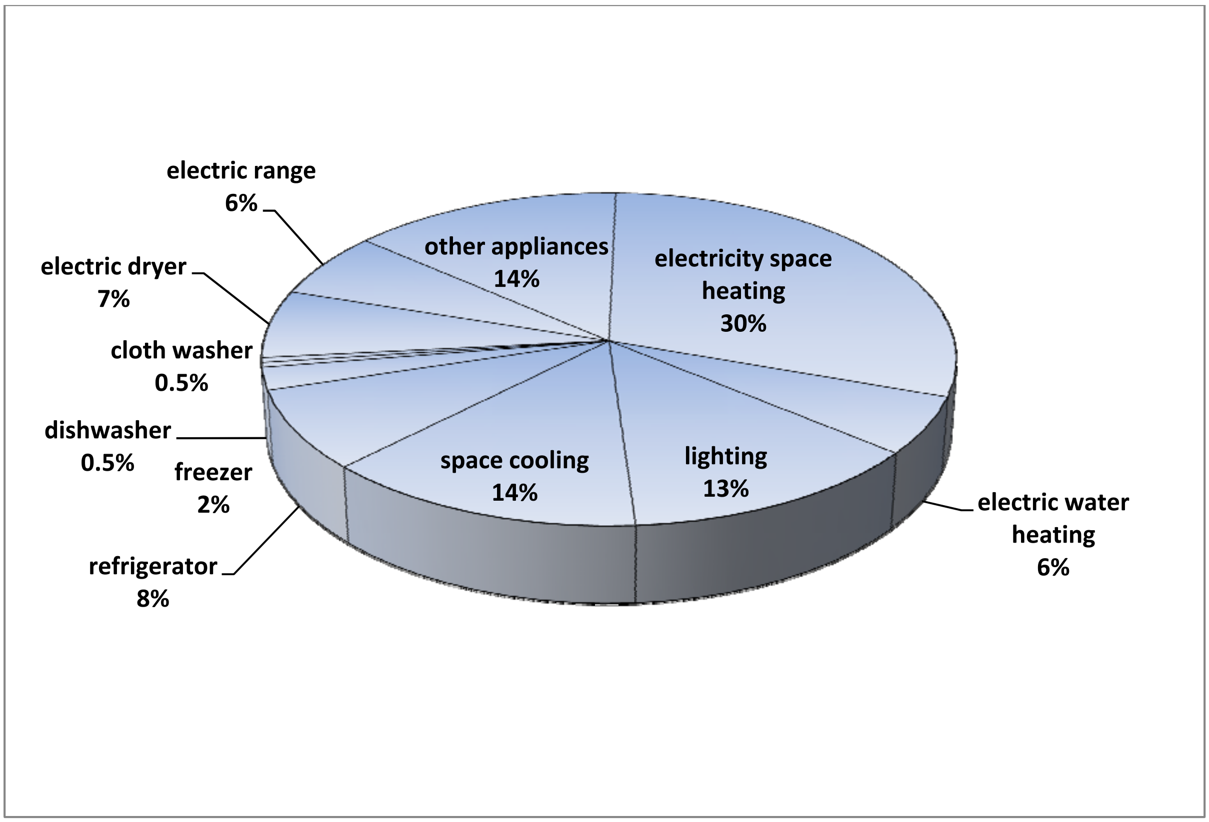

Figure 1-6: Electrical energy use in residential sector in Ontario [14].

1.5 Emissions from Power Sector

Power sector utilizes various sources to generate electricity which include coal, natural gas, nuclear, hydro-electric and renewables. Coal remains the major source for electricity generation in the last four decades, while the generations from nuclear power and natural-gas-fired generators has increased rapidly. With the rising prices of fossil-fuels and increasing environmental concerns, there has been a greater interest towards power generation from nuclear and sustainable sources. Nuclear power and renewable sources (water, wind and solar) produce no CO_2 emissions. Therefore, with the decline in the use of oil for power generation, coal and natural-gas remains the most carbon intensive sources in the power sector. In 2007, coal-fired generation accounted for 42% of world's total electricity and is expected to supply 43% by 2035. Similarly, natural gas fired generation is projected to increase by 2.1% from current level, by 2035 [15]. As fossil-fueled generation is estimated to dominate the electricity generation in the future (Figure 1-7), in order to reduce CO_2 emissions, alternative steps would be taken, such as imposing a price on CO_2 emissions (i.e. carbon tax), reducing energy consumption by CDM programs and replacing coal-fired generation with no- or low-emissions technologies.

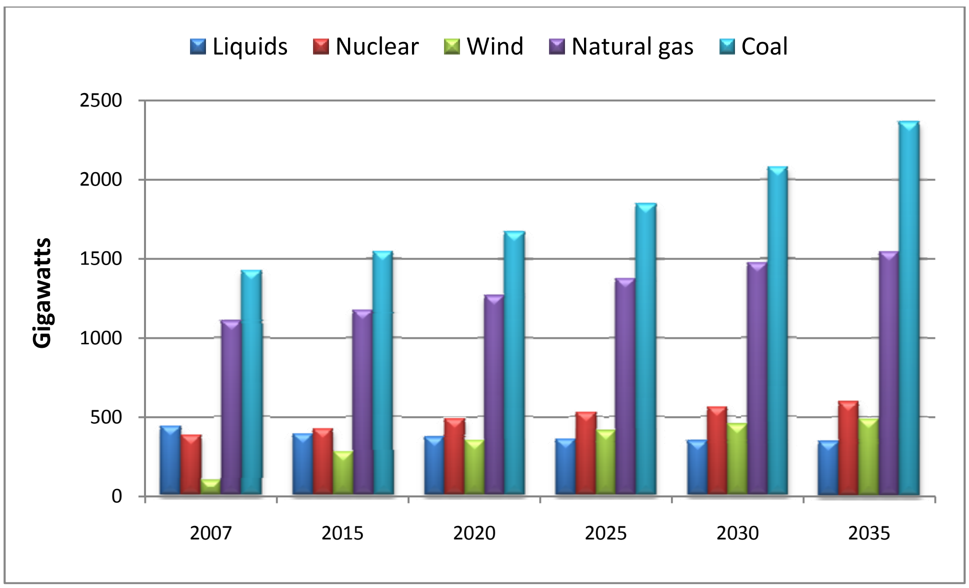

Figure 1-7: World net electricity generation by fuel [15].

1.5.1 GHG emissions from residential sector

Canada's total GHG emissions from the electricity sector are estimated to be 131 Mt (Mega tonnes of CO_2 equivalent) in 2010, 30% of which will be contributed by Ontario. Table 1-2 presents the GHG emissions in Ontario over the last 20 years for different sectors. In the longer run, residential emissions are effected by energy efficiency programs and population growth. Emissions from the power generation sector in Ontario are expected to decrease by 30% in 2020, mainly because of Ontario Government' planned phasing out of its coal-fired power generators [3].

Table 1-2: Total GHG emissions in Ontario by sector (Mt CO_2 equivalent) [3].

	1990	1995	2000	2005	2010	2015	2020
Power Generation	26.6	19.1	42.7	28	38.8	36.3	27.1
Industrial	56.6	55.7	47.2	47	49.6	52.6	55.3
Residential & Agricultural	18.2	20.5	20	19.2	20.1	21	22
Commercial/Institutional	9.2	9.9	13.2	13.5	15.3	17.4	19.3
Oil & Gas Industry	1.3	1.5	1.7	0.5	1.7	2.5	2.5
Transportation	48.1	52.7	61.1	63	69.2	73.9	79.6
Others	16.5	17.4	18	22.4	22.4	23.7	26.6

GHG emissions from coal-based electricity generation account for 79% of the total emissions from the power sector in Canada, followed by emissions from natural-gas and liquid-fuel generations, sharing 14% and 6% respectively [16]. In the residential sector, CO_2 emissions are mainly because of consumption of natural gas for heating and cooking, and electricity for cooling/heating, appliances, lighting and other household electronic devices. Figure 1-8 and 1-9 presents the distribution of GHG emissions by end use and by energy source from Canada's residential sector, respectively. It is evident from the break up that space heating is the major contributor of GHG emissions in the residential sector (59%), while electricity and natural gas contributes 46% of GHG emissions from residential energy use.

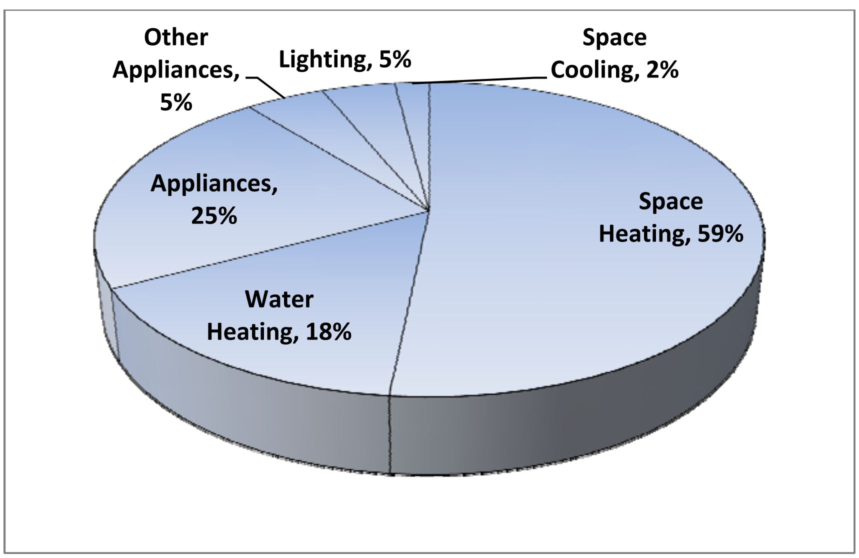

Figure 1-8: GHG Emissions by end use from Canadian residential sector [16].

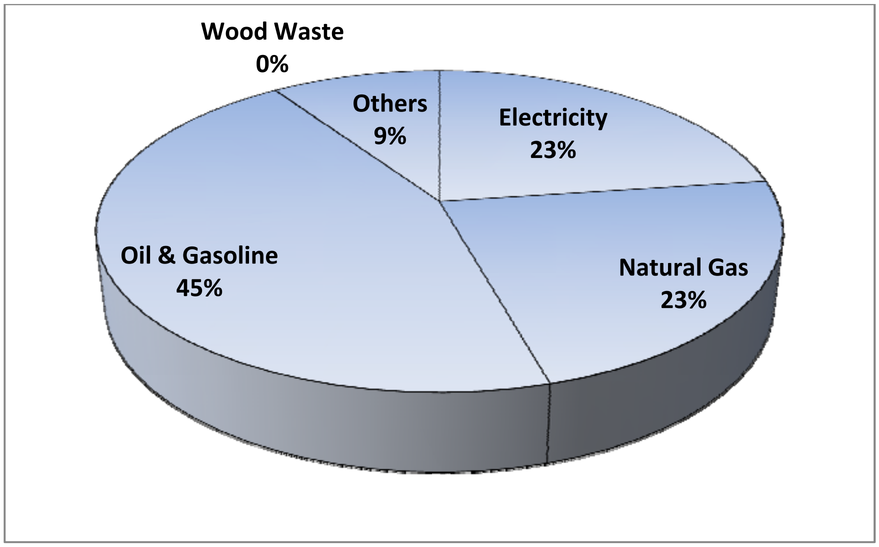

Figure 1-9: GHG emissions by energy source from Canadian residential sector [16].

1.6 Objectives of this Thesis

Previous researchers have proposed mathematical model for the EHMS pertaining to the residential sector [8], [9]. However, these models need to be appropriately validated through development of realistic scenarios and case-studies to establish their goodness, identifying and quantifying the benefits accrued from them. Furthermore, it is also important that the EHMS model takes into consideration the impact a residential customer may have on the emissions reduction of the system. In view of these, the objectives of this thesis are as follows:

- Develop simple and easy to implement models to forecast the CO_2 emissions from the power generation sector in Ontario.
- Introduce the simultaneous optimization of electricity and natural gas consumption into the EHMS residential sector model.
- Simulate the EHMS residential sector mathematical model with realistic weather conditions, actual appliance power ratings, indoor temperature settings and typical customer behavior.
- Test the realistic model parameters for each residential sector appliance and parameters for the household as estimated in [9] for various operating conditions such as summer and winter.

- Construct and simulate various case studies taking into account a typical customer's operational choices, and thus develop comparative analysis of the decisions hence made.

1.7 Thesis Organization

This thesis constitute of five chapters. Chapter 2 presents a single-variable econometric time-series method to forecast the CO_2 emissions in Ontario. In Chapter 3, five different objective functions are developed corresponding to typical residential customer behavior; this chapter describes the mathematical model for individual household appliances with some suggested modifications. In Chapter 4, six case-studies are constructed. Results of these case studies and their comparison with the base case are presented; this chapter also describes the performance of individual appliances, savings in energy cost, energy consumption and emissions, and the effect of using different energy prices. Chapter 5 summarizes the work reported in the thesis, highlights the main conclusions and identifies scope for further work.

Chapter 2

Forecasting CO_2 Emissions from Power Generation in Ontario

This chapter addresses the issue of forecasting hourly CO_2 emissions in Ontario from the power generation sector. This is to be used in EHMS residential sector model to estimate a customer's contribution to Ontario's overall emissions. Emissions of GHG, especially CO_2, from fossil fuel based electric generators have damaging impact on our environment and therefore a social cost can be associated with these emissions; this social cost is used here to estimate the average emissions cost for Ontario. Finally an analysis of errors associated with the proposed forecasting method is presented.

2.1 CO_2 Emissions from Fossil-fuel Based Generators

Ontario has a diverse power generation mix which includes nuclear, hydro-electric, gas, coal and a small percentage of wood-waste, wind and solar. Nuclear and large hydro-electric facilities provide the base load generation. Fossil-fuel generators are generally operated during the day but also supply some power during the base demand conditions. These plants, mainly coal- and gas-fired units, are responsible for the CO_2 emissions in Ontario.

Ontario's total GHG emissions are estimated to be 216.5 Mt (CO_2 equivalent) by the end of 2010, out of which 38.8 Mt is expected from the power generation sector [3]. CO_2 emissions per unit of energy output from various types of electric generators in Ontario are presented in Table 2-1 [17]. There are indirect emissions associated with the power generation from nuclear power plants which involves the extraction, enrichment and chemical treatment of nuclear fuel. Biomass, coal and natural gas show the maximum emissions per kWh; the contribution of biomass towards Ontario's total emissions can be ignored since the percentage share of all the alternative energy resources in Ontario's generation mix is only 0.7% [18]. Therefore the electric generators using coal and gas as fuel are the major contributors to CO_2 emissions. Emission factors provided by Natural Resources Canada [3] for natural gas and coal fired plants are 181.1 and 349.2 g CO_2 equivalent/kWh. These factors are smaller than those presented in Table 2-1[1] because they are calculated considering the

[1] The two emission factors are different because, one is estimated using the energy that produces electricity and the other uses the generated electricity. This represents the energy conversion losses in the power plants.

input equivalent fuel energy to the power plant, instead of the net power output, and hence ignore the plant efficiency in the emissions calculations.

Table 2-1: GHG Emissions from electricity generators in Ontario [17].

Source	GHG Emissions (g CO_2 equivalent/ kWh)
Solar	72.63
Wind	9.14
Hydro (run-of-river)	3.03
Hydro (reservoir)	4.1
Biomass	1097.55
Natural gas	478.55
Nuclear	7.18
Coal	1035.41

According to the World Resources Institute [19], CO_2 accounts for 72% of total GHG emissions to the atmosphere and thus are the most important source of global warming. Economists have associated a social cost with these emissions to account for the damage caused by CO_2. As per [20]; "The Social Cost of Carbon (SCC) is usually estimated as the net present value of climate change impacts over the next 100 years (or longer) of one additional tonne of carbon emitted to the atmosphere today. It is the marginal global damage cost of carbon emissions." Many studies have been carried out to estimate the value of SCC but these estimates have varied widely because of various uncertainties associated with climate change. A study carried out by Department of Environment, London [21], suggested a range for SCC of $6.8 – 154 per tonne for emissions between 2001 and 2010, underestimating the large uncertainties associated with climate change damages. In [22], the author found significant uncertainties in SCC studies and concluded that marginal damage costs are unlikely to exceed $50 per tonne of carbon and estimated a mean rate of $16 per tonne of carbon emission. The authors in [23] suggest that the social cost of carbon would be in the order of $85/tonne as of 2005. This figure is well above the estimated values reported in some other studies but lies well within the suggested range of published estimates. Based on these references, a value of $100/tonne is used here.

2.2 Forecasting Ontario's CO_2 Emissions from Power Generation

The IESO does not provide generation forecasts; therefore; in order to estimate CO_2 emissions and develop a forecast model, the power generation from coal and gas-fired generating units in Ontario needs to be forecasted. Rather than considering each individual unit separately, the estimation can be carried out by considering aggregate generation from coal-fired plants and from gas-fired plants, separately. These forecasts are carried out here using a simple econometric model.

2.2.1 Time Series Analysis Based Forecasting

A time series represents a collection of observations made sequentially in time. There are various types of time series such as economic time series, physical time series, marketing time series and demographic time series. There exist several possible objectives in time series analysis; these may be classified as description, explanation, prediction and control. Power generation data represents a physical time series that is used in this thesis for prediction purposes and it may have seasonal effect, cyclic changes or it may follow a certain trend.

In the following work, a single-variable econometric time series analysis is considered to forecast the generation for the next day, based on the mean power generation and variation of each individual observation from mean value. The next section describes the mathematical model used for forecasting studies.

2.2.2 Mathematical Model

The following are the external inputs, publically available at the IESO website, required by the forecasting model:

- A 24-hour ahead total market demand profile for Ontario. This is obtained from pre-dispatch data.
- Hourly values of Ontario's system demand for the past 14 days.
- Hourly values of cumulative generation from coal- and gas-fired units for the past 14 days.

The model described next is used to forecast the power generation from coal and gas fired power plants, separately. The following set of equations describes the forecasting model based on single-variable econometric time-series equation [24]:

$$\hat{\hat{Y}}_{k,p} = \bar{Y}_{k,p} + B_k \left(\hat{X}_k - \bar{X}_k\right) \qquad \forall\, k \in \{1,2,\ldots,24\}, \forall\, p \in \{coal, gas\} \qquad (2.1)$$

$$\bar{X}_k = \frac{1}{n}\sum_{j=1}^{n} X_{j,k} \qquad \forall\, k \in \{1,2,\ldots,24\}, \forall\, j \in \{1,2,\ldots,14\} \qquad (2.2)$$

$$\bar{Y}_{k,p} = \frac{1}{n}\sum_{j=1}^{n} Y_{j,k,p} \qquad \forall\, k \in \{1,2,\ldots,24\},\ \forall\, j \in \{1,2,\ldots,14\},\ \forall\, p \in \{coal, gas\} \qquad (2.3)$$

$$B_k = \frac{\sum_{j=1}^{n} Y_{j,k}\left(X_{j,k} - X_{mean}\right)}{\sum_{j=1}^{n}\left(X_{j,k} - X_{mean}\right)^2} \qquad \forall\, k \in \{1,2,\ldots,24\},\ \forall\, j \in \{1,2,\ldots,14\},\ \forall\, p \in \{coal, gas\} \qquad (2.4)$$

where all variables and parameters, for all equations in this chapter, are defined in the Nomenclature section.

2.2.2.1 Forecast for Weekdays and Weekends

Ontario's market demand varies considerably from weekdays to weekends. Since market demand is an important variable in the forecasting model therefore variation in it will affect the estimates. Therefore separate forecast for weekdays and weekends is proposed although the structure of the two models is the same. The weekday forecasting model uses data for the last 14 days, while the weekend forecasting model uses last 8 weekend days' data.

Therefore Equations (2.1) to (2.4) can be used for weekend estimates with $X_{j,k}$ and $Y_{j,k,p}$ are requird to be replaced by weekends data where $j \in \{1,2,\ldots,8\}$.

2.3 Results and Analysis

The following example illustrates the forecasting procedure: First, a generation forecast for Jan. 19, 2009 is carried out for coal-fired power plants. Table A-1 presents the 24-hour actual demand data in Ontario for the previous 14 days obtained at [25]. Table A-2 shows the corresponding generation from coal-fired plants obtained at [26]. Table 2-2 shows the forecasted generation profile from coal-fired power plants; equations (2.1) to (2.4) are used to calculate $\hat{Y}_{k,p}$, $\bar{X}_k$, $\bar{Y}_{k,p}$ and B_k, respectively.

Table 2-2: Day-ahead forecasted generation from coal-fired units $\hat{Y}_k$.

Time (hr)	$\bar{Y}_{k,p}$ (MW)	$\bar{X}_k$ (MW)	B_k	Ontario's dayahead demand X_k (MW)	Forecast $\hat{Y}_k$ (MW)
1	2418	18600	0.844	18133	2023
2	2277	18322	0.970	17955	1921
3	2213	18171	0.939	18044	2093
4	2179	18109	0.895	17962	2048
5	2294	18250	0.825	18161	2221
6	2408	18822	0.696	19278	2725
7	2793	20255	0.612	21048	3278
8	3100	21708	0.601	22578	3623
9	3150	22013	0.707	22887	3768
10	3026	22109	0.658	23065	3655
11	3109	22195	0.676	23123	3737
12	3196	22234	0.709	23251	3917
13	3155	22084	0.704	22749	3624
14	3136	21992	0.662	22782	3659
15	3126	21755	0.689	21851	3192
16	3153	21932	0.663	22292	3392
17	3237	22516	0.548	23137	3578
18	3422	23550	0.414	23911	3571
19	3448	23434	0.454	23986	3699
20	3342	23098	0.512	24091	3850
21	3325	22579	0.456	23585	3784
22	3237	21738	0.543	22707	3763
23	2948	20737	0.556	21548	3399
24	2756	19477	0.564	19964	3031

Similarly generation forecasts for gas-fired power plants can be obtained by replacing the corresponding $\boldsymbol{Y_{j,k}}$ values with historical data of gas-fired generating units. The historical values of gas-fired plants obtained from [26] are shown in Table A-3, and the corresponding forecasted generation is shown in Table 2-3.

Table 2-3: Day-ahead forecasted generation from gas-fired units $\widehat{Y}_k$.

Time (hr)	$\bar{Y}_{k,p}$ (MW)	$\bar{X}_k$ (MW)	B_k	Ontario's dayahead demand X_k (MW)	Forecast $\hat{Y}_k$ (MW)
1	1141	18600	0.041	18133	1122
2	1101	18322	0.004	17955	1099
3	1093	18171	0.027	18044	1089
4	1101	18109	0.061	17962	1092
5	1127	18250	0.119	18161	1117
6	1280	18822	0.249	19278	1393
7	1538	20255	0.251	21048	1737
8	1928	21708	0.256	22578	2151
9	2186	22013	0.245	22887	2401
10	2249	22109	0.188	23065	2428
11	2379	22195	0.185	23123	2551
12	2498	22234	0.228	23251	2730
13	2506	22084	0.199	22749	2639
14	2514	21992	0.202	22782	2674
15	2363	21755	0.216	21851	2384
16	2275	21932	0.188	22292	2343
17	2281	22516	0.297	23137	2466
18	2428	23550	0.351	23911	2554
19	2473	23434	0.405	23986	2696
20	2356	23098	0.378	24091	2732
21	2249	22579	0.251	23585	2501
22	1988	21738	0.271	22707	2250
23	1644	20737	0.230	21548	1830
24	1283	19477	0.291	19964	1424

2.3.1 Day-ahead Emissions Profile from Power Generation in Ontario

Natural gas and coal have different chemical compositions and hence produce different amount of CO_2. Natural gas is the least carbon-intensive fossil fuel; combustion of natural gas emits 45% less CO_2 than coal [27]. The CO_2 emissions factor is defined as the average amount of CO_2 discharged into the atmosphere by power generators and is expressed in terms of tonne/MWh. Study carried out by CIRAIG to estimate emissions rates in Ontario from various electrical generators is shown in Table 2-1; the emissions factor of coal fired units presented in this study is approximately equal to the emissions rate given by US-Environmental Protection Agency [28], [29] but the emissions factor of gas fired units is based on average United Kingdom values. Thus, in this thesis, data available from [28], [29] is used; accordingly, the day-ahead emissions profile is calculated as follows:

$$E_k = R_c * Pc_k + R_g * Pg_k \qquad \forall k \in \{1,2,\dots,24\} \qquad (2.5)$$

where R_c=1.0201 tonne/MWh [28] and R_g=0.5148 tonne/MWh [29], represents the CO_2 emissions from direct burning of fuel. There are additional emissions associated with coal-fired power plant because of mining, cleaning and transporting coal to the power plant. Similarly, for gas-fired power plants, the process of extraction, treatment and transportation of gas to the plant produces additional emissions. However, these indirect emissions are estimated based on whole life cycle of plants and therefore not considered in this model. Thus, from the forecasts obtained in Tables 2-2 and 2-3, the forecasted hourly emissions obtained from equation (2.5) are shown in Table 2-4.

Table 2-4: Day-ahead forecasted emissions profile.

Time (hr)	Forecasted generation of coal fired units Pc_k (MW)	Forecasted generation of gas fired units Pg_k (MW)	Total CO_2 emisions E_k (tonne/hr)
1	2023	1122	2641
2	1921	1099	2526
3	2093	1089	2696
4	2048	1092	2651
5	2221	1117	2840
6	2725	1393	3497
7	3278	1737	4238
8	3623	2151	4803
9	3768	2401	5079
10	3655	2428	4978
11	3737	2551	5125
12	3917	2730	5401
13	3624	2639	5055
14	3659	2674	5109
15	3192	2384	4484
16	3392	2343	4666
17	3578	2466	4919
18	3571	2554	4957
19	3699	2696	5161
20	3850	2732	5334
21	3784	2501	5148
22	3763	2250	4997
23	3399	1830	4410
24	3031	1424	3825

2.3.2 Average Cost of CO_2 Emissions

The average cost of CO_2 emissions per kWh energy produced is calculated based on the SCC as follows:

$$CE_k = \frac{E_k * SCC}{\hat{X}_k} \qquad \forall\, k \in \{1,2,\dots,24\} \tag{2.6}$$

with SCC = \$100/tonne and $\hat{X}_k$ is in kW.

Table 2-5 represents the forecasted marginal costs of CO_2 emissions.

Table 2-5: Average cost of CO_2 emissions.

Time (hr)	Total CO_2 emisions E_k (tonne/hr)	Hourly emissions cost profile (\$/hr)	Hourly average emissions cost CE_k (cents/kWh)
1	2641	264104	1.46
2	2526	252571	1.41
3	2696	269622	1.49
4	2651	265109	1.48
5	2840	284028	1.56
6	3497	349740	1.81
7	4238	423848	2.01
8	4803	480346	2.13
9	5079	507917	2.22
10	4978	497835	2.16
11	5125	512479	2.22
12	5401	540096	2.32
13	5055	505517	2.22
14	5109	510935	2.24
15	4484	448356	2.05
16	4666	466576	2.09
17	4919	491893	2.13
18	4957	495746	2.07
19	5161	516138	2.15
20	5334	533424	2.21
21	5148	514790	2.18
22	4997	499694	2.20
23	4410	440968	2.05
24	3825	382486	1.92

2.3.3 Error Analysis of Generation Forecasts

The Mean Absolute Percentage Error (MAPE) for the forecasted power generation from coal or gas fired plants can be defined as:

$$MAPE = \frac{1}{24} * \sum_{k=1}^{24} \frac{\left|\hat{Y}_{k,p} - Y_{j,k,p}\right|}{Y_{j,k,p}} \quad (2.7)$$

Figure 2-1 and 2-2 compares the forecasted and observed power generation from coal and gas fired units in Ontario, respectively. The MAPE for coal and gas fired units in this case 8.4% and 9.2%, respectively, for a winter day (Jan. 19, 2009).

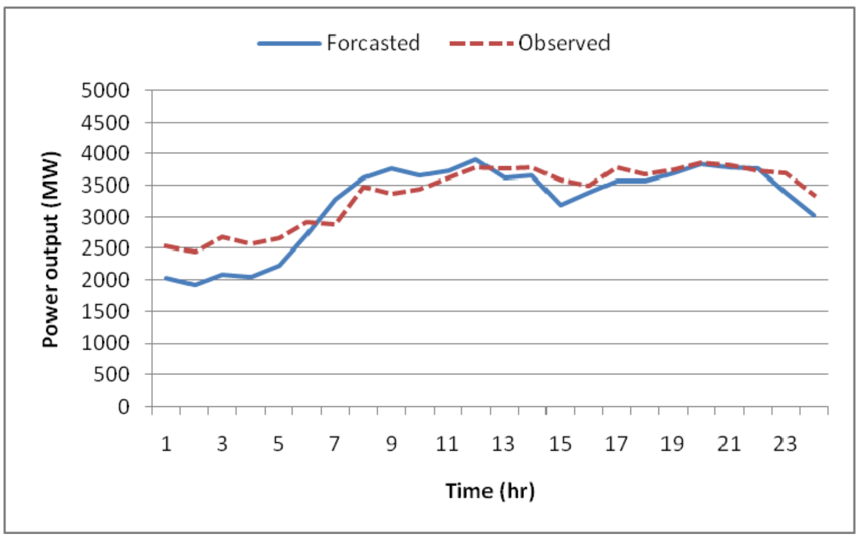

Figure 2-1: Comparison of forecasted and actual power generation from coal fired plants on a winter weekday.

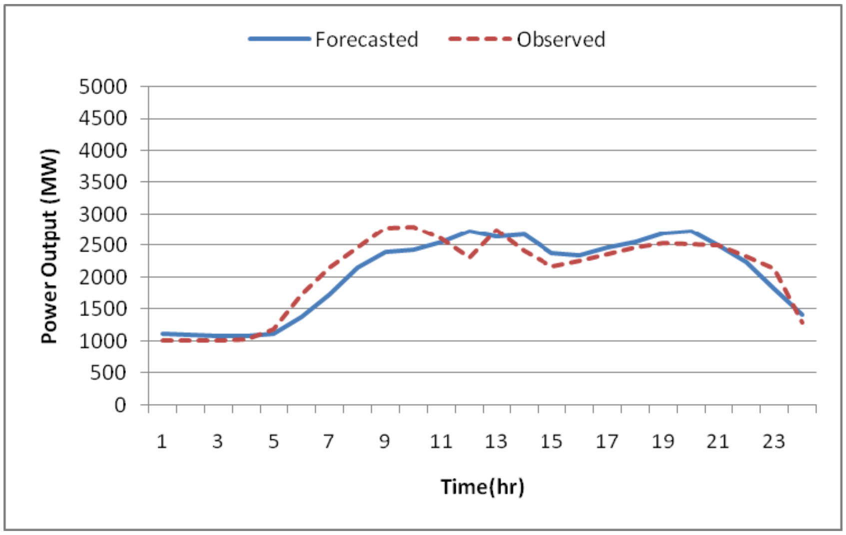

Figure 2-2: Comparison of forecasted and actual power generation from gas fired plants on a winter weekday.

Similarly, a comparison of forecasted and observed power generation from coal and gas fired units in Ontario for a summer day (July 14, 2009) is presented in Figure 2-3 and 2-4. The MAPE for coal and gas fired units is 44.1% and 10.9% respectively.

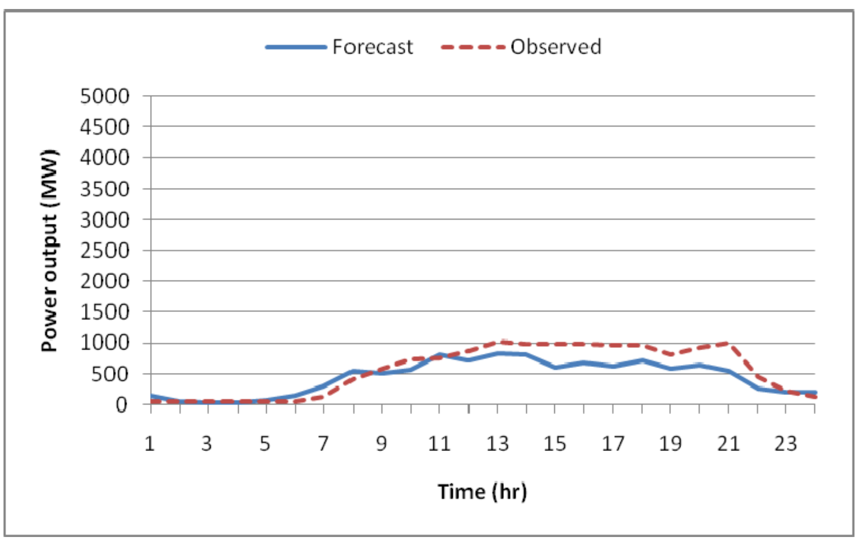

Figure 2-3: Comparison of forecasted and actual power generation from coal fired plants on a summer weekday.

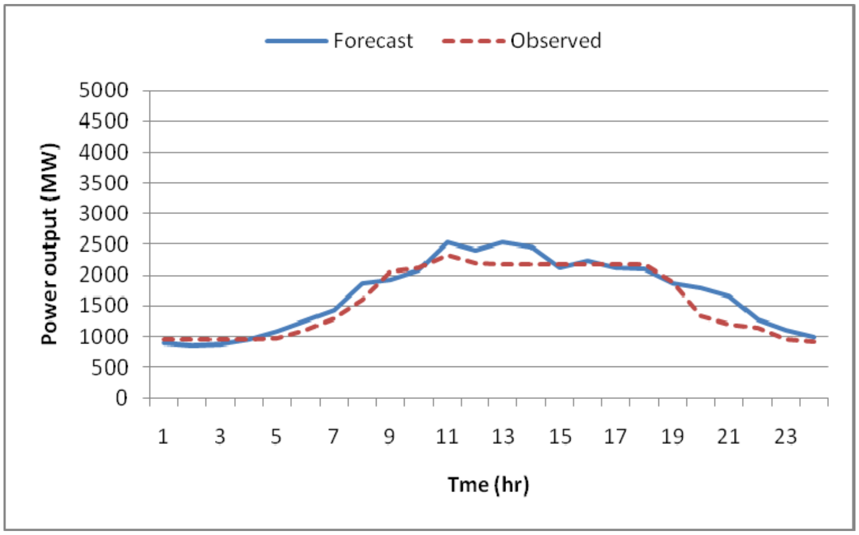

Figure 2-4: Comparison of forecasted and actual power generation from gas fired plants on a summer weekday.

Forecasted power generation is not always very similar to the observed values. During weekends and holidays, since the demand of electricity is lower than the weekdays, generation from fossil-fueled generators is usually lower than the regular weekdays. Because of this, the coal-fired generation forecast for a public holiday in April shows erroneous results as presented in Figure 2-5. On the other hand, the forecast for gas-fueled generation presented in Figure 2-6 for the same day shows much better results with MAPE of 26.1%.

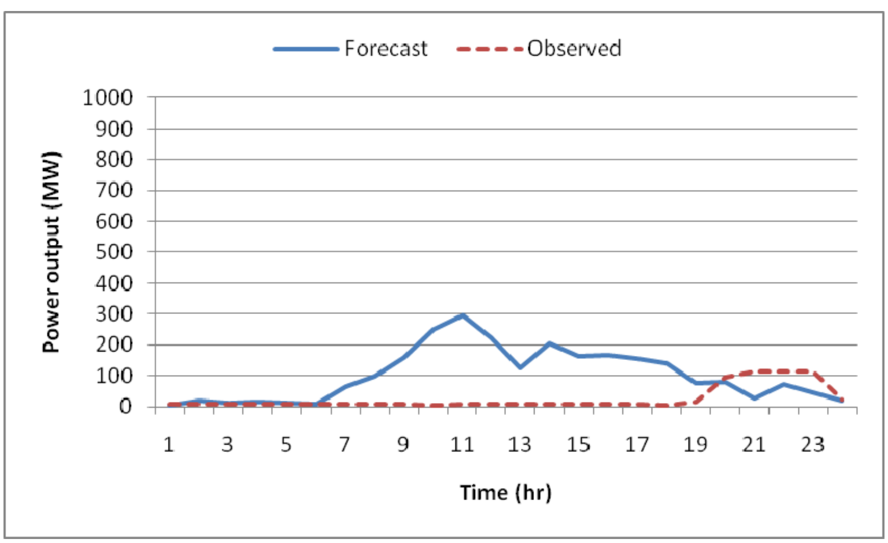

Figure 2-5: Comparison of forecasted and observed power generation from coal-fired plants for a public holiday.

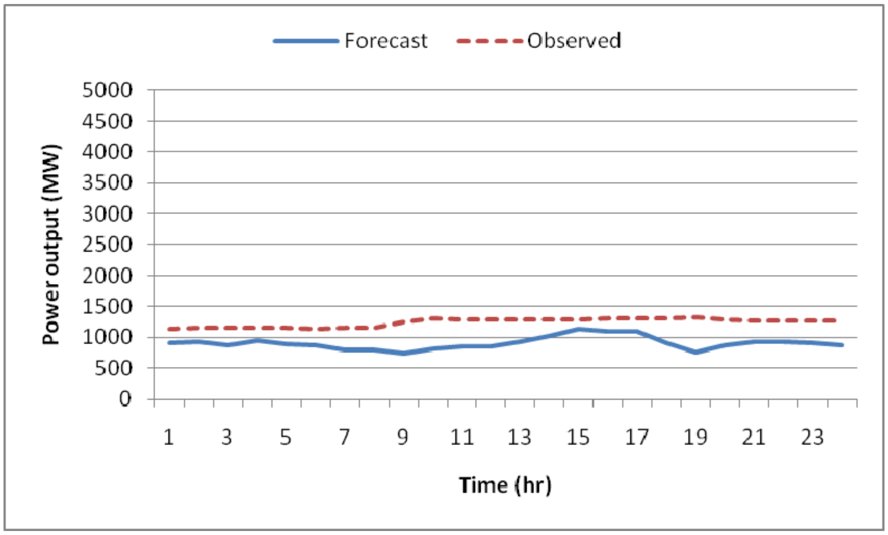

Figure 2-6: Comparison of forecasted and observed power generation from gas fired plants for a public holiday.

The proposed forecasting model, which estimates power generation based on preceding trends, is unable to estimate generation accurately. However, aggregated estimate of fossil-fueled generation as shown in Fig 2-7 depicts improved forecast with MAPE equals 20.4%. Therefore this result is acceptable for the EHMS model which will require the combined emission profile.

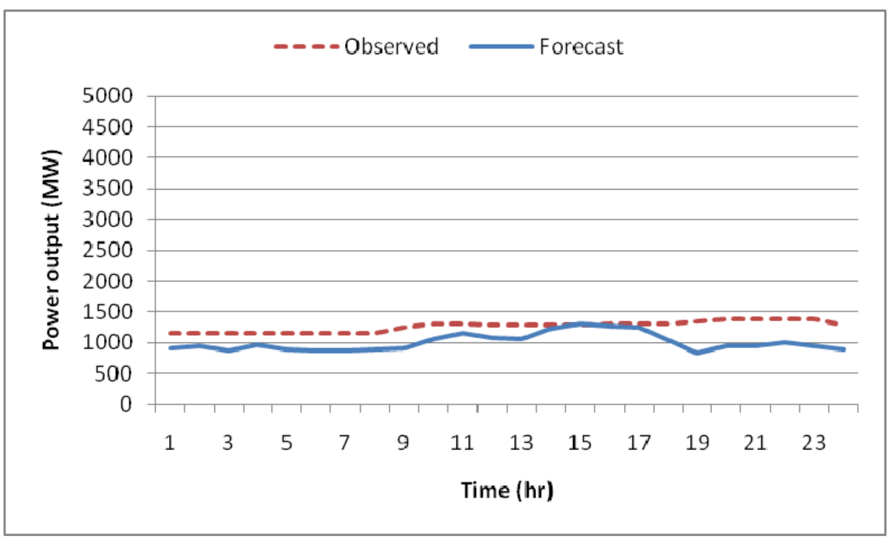

Figure 2-7: Comparison of total forecasted and observed power generation from fossil-fueled plants for a public holiday.

2.3.3.1 Root Mean Square Error

The following standard deviation or Root Mean Square Error (RMSE) of the relative error for each hour is used as an indicator of the size of the error during that certain hour:

$$\mathrm{RMSE}(t) = \sqrt{\frac{1}{N} * \sum_{k=1}^{N} \left(\frac{Y_k - Y_k^*}{Y_k^*}\right)^2} \quad (2.8)$$

where all variables and parameters are defined in the Nomenclature section. The RMSE calculated for combined generation from coal- and gas-fired generators is shown in Figure 2-8. The graph illustrates higher errors in the summer, since these vary at each hour from 13% to 26% in the summer while 6% to 13% in the winter.

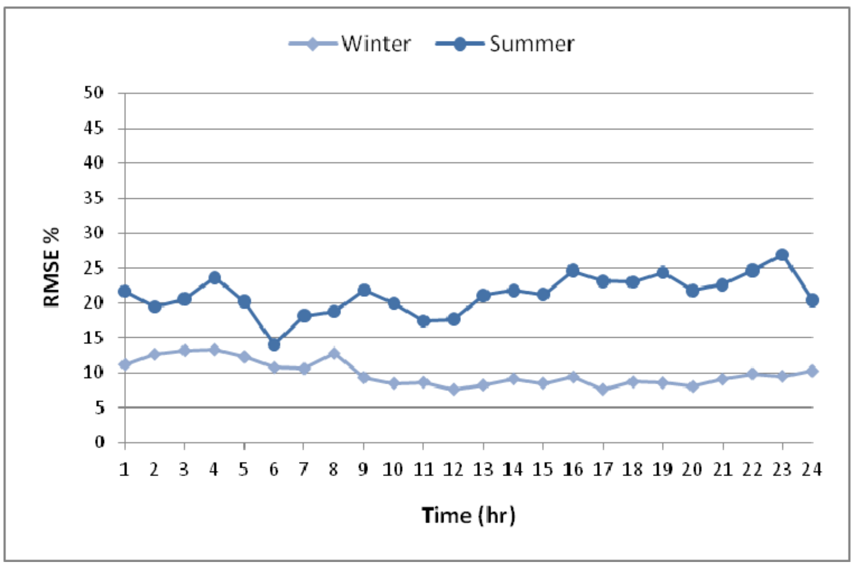

Figure 2-8: RMSE for the relative errors for summer and winter weekdays.

2.4 Summary

This chapter presented a methodology to forecast Ontario's emissions profile by estimating the power generation from coal-fired and gas-fired generating units. A simple mathematical model was developed based on single-variable econometric time-series, so that it can be readily implemented in the EHMS residential sector model. The results obtained are reasonably acceptable for the EHMS residential sector model. However, the forecast model has certain limitations and it produces errors in estimates on holidays and some weekends. The model basically follows the trend of preceding generation data, and thus generates poor estimates if the system operator decides to introduce a new generator or shut down a unit for maintenance.

The social cost associated with CO_2 emissions from power generation in Ontario is also described. Using the aggregate emissions profile, the marginal cost of CO_2 emissions are calculated, which serves as important information to the EHMS optimization model and case-studies described in the next chapters.

Chapter 3
EHMS Residential Sector Model

This chapter presents the details of the EHMS residential sector model used in this thesis. Different objective functions are defined including minimization of cost, minimization of energy consumption and minimization of CO_2 emissions. The mathematical models of individual appliances, and an Energy Storage Device (ESD), are described with some suggested modifications to the models described in [9]. Finally, realistic input data for the simulation of the EHMS model is presented corresponding to different energy pricing schemes, Ontario's emissions profile, weather conditions, and typical power ratings of home appliances, are presented and discussed.

3.1 EHMS Mathematical Model for Residential Sector

In this section, the EHMS optimization model used for residential sector is presented. The mathematical model is described in detail in [8], and certain modification to the model were proposed in [9] from the view point of practical implementation. In this work, the revised model of [9] is used for validation/simulation purposes, with more realistic room temperature settings, operational hours and name plate ratings. Also the optimization of customer's natural gas consumption is included in addition to electricity consumption. Furthermore, the minimization of CO_2 is also integrated into the model. All the devices in [9] are assumed to be working over a scheduling period of fifteen minute intervals; however the granularity of fridge and water heater has been decreased here to seven and half minute intervals in this work, given their thermodynamic characteristics.

3.1.1 Objective Functions

3.1.1.1 Maximization of Comfort

This simulates the behavior of a typical home energy customer. The objective is to maximize the customer comfort by minimizing the temperature deviation from the pre-defined set points, while satisfying the devices' individual constraints, as follows:

$$\min J_0 = \sum_{t=1}^{T} \left[\theta_{in}(t) - \theta_{set,AC/H}(t)\right]^2 + \sum_{t=1}^{T'} \left[\left(\theta_{FR}(t) - \theta_{set,FR}(t)\right)^2 + \left(\theta_{WH}(t) - \theta_{set,WH}(t)\right)^2\right] \tag{3.1}$$

where all variables and parameters are defined in the Nomenclature section. In this case, no consideration is given to the minimization of energy cost, energy consumption or emissions.

3.1.1.2 Minimization of Cost

The objective in this case is to minimize the cost of energy and maximize the operation of energy storage device while satisfying the individual device constraints as follows:

$$min\, J_1 = \sum_{t=1}^{T} \left[\sum_{i\epsilon A} P_i C(t) S_i(t) + P_{LI} C(t) S_{LI}(t) - P_{ESD} C_{ESD}(t) S_{ESD}(t) + \{ P_H C(t) + HR_H CG(t)\} S_H(t)\right] + \sum_{t=1}^{T'} [P_{FR} C(t) S'_{FR}(t) + \{ P_{WH} C(t) + HR_{WH} CG(t)\} S'_{WH}(t)] \tag{3.2}$$

This objective function represents the total energy cost of most appliances over scheduling horizon T (96, 15 min. intervals), and for appliances FR and WH over a scheduling horizon T' (192, 7½ min. intervals). The ESD corresponds to a solar energy source, and the objective is to maximize its operation.

3.1.1.3 Minimization of Energy Consumption

This objective function minimizes the operational hours of all devices and maximizes the operation of energy production/storage device as follows:

$$min\, J_2 = \sum_{t=1}^{T} \left[\sum_{i\epsilon A} P_i S_i(t) + P_{LI} S_{LI}(t) - P_{ESD} S_{ESD}(t) + (P_H + HR_H) S_H(t)\right] + \sum_{t=1}^{T'} [P_{FR} S'_{FR}(t) + (P_{WH} + HR_{WH}) S'_{WH}(t)] \tag{3.3}$$

3.1.1.4 Minimization of Emissions

This objective here is to minimize CO_2 emissions as follows:

$$min\, J_3 = \sum_{t=1}^{T}\left[\sum_{i\epsilon A} P_i CE(t)S_i(t) + P_{LI}CE(t)S_{LI}(t) - P_{ESD}C_{ESD}(t)S_{ESD}(t) + \{\, P_H CE(t) + HR_H CG(t)\,\} S_H(t)\right]$$
$$+ \sum_{t=1}^{T'} [P_{FR}CE(t)S'_{FR}(t) + \{\, P_{WH}CE(t) + HR_{WH}CG(t)\} S'_{WH}(t)] \qquad (3.4)$$

The model in this case generates optimum schedules for all appliances based on Ontario's emissions profile, and maximizes the operation of ESD to reduce the customer's contribution to CO_2 emissions.

3.1.1.5 Minimization of Cost Subject to Peak Power Constraint

In this case, the objective is the minimization of total energy cost (3.2), with the following additional constraint on peak power for electricity consumption at each interval:

$$\sum_{i=All\ devices} P_i(t)S_i(t) \leq P_{max}(t) \qquad \forall\, t\ \in T \qquad (3.5)$$

Since the peak power has an upper limit at each time interval, the optimum schedule generated for all devices are inter-dependent. This case is of interest to the power system operators or LDCs, which can use it to reduce the peak load of the system during on-peak hours.

3.1.1.6 Minimization of Cost, Energy Consumption and Emissions

In this case, the individual objective functions of minimizing total energy costs, energy consumption and emissions are assigned "equal" weights to build the following objective function that minimizes all of them at the same time as follows:

$$\min J_4 = w_1 J_1 + w_2 J_2 + w_3 J_3 \qquad (3.6)$$

where, w_1, w_2 and w_3 are the weights attached to the customer's total energy cost, total energy consumption, and total emissions cost, respectively. These weights are calculated by simulating the EHMS model with the individual objective functions each time. Thus, using "minimization of cost" as objective function results in $\$X$, similarly "minimization of energy" and "minimization of emissions" yield $Y\ kWh$ and $\$Z$, respectively. Therefore, the weights are given as follows:

$$w_1 = 1 \tag{3.7}$$

$$w_2 = \frac{X}{Y} \tag{3.8}$$

$$w_2 = \frac{X}{Y} \tag{3.9}$$

3.1.2 Device Models

3.1.2.1 Air Conditioner and Furnace

The house temperature is normally set by the customers according to their comfort level; when they are not at home or asleep, temperature settings can be different. Since some household customers may or may not have a programmable thermostat, the air conditioner/heating model is developed considering two different thermostat settings for the house. One is based on a fixed temperature setting and the other on Programmable thermostat. In the former, the room temperature is preset at a fixed value all through the day, and in the later temperature set points are different for different periods of the day.

The combined mathematical model of air conditioner (AC) and furnace (H) as presented in [9], is as follows:

$$S_i(t) = \begin{cases} 0 \text{ or } 1 & \text{if } t \in T_i\,, i = AC/H \\ 0 & \text{if } t \notin T_i\,, i = AC/H \end{cases} \tag{3.10}$$

$$S_i(t=1) = \begin{cases} 1 & \text{if } \theta_{in}(t=0) < \theta_{in}^{low} \\ 0 & \text{if } \theta_{in}(t=0) > \theta_{in}^{up} \end{cases} \tag{3.11}$$

$$\theta_{in}^{low} \leq \theta_{in}(t) \leq \theta_{in}^{up} \qquad \forall t \in T_i\,, i = AC/H \tag{3.12}$$

$$\theta_{in}(t) = \theta_{in}(t-1) + \beta_{AC}\, AL(t) - \alpha_{AC}\, S_{AC}(t) + \alpha_H\, S_H(t) \tag{3.13}$$

$$+\gamma_{AC}\big(\theta_{out}(t) - \theta_{in}(t)\big) \qquad \forall t \in T_i\,, i = AC/H$$

$$S_C(t) + S_H(t) \leq 1 \qquad \forall t \in T_i\,, i = AC/H \tag{3.14}$$

where β_{AC} represents the effect of Activity Level on the AC/H temperature (ºC per unit of Activity Level), and α_{AC} corresponds to the cooling/heating effect of one (ON) state of AC/H (ºC per interval). The parameter γ_{AC} represents the effect of energy losses on room temperature associated with the indoor and outdoor temperature differences. The calculation of these parameters is explained in [9]. Equation (3.14) is defined to ensure that the air conditioner and furnace do not operate simultaneously.

To introduce a set point temperature for the house, (3.12) is replaced by (3.15), (3.16) and (3.17):

$$\theta_{in}^{low}(t) \leq \theta_{in}(t) \leq \theta_{in}^{up}(t) \qquad \forall\, t \in T_i\,, i = AC/H \tag{3.15}$$

$$\theta_{in}^{up}(t) = \theta_{set,i}(t) + \Delta T^{up}(t) \qquad \forall\, t \in T_i\,, i = AC/H \tag{3.16}$$

$$\theta_{in}^{low}(t) = \theta_{set,i}(t) + \Delta T^{low}(t) \qquad \forall\, t \in T_i\,, i = AC/H \tag{3.17}$$

where $\theta_{set,i}(t)$ is the temperature set point, and $\Delta T^{up}(t)$ and $\Delta T^{low}(t)$ are the allowed temperature deviations from the set point.

3.1.2.2 Refrigerator

The refrigerator (FR) mathematical model in [8] and [9] is represented by the following set of equations:

$$S'_i(t) = \begin{cases} 0 \text{ or } 1 & \text{if } t \in T_i^{'}, i = FR \\ 0 & \text{if } t \notin T_i^{'}, i = FR \end{cases} \tag{3.18}$$

$$S'_i(t = 1) = \begin{cases} 1 & \text{if } \theta_{FR}(t = 0) < \theta_{FR}^{low} \\ 0 & \text{if } \theta_{FR}(t = 0) > \theta_{FR}^{up} \end{cases} \tag{3.19}$$

$$\theta_{FR}^{low} \leq \theta_{FR}(t) \leq \theta_{FR}^{up} \qquad \forall t \in T_i^{'}, i = FR \tag{3.20}$$

$$\theta_{FR}(t) = \theta_{FR}(t-1) + \beta_{FR}\, AL_{FR}(t) - \alpha_{FR}\, S'_i(t) + \gamma_{FR} \qquad \forall t \in T_i^{'}, i = FR \tag{3.21}$$

where $AL_{FR}(t)$ is the refrigerator activity level during each time interval, β_{FR} represents the effect of activity level on the refrigerator temperature (ºC per unit of AL), α_{FR} corresponds to the cooling effect of the ON state of the refrigerator (ºC per interval) and γ_{FR} reflects the warming effect of the OFF state of the refrigerator (ºC per interval).

3.1.2.3 Water heater

Similar to a gas furnace, a gas water heater also requires natural gas as fuel with a minor percentage share of electricity consumption. Gas consumption depends on the burner operation hours and the fuel input rate, while electricity consumption is due to the blower motor.

The simplified mathematical model for water heater (WH) is described in [8] and [9] and is given by the following set of equations:

$$S'_i(t) = \begin{cases} 0 \text{ or } 1 & \text{if } t \in T_i^{'}, i = WH, \\ 0 & \text{if } t \notin T_i^{'}, i = WH, \end{cases} \qquad EOT_i \leq T_i^{'} \leq LOT_i \quad (3.22)$$

$$S'_i(t = 1) = \begin{cases} 1 & \text{if } \theta_{WH}(t = 0) < \theta_{WH}^{low} \\ 0 & \text{if } \theta_{WH}(t = 0) > \theta_{WH}^{up} \end{cases} \quad (3.23)$$

$$\theta_{WH}^{low} \leq \theta_{WH}(t) \leq \theta_{WH}^{up} \qquad \forall t \in T_i^{'}, i = WH \quad (3.24)$$

$$\theta_{WH}(t) = \theta_{WH}(t-1) - \beta_{WH}\, HWU(t) + \alpha_{WH}\, S'_i(t) - \gamma_{WH} \qquad \forall t \in T_i^{'}, i = WH \quad (3.25)$$

where β_{WH} represents the effect of hot water usage on water temperature (ºC per liters of hot water usage), α_{WH} corresponds to the warming effect of one ON state (ºC per time interval), γ_{WH} reflects the cooling effect of one OFF state (ºC per time interval), and $HWU(t)$ represents the hot water usage at time *t*. Equation (3.22) enables the customer to specify the period, $T_i^{'}$ of the water heater operation between EOT_i (early operating time) and LOT_i (late operating time).

3.1.2.4 Lighting

The mathematical model for indoor lighting (LI) is described in [8] and [9] and is given by the following set of constraints:

$$S_i(t) = \begin{cases} 0 \text{ or } 1 & \text{if } t \in T_i, i = LI \\ 0 & \text{if } t \notin T_i, i = LI \end{cases} \quad (3.26)$$

$$IL(t) + IL_{out}(t) \geq (1 + K_t)\, IL_{req}(t) \qquad \forall t \in T_i \quad (3.27)$$

$$K_t = -0.926\, C_t + 1.39 \qquad \forall t \in T_i \quad (3.28)$$

where $IL(t)$ represents the illumination level of the house at time t, $IL_{out}(t)$ corresponds to the normalized outdoor daylight illumination that can enter the house, $IL_{req}(t)$ represents the required illumination inside the house and K_t is a coefficient that represents the dependence of additional lighting on the electricity price [8] and is equal to unity at off-peak periods and zero at on-peak periods of electricity price. Equation (3.27) ensures that the illumination level is equal to or more than the required illumination during on-peak periods, whereas the illumination during off-peak periods can be twice or more than the required illumination. For maximization of comfort, illumination level has to be independent of the energy price; therefore K_t is set to unity in this case.

3.1.2.5 Stove

The operational constraints for daily operation of the stove (Stv) are reported in [8] and [9], are as follows:

$$S_i(t) = \begin{cases} 0 \text{ or } 1 & \text{if } t \in T_i, i = Stv \\ 0 & \text{if } t \notin T_i, i = Stv \end{cases} \tag{3.29}$$

$$U_i(t) - D_i(t) = S_i(t) - S_i(t-1) \qquad \forall t \in T_i, i = Stv \tag{3.30}$$

$$U_i(t) - D_i(t) \leq 1 \qquad \forall t \in T_i, i = Stv \tag{3.31}$$

$$\sum_{t \in T_i} S_i(t) = ROT_i \qquad \forall t \in T_i, i = Stv \tag{3.32}$$

$$\sum_{k=t-1}^{t-MUT_i+1} U_i(k) \leq S_i(t) \qquad \forall t \in T_i, i = Stv \tag{3.33}$$

This mathematical model simply tries to optimally allocate the operating hours of the stove according to the objective function. For example, if the with objective is minimize cost, the model assigns the operating hours during the periods of lower energy cost.

3.1.2.6 Dishwasher

The simplified mathematical model for a dishwasher (DW) described in [9] is represented by the following set of equations:

$$S_i(t) = \begin{cases} 0 \text{ or } 1 & \text{if } t \in T_i, i = DW \\ 0 & \text{if } t \notin T_i, i = DW \end{cases} \tag{3.34}$$

$$U_i(t) - D_i(t) = S_i(t) - S_i(t-1) \qquad \forall t \in T_i, i = DW \tag{3.35}$$

$$U_i(t) - D_i(t) \leq 1 \qquad \forall t \in T_i, i = DW \tag{3.36}$$

$$\sum_{t \in T_i} S_i(k) = ROT_i \qquad \forall t \in T_i, i = DW \tag{3.37}$$

$$\sum_{k=t-1}^{t-MUT_i+1} U_i(k) \leq S_i(t) \qquad \forall t \in T_i, i = DW \tag{3.38}$$

$$\sum_{k=t-1}^{t+MDT_i+\mathbf{1}} D_i(k) \leq (1 - S_i(t)) \qquad \forall t \in T_i, i = DW \tag{3.39}$$

Similar to the stove, these set of equations also try to schedule the dishwasher operation according to the objective function of the model. For example, to minimize cost, the model solution allocates the dishwasher to off-peak periods when energy prices are low.

3.1.2.7 Cloth Washer and Dryer

The simplified mathematical model of the cloth washer (W) as given in [9] is represented by the following set of equations:

$$S_i(t) = \begin{cases} 0 \text{ or } 1 & \text{if } t \in T_i, i = W \\ 0 & \text{if } t \notin T_i, i = W \end{cases} \tag{3.40}$$

$$U_i(t) - D_i(t) = S_i(t) - S_i(t-1) \qquad \forall t \in T_i, i = W \tag{3.41}$$

$$U_i(t) - D_i(t) \leq 1 \qquad \forall t \in T_i, i = W \tag{3.42}$$

$$\sum_{t \in T_i} S_i(k) = ROT_i \qquad \forall t \in T_i, i = W \tag{3.43}$$

$$\sum_{k=t-1}^{t-MUT_i+1} U_i(k) \leq S_i(t) \qquad \forall t \in T_i, i = W \tag{3.44}$$

$$\sum_{k=t-1}^{t+MDT_i+\mathbf{1}} D_i(k) \leq (1 - S_i(t)) \qquad \forall t \in T_i, i = W \qquad (3.45)$$

Equations (3.40) to (3.45) are similar to the dishwasher model equations, and try to schedule the cloth washer depending on the objective function used. For example to minimize CO_2 emissions, the model allocates the cloth washer operations to periods of lower emissions.

A mathematical model similar to cloth washer is used for the dryer (DRY) as presented in [8] and [9]:

$$S_i(t) = \begin{cases} 0 \text{ or } 1 & \text{if } t \in T_i, i = DRY \\ 0 & \text{if } t \notin T_i, i = DRY \end{cases} \qquad (3.46)$$

$$U_i(t) - D_i(t) = S_i(t) - S_i(t-1) \qquad \forall t \in T_i, i = DRY \qquad (3.47)$$

$$U_i(t) - D_i(t) \leq 1 \qquad \forall t \in T_i, i = DRY \qquad (3.48)$$

$$\sum_{t \in T_i} S_i(k) = ROT_i \qquad \forall t \in T_i, i = DRY \qquad (3.49)$$

$$\sum_{k=t-1}^{t-MUT_i+1} U_i(k) \leq S_i(t) \qquad \forall t \in T_i, i = DRY \qquad (3.50)$$

$$\sum_{k=t-1}^{t+MDT_i+\mathbf{1}} D_i(k) \leq (1 - S_i(t)) \qquad \forall t \in T_i, i = DRY \qquad (3.51)$$

The operation of cloth washer and dryer is inter-dependent. Therefore, to ensure that the dryer operates after the washer and without exceeding the maximum time gap MAT_{GAP} the following equations are defined in [8] and [9]::

$$S_{DRY}(t) \leq \sum_{k=1}^{MAT_{GAP}} S_W(t-k) \qquad \forall t \in T_i \qquad (3.52)$$

$$S_{DRY}(t) + S_W(t) \leq 1 \qquad \forall t \in T_i \qquad (3.53)$$

$$\sum_{t \in DRY} S_{DRY}(t) = \sum_{t \in T_W} S_W(t) \qquad (3.54)$$

3.1.2.8 Pool pump

The pool pump ($Ppump$) needs to run for certain hours in a day to filter the swimming pool water at least once. The required number of operating hours depends on size of the pool and the water flow rate through the filter. The following set of equations represents the mathematical model of a pool pump as described in [8] and [9]:

$$S_i(t) = \begin{cases} 0 \text{ or } 1 & \text{if } t \in T_i, i = Ppump \\ 0 & \text{if } t \notin T_i, i = Ppump \end{cases} \tag{3.55}$$

$$U_i(t) - D_i(t) = S_i(t) - S_i(t-1) \qquad \forall\, t \in T_i, i = Ppump \tag{3.56}$$

$$U_i(t) - D_i(t) \leq 1 \qquad \forall\, t \in T_i, i = Ppump \tag{3.57}$$

$$\sum_{t \in T_i} S_i(t) = ROT_i \qquad \forall\, t \in T_i, i = Ppump \tag{3.58}$$

$$\sum_{k=t-1}^{t-MUT_i+1} U_i(k) \leq S_i(t) \qquad \forall\, t \in T_i, i = Ppump \tag{3.59}$$

$$\sum_{k=t-1}^{t+MDT_i+\mathbf{1}} D_i(k) \leq (1 - S_i(t)) \qquad \forall t \in T_i, i = Ppump \tag{3.60}$$

This model schedules the pump operation during off-peak price hours to save cost. The savings depend on whether the home owner wants to run the pool pump during the day or night.

3.1.2.9 Energy Storage Device

The ESD system considered here comprises of a solar PV rooftop panel and battery. The system can charge the battery and sell it to the grid at the same time. In Ontario, residential customers can install a solar PV panel up to 10 kW rating, to be eligible for the microFIT program [30]. The generic model for ESD is given by the following equations as per [8]:

$$S_i(t) = \begin{cases} 0 \text{ or } 1 & \text{if } t \in T_i, i = ESD \\ 0 & \text{if } t \notin T_i, i = ESD \end{cases} \tag{3.61}$$

$$ESL_{ESD}(t) \geq ESL_{ESD}^{min} \qquad \forall\, t \in T_i, i = ESD \tag{3.62}$$

$$\begin{aligned} ESL_{ESD}(t) = ESL_{ESD}(t-1) - \; & S_i(t)\, Discharg_{ESD} \\ & + Charge_{ESD}(t) \qquad \forall\, t \in T_i, i = ESD \end{aligned} \tag{3.63}$$

$$U_i(t) - D_i(t) = S_i(t) - S_i(t-1) \qquad \forall\, t \in T_i, i = ESD \quad (3.64)$$

$$U_i(t) - D_i(t) \leq 1 \qquad \forall\, t \in T_i, i = ESD \quad (3.65)$$

$$\sum_{k=t}^{t+MUT_i} S_i(k) \geq MUT_i - LPN\big(1 - U_i(t)\big) \qquad \forall\, t \in T_i, i = ESD \quad (3.66)$$

$$\sum_{k=t}^{t+MUT_i-\mathbf{1}} S_i(k) \leq LPN\big(1 - D_i(t)\big) \qquad \forall t \in T_i, i = ESD \quad (3.67)$$

Equations (3.65) to (3.67) are ignored here since intermittent charging/discharging of ESD is allowed. Equation (3.62) is modified as follows, in order to constraint the maximum storage level of the battery:

$$ESL_{ESD}^{min} \leq ESL_{ESD}(t) \leq ESL_{ESD}^{max} \qquad \forall t \in T_i, i = ESD \quad (3.68)$$

3.2 Data Used for Model Simulation

The data described hereafter are for a typical residential customer in Waterloo, Ontario.

3.2.1 Energy Price

Three different price structures have been used in the simulations, i.e. Flat Rate Price (FRP), Time of Use (TOU) and Real Time Price (RTP). The FRP and TOU prices are defined by the Ontario Energy Board (OEB), and are revised every six months for summer (May-October) and winter (November-April) seasons. The RTP is defined by the IESO, and corresponds to the Hourly Ontario Electricity Price (HOEP). The FRP and TOU price data used in the model corresponds to the values set by OEB in November 2009. The RTP values adopted here corresponds to the HOEP for June 2010.

The following additional components are also associated with the energy price in Ontario [31]:

- Delivery Charges ($0.0203/ kWh): These correspond to the Distribution Cost, i.e. the LDC cost of delivering electricity to residential customer, and Transmission Cost, i.e. the costs to deliver electricity from generating stations to the LDC along a high voltage transmission system.

- Regulatory Charges ($0.0065/ kWh): These correspond to the cost of administering the wholesale electricity system and maintaining the reliability of the provincial grid, and include the costs associated with funding the Ministry of Energy and Infrastructure's conservation and renewable energy programs.
- Debt Retirement Charges ($0.007/ kWh): These correspond to the costs associated with a paying down the residual stranded debt of the former Ontario Hydro.

Therefore an energy bill is considered here to increase by 3.4 cents per kWh.

3.2.1.1 Time of Use (TOU) Pricing

In TOU rates, there are three different rates of energy price: 4.4 cents/kWh for off-peak, 8 cents/kWh for mid-peak and 9.3 cents/kWh for on-peak periods, as of Nov. 1, 2009 [32]. The different energy prices reflect the fact that cost of supplying energy changes throughout the day; when the demand is low, less expensive power generators are used, while during on-peak periods the demand is high and therefore expensive sources of electricity are used. Smart Meters are essential for the application of TOU prices, since it can track how much electricity is used and when.

In summer, on-peak prices are applied during the middle period of the day from 11:00 AM to 5:00 PM [33]. The reason for this is the increased use of air conditioners during the day, which raises the overall electricity demand and hence more expensive generators are used. Weekends have off-peak price all day. Figure 3-1 shows the TOU prices for a summer weekday.

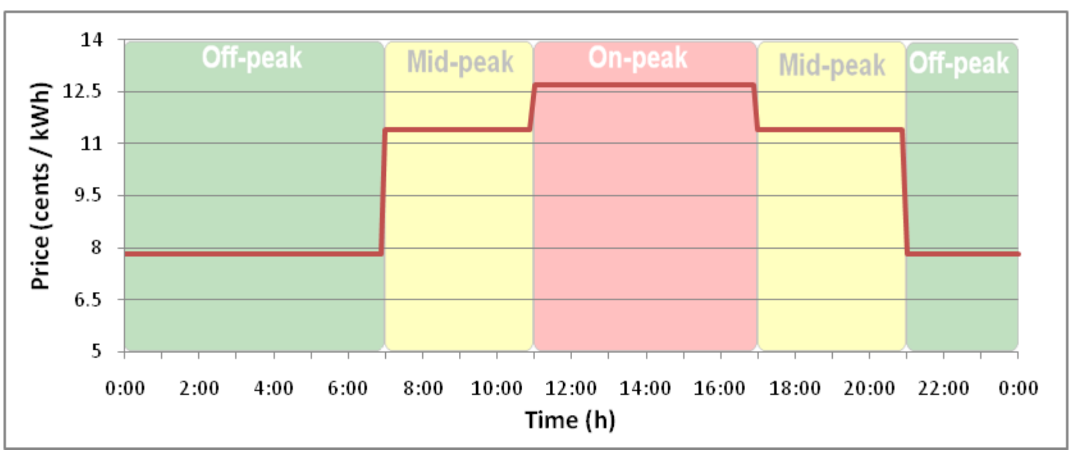

Figure 3-1: TOU price in Ontario for summer weekday.

In winter, the on-peak prices are applied during morning (7:00AM to 11:00AM) and evening (5:00PM to 9:00PM) periods, since the customers are at home during these periods and the demand rises [33]. Weekends have off-peak prices all day. Figure 3-2 shows the TOU prices for a winter weekday.

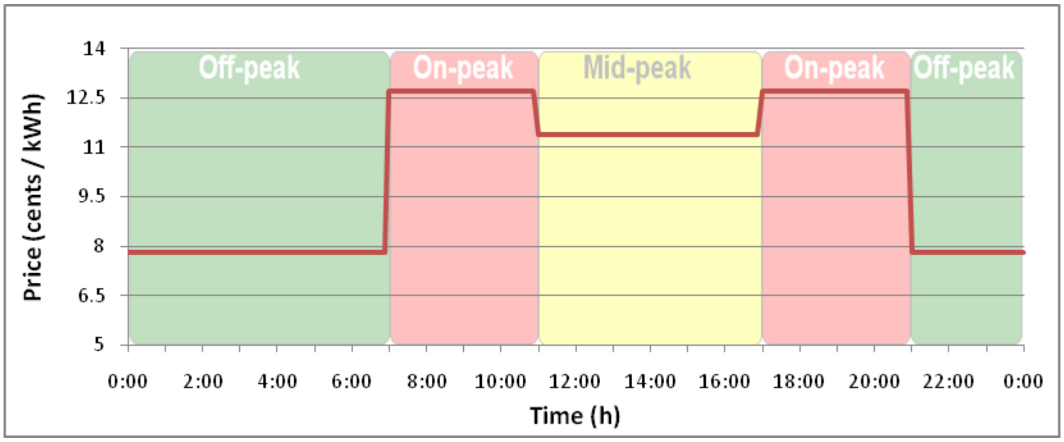

Figure 3-2: TOU price in Ontario for winter weekday.

3.2.1.2 Real Time Price (RTP)

RTPs are set every hour and fluctuate more as compared to TOU prices. The RTPs vary from day to day; hence a 5-day average value is used here [34]. The effect of fluctuating RTPs may result in a very different output from the EHMS residential sector model; therefore, a Monte Carlo simulation is carried out in Chapter 4 to examine the effect of varying RTPs. Figure 3-3 and 3-4 show the typical summer and winter 5-day average RTPs in Ontario, used in this thesis. Observed that the peak RTP in summer occur at mid day, as mentioned earlier.

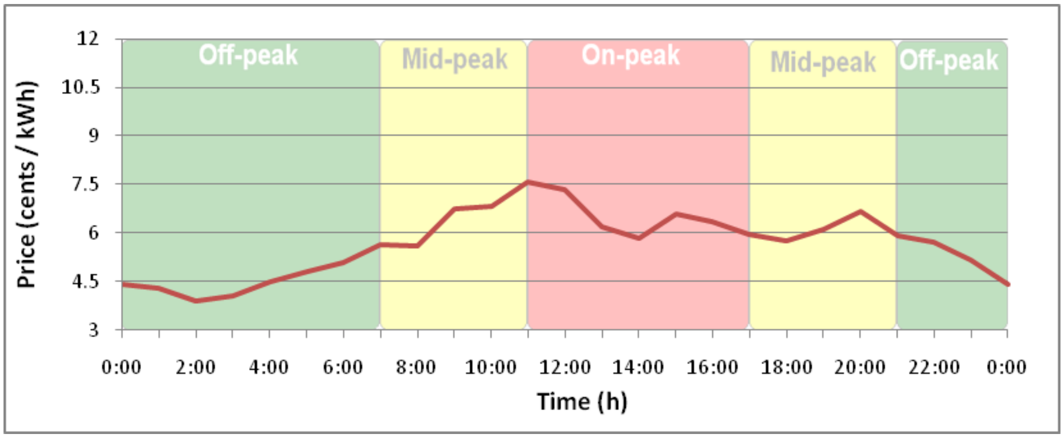

Figure 3-3: Typical summer 5-day averaged RTP in Ontario.

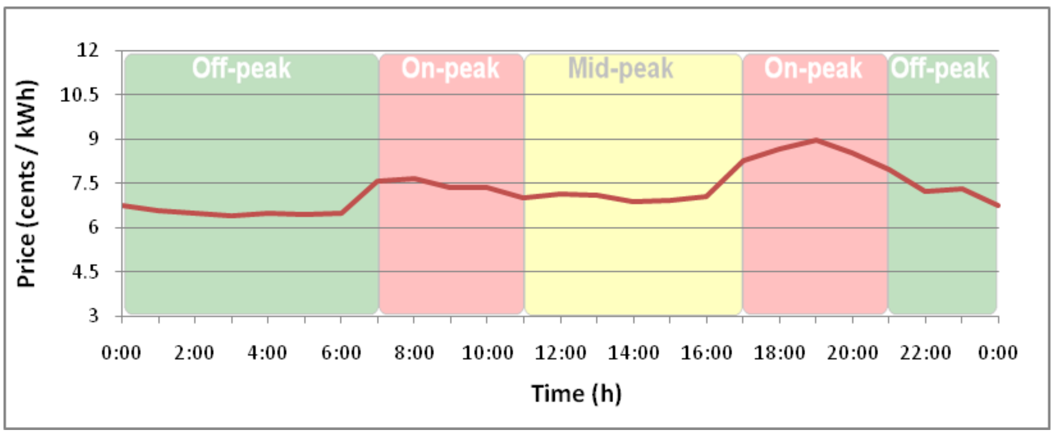

Figure 3-4: Typical winter 5-day averaged RTP in Ontario.

3.2.1.3 Flat Rate Pricing (FRP)

These energy prices are fixed irrespective of the time of day the electricity is being used. A threshold of energy consumption of residential customer is set by the OEB at which the rate increases. For summer, this threshold is 600 kWh/month (May to October), and for winter it is 1,000 kWh/month (November to April); the higher threshold for winter is due to more usage of lighting and also the usage of electricity for space heating by some residential customers. The prices of the first and second tier are 5.8 and 6.7 cents/kWh, respectively, as of Nov. 1, 2009 [32]. Considering the additional 3.4 cents/kWh extra charges, a fixed value of 9.2 cents/kWh is used for simulations in this thesis, since only daily studies are presented and discussed in this thesis.

3.2.1.4 Natural Gas Rates

Union Gas Limited is the company that supplies natural gas in various cities in Ontario, including the cities of Milton and London, Ontario, which are the focus of the EHMS project. Natural gas rates for residential customers include transportation, storage and delivery charges beside the commodity charges. These rates are revised every three month and approved by the OEB. Union Gas provides historical natural gas rate information for different operations area. The gas rate used in the model is 29.385 cents/m^3, as charged by Union Gas to its residential customers in its Southern Operations area [35].

3.2.2 Emissions Profile

Ontario's CO_2 emissions profile is considered for a summer weekday using the forecasting method described in Chapter 2. Using the actual demand profile of July 14, 2009 (Figure 3-5) [25], the Ontario's emissions profile depicted in Figure 3-6, is obtained using the proposed method; this emissions profile is used in the case studies presented in this thesis. Similarly, considering a winter weekday (Jan. 15, 2009) with a demand profile as per Figure 3-7 [25], the obtained Ontario's CO_2 emissions profile shown in Figure 3-8 is used here.

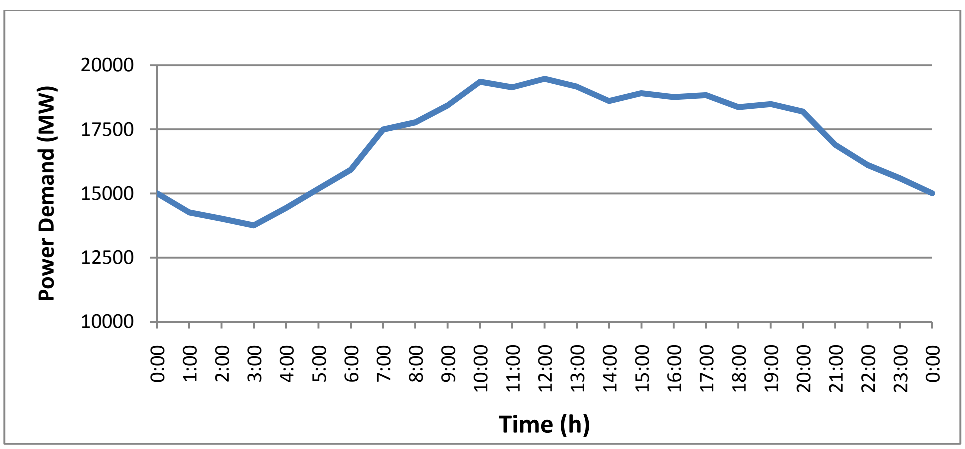

Figure 3-5: Demand profile in Ontario, July 14, 2009 [25].

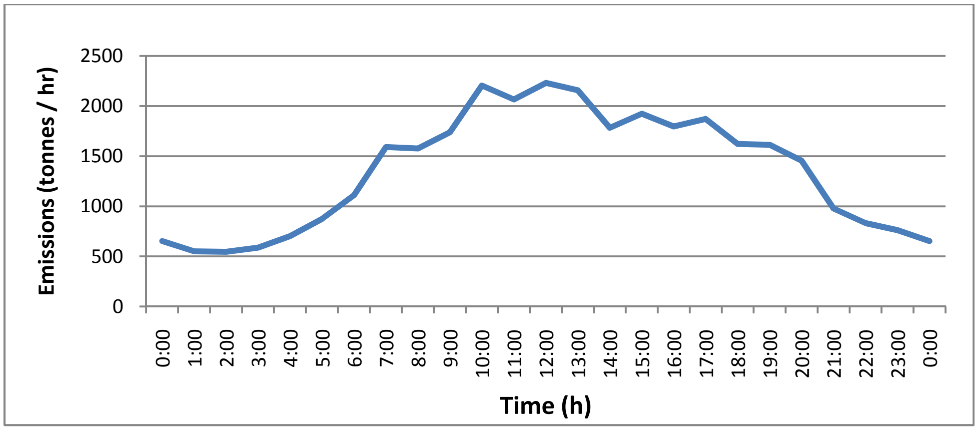

Figure 3-6: Forecasted Emission Profile in Ontario, July 14, 2009.

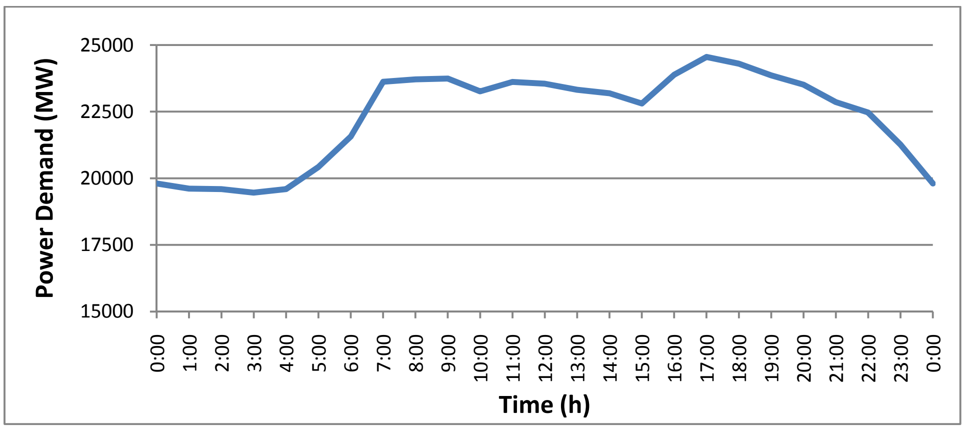

Figure 3-7: Demand profile in Ontario, Jan. 15, 2009 [25].

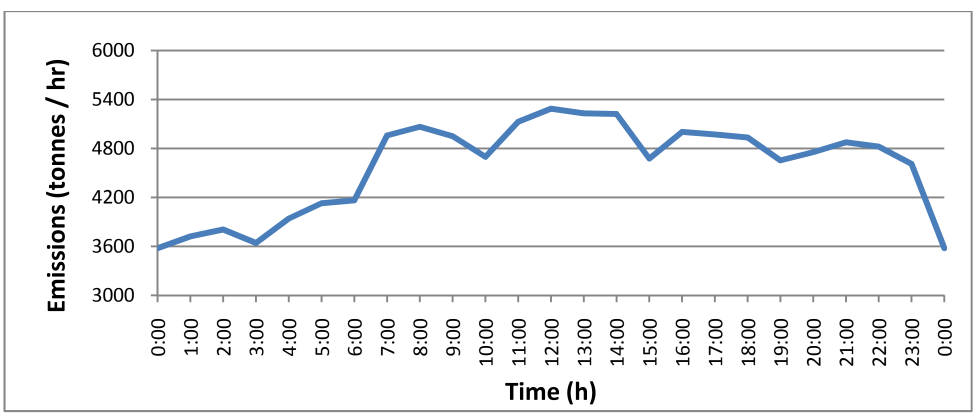

Figure 3-8: Forecasted Emission Profile in Ontario, Jan. 15, 2009.

3.2.3 Ambient Air Temperature

Figure 3-9 shows the outside ambient air temperatures for a specific summer (July) and a winter (January) day and is considered for our studies reported in this thesis. The average temperature for the specific summer day is 27˚C, which is higher than the average monthly temperature in July of 21˚C. Similarly, the average temperature for the specific winter day is -16˚C, which is higher than the average monthly temperature in January of -6.3˚C [36]. Relatively warmer summer and cooler winter days are chosen in this work to test and evaluate the device parameters developed in [9].

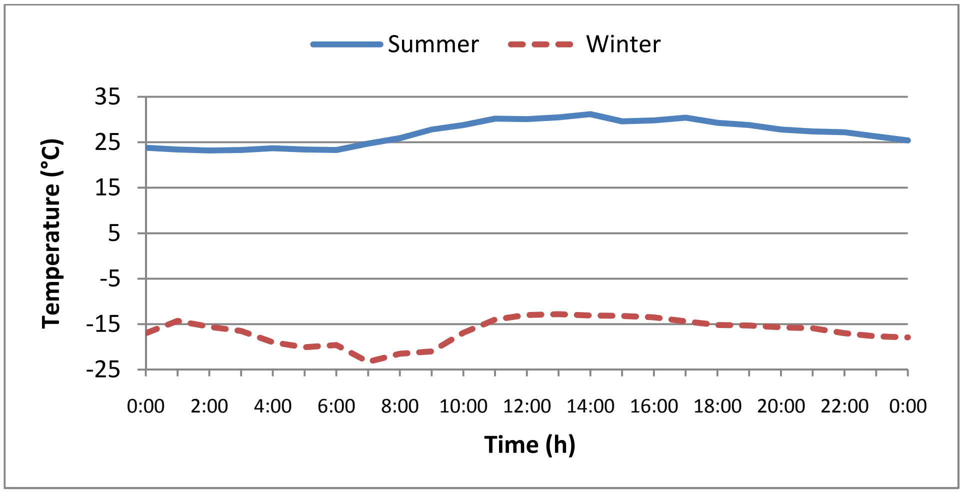

Figure 3-9: Ambient air temperatures for summer and winter simulations.

3.2.4 Outside Illumination Level

Illuminance is the measure of total luminous flux incident over a surface of unit area. The SI unit of illuminance is Lux, and the corresponding unit of Lux in radiometry is W/m^2, which is the measure of irradiance [37]. The data of incoming short wave radiations in W/m^2 used here is taken from the University of Waterloo Weather Station [38]. The illumination level data is chosen for summer and winter days with mainly clear skies. Outside illumination level information required by the model for residential lighting, is assumed to be in per unit; therefore, normalized data is used as shown in Figure 3-10 and 3-11. The required illumination levels assumed here inside a house are given in Figure 3-12 [8].

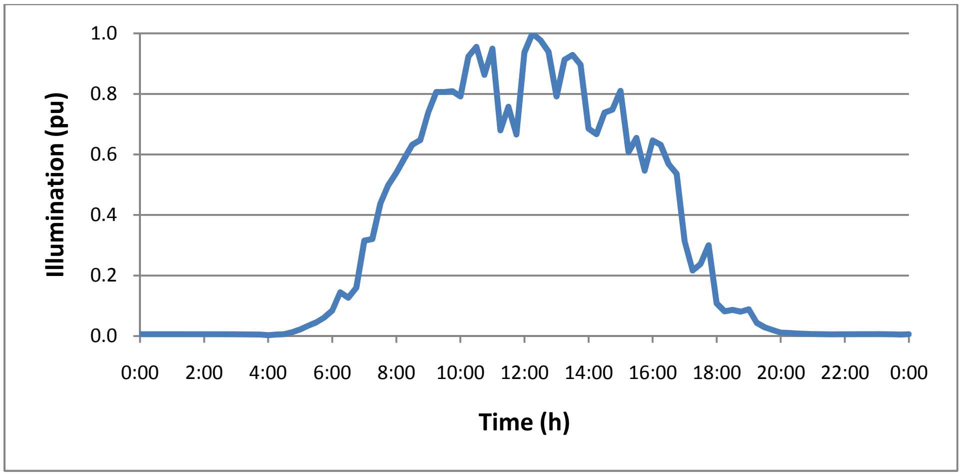

Figure 3-10: Outside illumination level in summer [38].

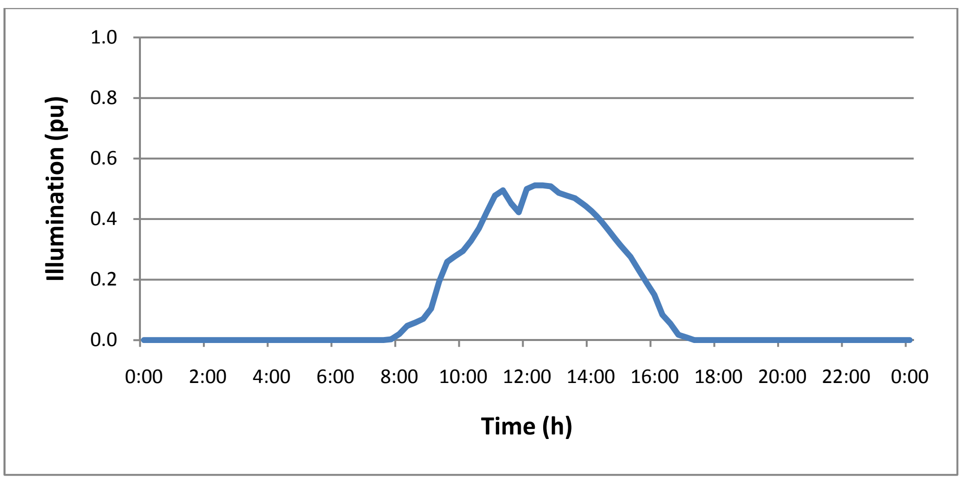

Figure 3-11: Outside illumination level in winter [38].

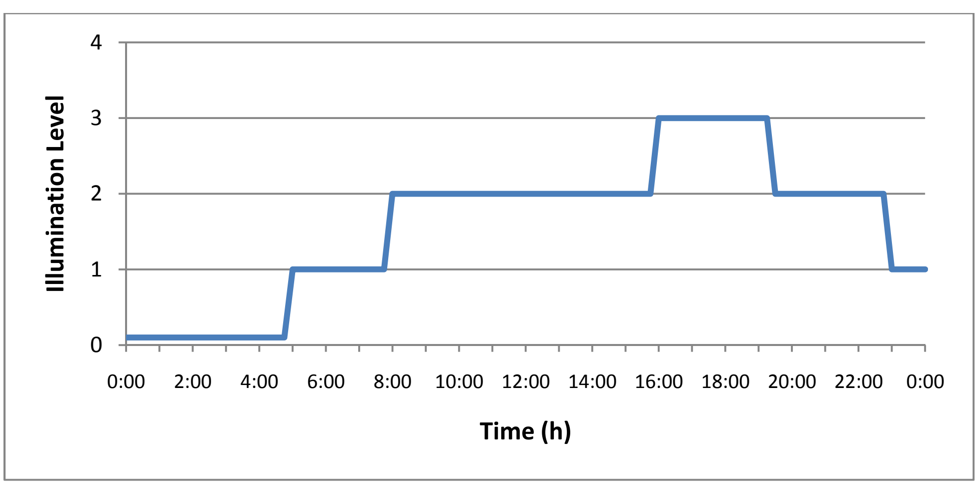

Figure 3-12: Required indoor illumination levels [8].

3.2.5 Solar PV Panel Power Generation

A 3 kW solar PV roof top panel with battery storage system is assumed for the ESD model. Minimum and maximum storage levels of battery are 6 kWh and 30 kWh, respectively. Energy is exported to the grid at 80.2 cents/kWh, which is the contract price set by OPA for residential participants of the micro FIT program [30]. Figures 3-13 and 3-14 show the typical power generation levels from the solar PV panel for summer and winter days used here [39].

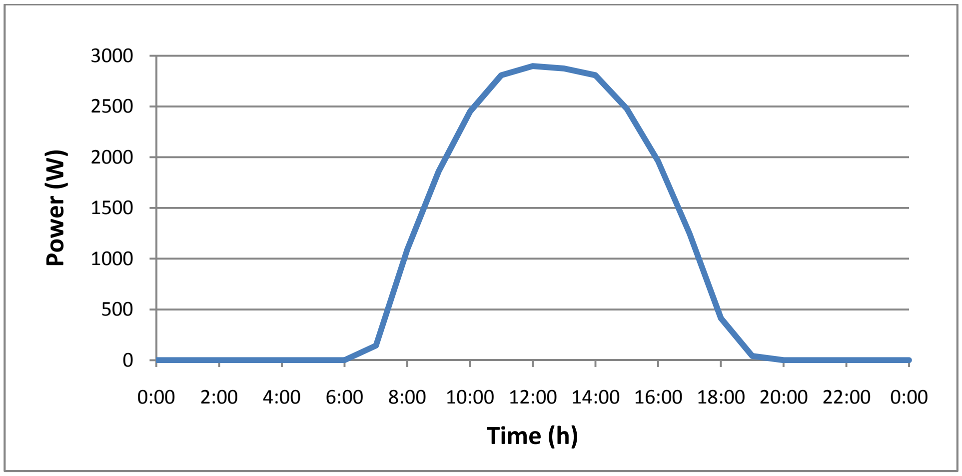

Figure 3-13: Power generation from 3 kW solar PV panel in summer [39].

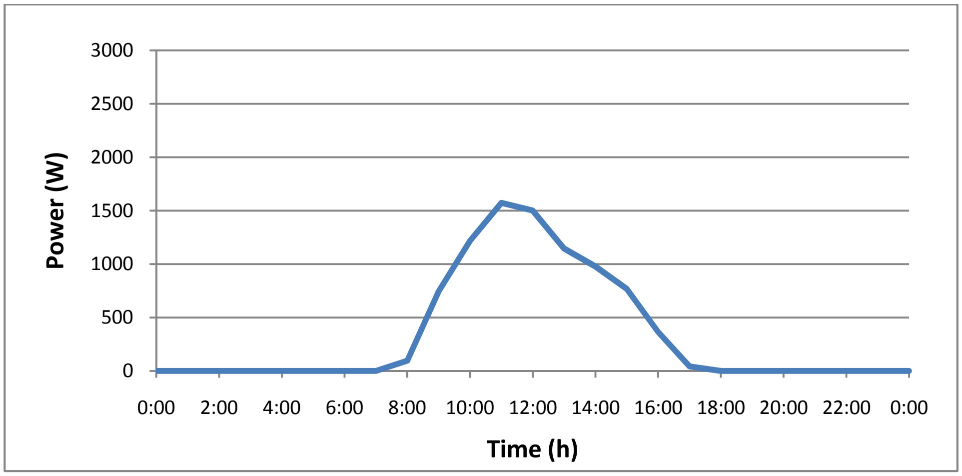

Figure 3-14: Power generation from 3 kW solar PV panel in winter [39].

3.2.6 Appliances

3.2.6.1 Air Conditioner and Furnace

The air conditioner size used in the model is 2.5 Ton (30,000 BTU) with a starting power rating of 3200 W and the running wattage of 2200 W. The actual running wattage of an air conditioner is a lower value than the starting wattage because it consumes rated power only for the first two or three seconds. On the other hand, a gas furnace requires fuel (natural gas) input and has a small percentage consumption of electricity for its complete operation. Fuel consumption depends on the burner operation hours and the fuel input rate, while electricity consumption is due to the blower motor, draft inducer and ignition device [40]. The gas furnace considered has a fuel input rate equals to 75.5 kBTU/hr, which is equivalent to 2.136 m^3/hr of gas consumption and a total electricity consumption of 1150 W/h.

In the case of fixed temperature settings, the data used for the temperature set point $\theta_{set,i}(t)$, and the allowed temperature deviations from the set points $\Delta T^{up}(t)$ and $\Delta T^{low}(t)$, are as follows:

$$\theta_{set,i}(t) = 22°C \qquad \forall\, summer, t \in T_i\,, i = AC/H \tag{3.69}$$

$$\theta_{set,i}(t) = 23°C \qquad \forall\, winter, t \in T_i\,, i = AC/H \tag{3.70}$$

$$\Delta T^{up}(t) = +1°C \qquad \forall\, t \in T_i\,, i = AC/H \tag{3.71}$$

$$\Delta T^{low}(t) = -1°C \qquad \forall\, t \in T_i\,, i = AC/H \tag{3.72}$$

In case of a house with a programmable thermostat, $\theta_{set,i}(t)$ varies according to the time of day and season. In winter, it is set to a lower value during nights and periods when the house is empty. In summer, a similar strategy is used by setting the house temperature to a higher value during nights and periods of the day when the house is empty. Therefore, in the model, the following temperature settings are used:

$$\theta_{set,i}(t) = \begin{cases} 22°C & \forall\, t \in (1-36, 89-96) \\ 30°C & \forall\, t \in (37-64) \\ 23°C & \forall\, t \in (65-88) \end{cases} \qquad \forall\, summer, t \in T_i\,, i = AC/H \tag{3.73}$$

$$\theta_{set,i}(t) = \begin{cases} 23°C & \forall\, t\ \in (1-36) \\ 15°C & \forall\, t\ \in (37-64) \\ 23°C & \forall\, t\ \in (65-96) \end{cases} \qquad \forall\, winter, t\ \in\ T_i\,, i = AC/H \quad (3.74)$$

$$\Delta T^{up}(t) = \begin{cases} +2°C & \forall\, t\ \in (1-36, 89-96) \\ +1°C & \forall\, t\ \in (37-64) \end{cases} \qquad \forall\, summer, t\ \in\ T_i\,, i = AC/H \quad (3.75)$$

$$\Delta T^{low}(t) = \begin{cases} -1°C & \forall\, t\ \in (1-36, 65-96) \\ -10°C & \forall\, t\ \in (37-64) \end{cases} \qquad \forall\, summer, t\ \in\ T_i\,, i = AC/H \quad (3.76)$$

$$\Delta T^{up}(t) = \begin{cases} +2°C & \forall\, t\ \in (1-36, 65-96) \\ +10°C & \forall\, t\ \in (37-64) \end{cases} \qquad \forall\, winter, t\ \in\ T_i\,, i = AC/H \quad (3.77)$$

$$\Delta T^{low}(t) = \begin{cases} -2°C & \forall\, t\ \in (1-36, 65-96) \\ -1°C & \forall\, t\ \in (37-64) \end{cases} \qquad \forall\, winter, t\ \in\ T_i\,, i = AC/H \quad (3.78)$$

3.2.6.2 Refrigerator

The nameplate rating of the refrigerator considered is 900 VA with a power factor of 0.66. Calculation of the parameters α_{FR} , γ_{FR} and β_{FR} is already explained in [9], yielding the values $\alpha_{FR} = 5.5°C, \gamma_{FR} = 1.21°C$ and $\beta_{FR} = 0.28°C$, all calculated for a 15-minute time interval. Using these parameters with $\theta_{FR}^{low} = 2°C$ and $\theta_{FR}^{up} = 8°C$ gives a feasible solution; however for a tighter temperature range the CPLEX solver gives infeasible solution. This forced the reduction of the time interval to 7.5-minutes. In this case, the model parameters are half of the previous values. i.e. $\alpha_{FR} = 2.75°C$, $\gamma_{FR} = 0.605°C$ and $\beta_{FR} = 0.14°C$. A temperature set point of $\theta_{set,i}(t) = 3.5°C$ is used for the comfort maximization simulations.

3.2.6.3 Water heater

The gas water heater used has a fuel input rate of 42 kBTU/hr, which is equivalent to 1.18 m^3/ hr of gas consumption and electricity consumption of 600 W/hr. Similar to the refrigerator, the water heater model also gives infeasible solutions for tight temperature ranges. Hence the parameters used are defined for 7.5 minute intervals, instead of 15 minute intervals; this yields $\alpha_{WH} = 2.2°C$, $\beta_{WH} = 0.034°C$ and $\gamma_{WH} = 0.05°C$ per 7.5 minutes time interval.

A temperature set point of $\theta_{set,i}(t) = 53°C$ is used for the comfort maximization simulations. The water heater temperature set point can be lowered for periods of the day when the house is empty or when the occupants are asleep, so that energy can be saved. The upper and lower limits on water temperature used here are $\theta_{WH}^{low} = 48°C$ and $\theta_{WH}^{up} = 58°C$. The upper limit has to be carefully chosen, since accidental exposure to hot water may cause scalding or thermal shock.

3.2.6.4 Stove

The power rating of a stove (range) may vary from 3.2 kW to 12.5 kW [41], but the actual energy consumption during a cycle depends on the on-status or cooking time and chosen heating process. Considering the power demand curve of an electric hob and power consumption pattern during a cycle [42], the average power consumption for the stove is chosen here as 1.5 kW per cycle.

Based on typical home owner behavior, the following assumptions are made regarding the stove operation:

- The stove operating hours are 4:00 PM to 10:00 PM.
- The stove is required to operate for a maximum of 3 hours per day.
- The stove should work for a minimum of two successive hours each time is turned on.

3.2.6.5 Dishwasher

Peak energy consumption during a cycle of a dishwasher, can be as high a value as 1.3 kW [31]. The appliance operation mainly involves three steps, i.e. wash, rinse and dry. A typical dishwasher energy consumption profile is given in [43]; therefore, an average power consumption of 0.7 kW during cycle is chosen here.

Considering a typical home owner behavior, the following assumptions are made for dishwasher operation:

- Dishwasher operation hours are 4:00 PM – 10:00 PM.
- Maximum operation duration is two hours.

3.2.6.6 Cloth washer and Dryer

A cloth washer consumes high power for short periods of time, with major energy consumption required for driving the drum motor and heating water. The average power consumption over one cycle is 0.45 kW [9], which is used here.

The cloth dryer has a very high rated power in the range of 2 kW to 5 kW, but the average power consumption during a cycle is lower. The main steps of the dryer operation involve the heating of air and tumbling of cloths. The heating of air is not required during the whole cycle (e.g. while cloths are tumbling). The average power consumption of the dryer used in this work is 1.1 kW [9].

Early and late operation times for both washer and dryer are assumed to be between 4:00 PM and 10:00 PM, with a maximum successive operation duration of two hours.

3.2.6.7 Summary

The name plate ratings and the actual wattage values used in this thesis are presented in Table 3-1:

Table 3-1: Power ratings of devices used.

Device	Name plate rating	Average power used
Air conditioner	3.2 kW	Running wattage = 2.2 kW
Furnace	75.5 kBtu/hr, 1150 W	Gas consumption rate = 2.136 m^3/hr Electricty consumption = 1.15 kW
Fridge	0.9 kVA	0.6 kW
Water heater	42 kBtu/hr, 600 W, 60 Gallon	Gas consumption rate = 1.187 m^3/hr Electricity consumption = 0.6 kW
Lighting	0.15 kW	0.15 kW
Stove	4.6 kW	Avg. power during cycle = 1.5 kW
Dishwasher	1.25 kW	Avg. power during cycle = 0.7 kW
Cloth washer	2 kW	Avg. power during cycle = 0.45 kW
Dryer	5 kW	Avg. power during cycle = 1.11 kW
Pool pump	0.75 kW	0.75 kW
Energy storage device	3 kW solar PV panel, battery storage level 30 kWh - 6 kWh	3 kW solar PV panel, battery storage level 6 kWh - 30 kWh

3.3 Summary

In this chapter, the details of the EHMS residential sector model are discussed, and realistic input data required for the simulations were presented, which included different energy pricing schemes, natural gas prices, Ontario's emissions profiles, temperature data, illumination levels, solar PV panel power outputs and typical power rating of home appliances. Various objective functions of the model were also discussed. The mathematical models for individual household appliances were presented including some modifications used in this thesis, such as the inclusion of CO_2 emissions and natural gas consumption of gas furnaces and water heaters.

Chapter 4
Analysis and Case Studies

In this chapter, simulation results for the EHMS residential sector model are presented as per the various operating objectives and data for the EHMS model discussed in Chapter 3. In this chapter, six different cases are considered and discussed. For each case, savings in energy cost, energy consumption, natural gas consumption and CO_2 emissions are compared with respect to a base case which represents a residential customer whose objective is solely maximizing comfort. Comparison of individual appliance schedules and their performances are also presented. Finally, the effect of using different energy price schemes on the EHMS model and the use of Monte Carlo simulations to examine the effect of varying RTP are presented and discussed.

It is to be noted that the cost comparisons and optimum schedules of household appliances, presented in this chapter, are based on operational costs only. The cost of installation of the EHMS is considered sunk and therefore has no impact on the short-term optimal operation decisions.

4.1 Summary of Case Studies

The base case (Case 0) represents a typical customer without any access to an optimization based decision making platform, with or without a programmable thermostat. Case 1 represents a customer seeking to minimize its total energy cost. Case 3 represents an environmentally conscious customer seeking to minimize the CO_2 emissions from its energy use. Case 4 represents a customer participating in a peak-saver program and thus operating appliances so as to limit its peak demand. Case 5 discusses results considering a multi-objective function of minimizing costs, energy use and CO_2 emissions. Finally, to study and analyze the EHMS residential sector model's output and evaluate its total benefits, a comparison among all cases is presented and discussed. Table 4-1 presents a brief summary of all the cases.

Table 4-1: Summary of Case Studies.

Item	Objective	Explanation
Case 0 (Base Case)	No optimization	Maximize customer comfort such that the temperature deviation from the set points is minimum. Two scenarios are considered: one with programmable thermostat, and the other with fixed temperature settings.
Case 1	Minimization of cost	Minimize total cost of energy from all devices and maximize the operation of energy storage device.
Case 2	Minimization of energy consumption	Minimize operational hours of all devices and maximize the operation of energy storage device.
Case 3	Minimization of CO_2 emissions	Minimization of CO_2 emissions considering Ontario's emissions profile and maximize the operation of energy storage device to reduce consumer's contribution to CO_2 emissions
Case 4	Minimization of cost	Minimize total cost of energy and ensure peak demand is within some given limits. The operational schedules of all devices are now inter-dependent.
Case 5	Minimization of cost, energy consumption and emissions	Individual objectives of cost, energy consumption and emissions are combined to form a single objective function.

4.2 Case 1: Minimization of Cost

In this case, the EHMS residential model is run with the objective to minimize the total cost over a period of 24 hours. Separate simulations are carried out for summer and winter days. TOU energy pricing is used.

4.2.1 Appliance Scheduling and Performance

In set of figures shown in this section, the schedule and performance of different devices modeled for the EHMS residential sector are presented. Results for each device, as obtained from the optimization model, are compared with the base case (Case 0). Section 4.2.1.1 and 4.2.1.2 presents the results for summer and winter days, respectively.

4.2.1.1 Summer

Air conditioner

Figure 4-1 and 4-2 represents the simulation results of air conditioner with a programmable thermostat. The temperature set points and allowed variation from the set point are based on a typical customer's behavior. Since the house is usually empty during the day, the temperature is set to a higher value from 9:00 AM to 4:00 PM, and for rest of the time the set point is preset to ensure the customer's comfort.

Figure 4-1 shows a comparison of indoor temperature for Case 1 and Case 0. Observe that the indoor temperature in Case 0 remains close to the set point and therefore more air conditioner operation is required during the day, while in Case 1 it varies around the set point and remains close to the upper limit of the allowed temperature range. Pre-cooling is carried out in off-peak periods between 4:00 AM and 7:00 AM and hence, during mid-peak and most part of on-peak period, the air conditioner stays off. It should be noted that, instead of pre-cooling in the off-peak period during night, indoor temperature in Case 1 is close to the upper limit; this is due to the fact that the model is simulated only for a 24 hour period and if the optimization is continued to the next day, then one may observe pre-cooling during the night off-peak period. In both cases the temperature remains within the user defined ranges.

Figure 4-2 shows the operational schedule of air conditioner, power consumption at each interval, inside house temperature, activity level, and outside temperature. During the on-peak period from 2:00 PM onwards, the air conditioner is turned on for most of the time since higher activity level is expected in the evening because of the presence of occupants in the house.

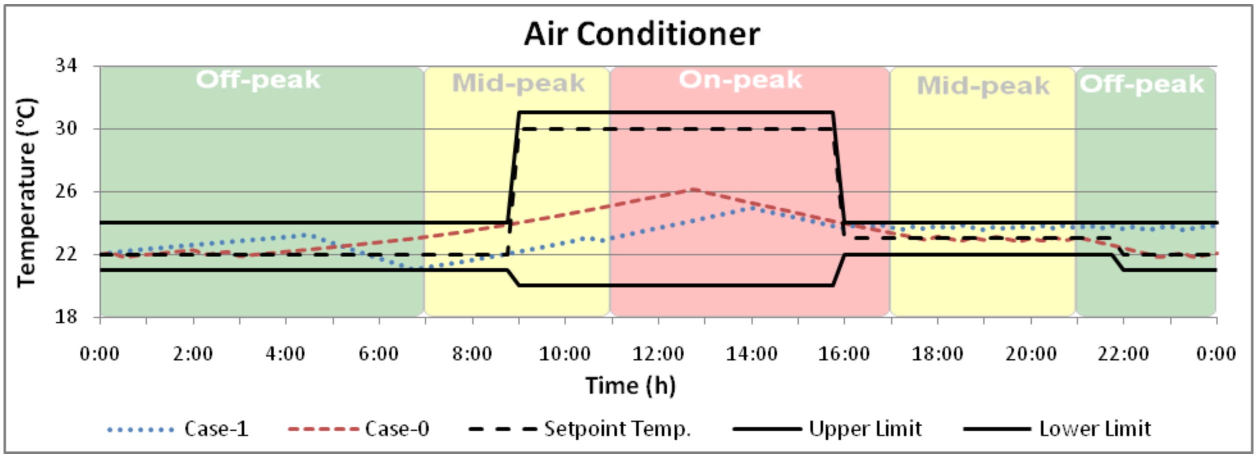

Figure 4-1: Comparison of indoor temperatures of Case 0 and Case 1.

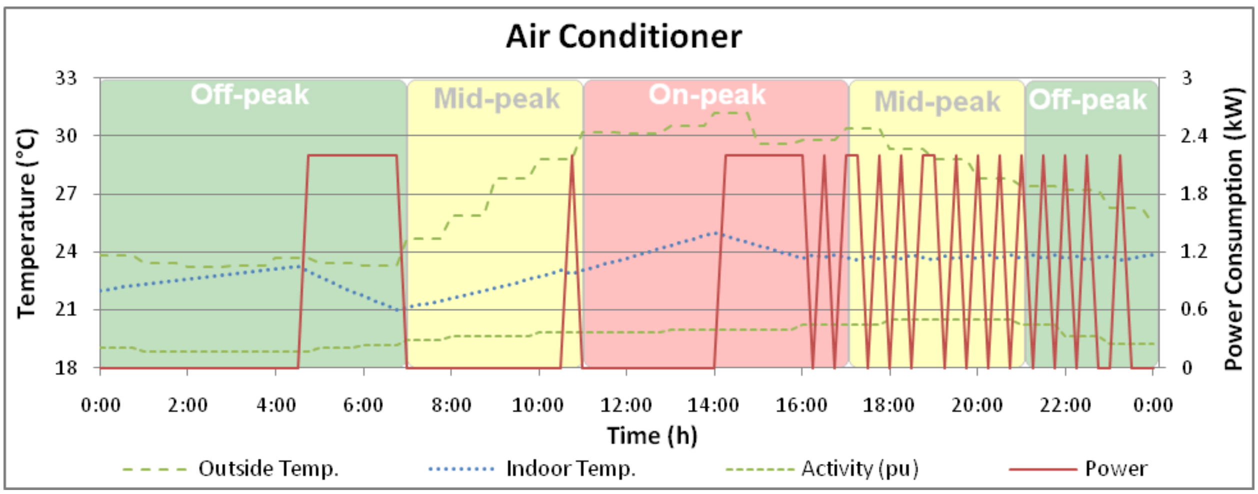

Figure 4-2: Operational schedule of the air conditioner in Case 1.

Fridge/Refrigerator

Figure 4-3 presents a comparison of inside temperature in the fridge in Case 1 vis-a-vis Case 0. The results shows that the inside temperature in Case 0 closely tracks the set point (3.5°C) while in Case 1 it varies within the user defined upper and lower limits of 2°C and 8°C respectively. Figure 4-4 shows the operational schedule in Case 1, power consumption of the compressor, and the activity level. Due to increased activity level in the evening from 5:00 PM to 9:00 PM, the number of operations are increased and hence the inside temperature of fridge is close to its set point. Similarly, due to lower activity level in the off-peak period, i.e. from midnight to 6:00 AM, the fridge temperature drifts away from the set point.

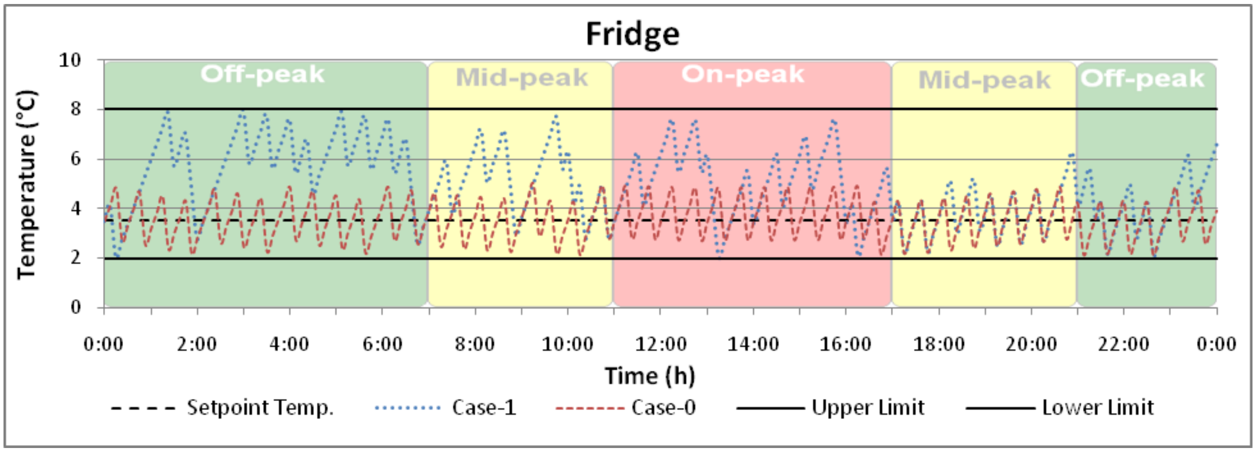

Figure 4-3: Comparison of inside fridge temperature in Case 1 and Case 0.

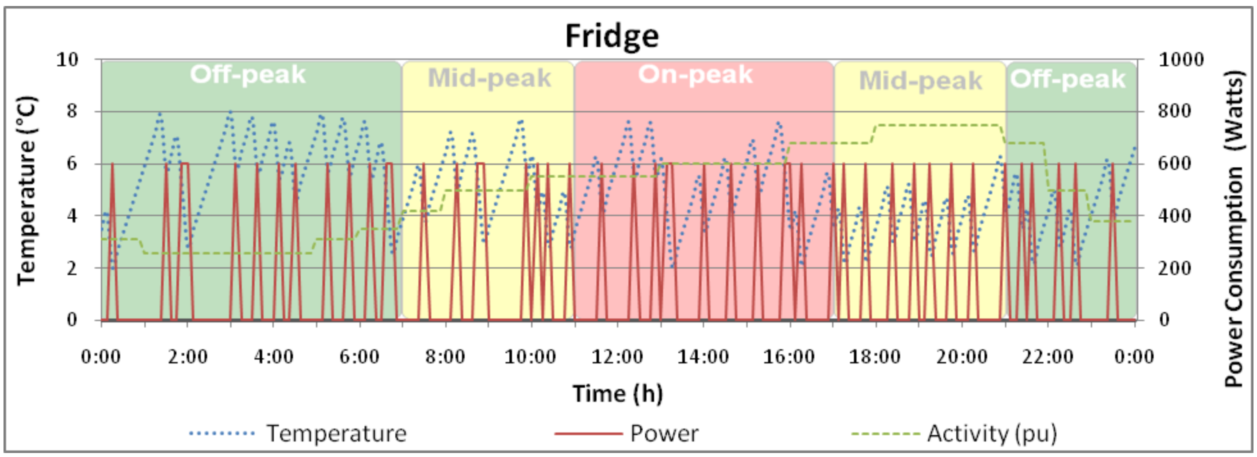

Figure 4-4: Operational schedule of fridge.

Water heater

Figure 4-5 and 4-6 presents the performance and schedule of the water heater. In Figure 4-5, a comparison is made between the water temperature for Case 1 and Case 0. Similar to the fridge model, the temperature stays very close to the fixed set point (53°C) in Case 0, while in Case 1 it varies within the user defined upper and lower limits (48°C and 58°C).

Figure 4-6 shows that in the off-peak price period, the water temperature stays close to the upper limit, i.e. pre-heating is carried out while during mid-peak price periods when the temperature is close to its lower limit. Operation of the water heater mainly depends on the hot water usage (HWU) level. For instance, during the two hour period from 5:00 AM to 7:00 AM, HWU is at its maximum and hence higher numbers of operations are observed; similarly, during the night, minimum water heater operations are observed when the HWU level is at its minimum.

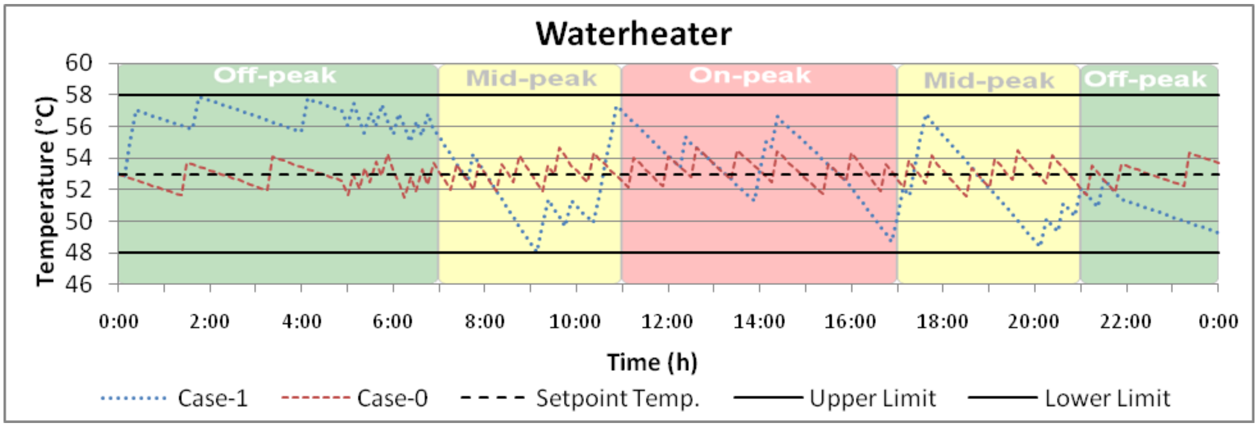

Figure 4-5: Comparison of water temperature in Case 1 and Case 0.

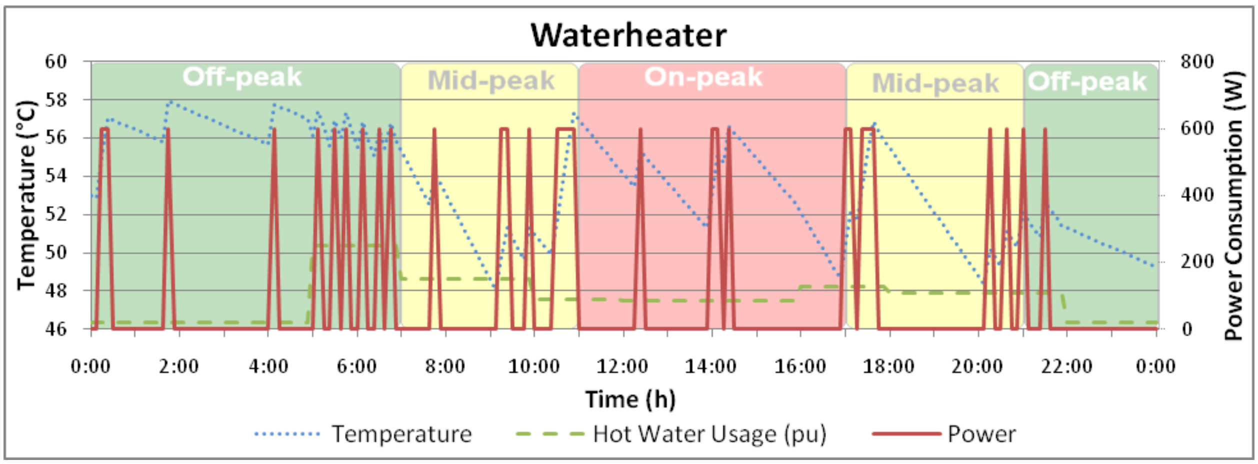

Figure 4-6: Operational schedule of water heater.

Lighting

Figure 4-7 represents the power consumption of lighting, minimum required illumination level and the outside illumination. The mathematical model ensures that the total illumination from the lighting system and outdoor sunshine is more than the minimum required level. Note that the illumination level obtained from Case 1 is always equal or less than Case 0, and hence the corresponding power consumption in Case 1 follows the same trend.

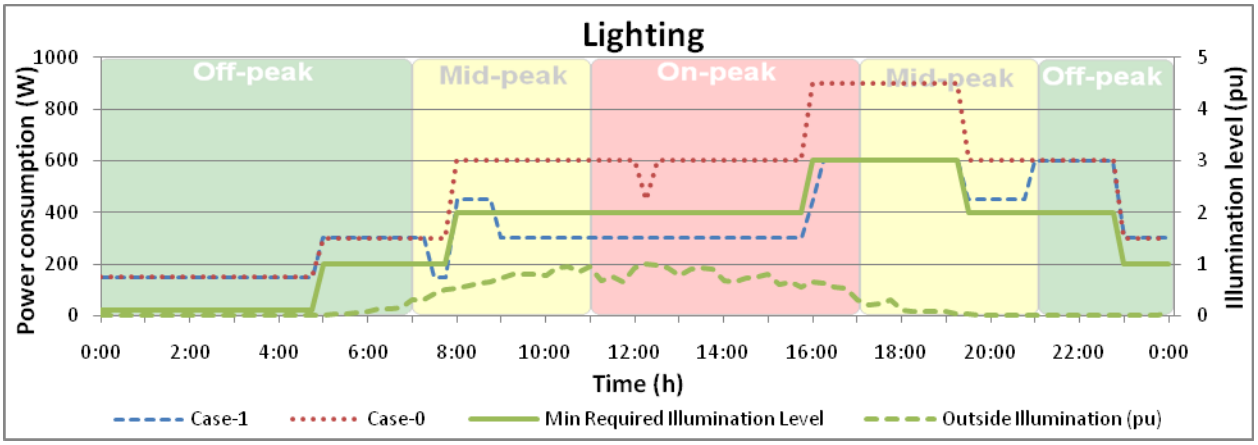

Figure 4-7: Comparison of power consumption of lighting in Case 1 and Case 0.

Dishwasher

Figure 4-8 compares the scheduling of the dishwasher between Case 1 and Case 0, considering that the user defined operation interval is between 4:00 PM and 11:00 PM. Case 0 schedules the dishwasher during mid-peak period while in Case 1, dishwasher is scheduled during off-peak price periods to achieve the cost savings.

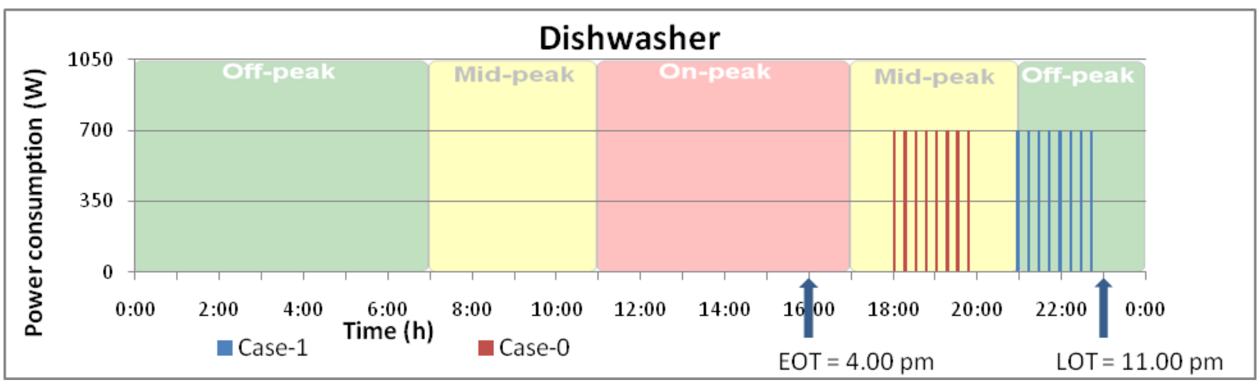

Figure 4-8: Comparison of operational schedule of dishwasher in Case 1 and Case 0.

Cloth washer and dryer

The operation of the cloth washer and dryer are inter-dependent. Figure 4-9 and 4-10 compares the operation schedule of both devices for Case 1 and Case 0, for a user defined operation interval between 4:00 PM and 11:00 PM. The cloth washer schedule obtained for both cases is during mid-peak period thus showing no cost savings. For the dryer, the optimization model ensures that it is operated during off-peak price period for Case 1.

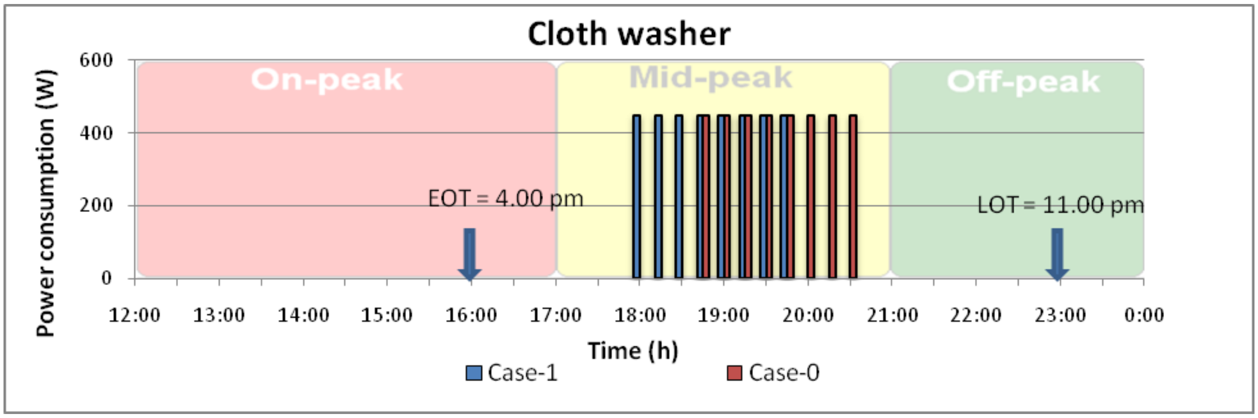

Figure 4-9: Comparison of operational schedule of cloth washer in Case 1 and Case 0.

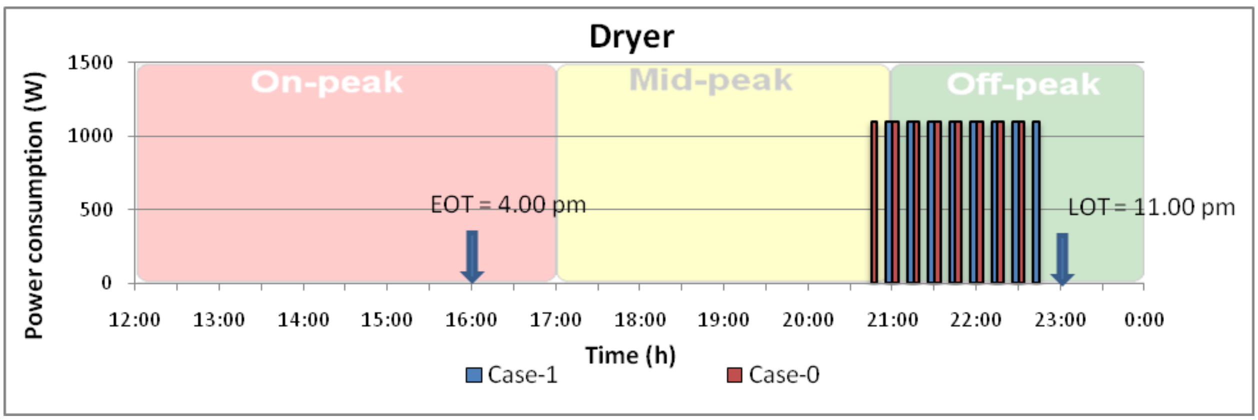

Figure 4-10: Comparison of operational schedule of dryer in Case 1 and Case 0.

Pool pump

Figure 4-11 shows the model results obtained for the pool pump considering that it is constrained to operate for 10 hours a day. The user defined operation interval for the pool pump is from 7:00 AM till midnight and hence in both cases, the pool pump is not operated at night. Figure 4-11 clearly shows that in Case 0, the pump is operated continuously for 10 hours while in Case 1 the operation is avoided during on-peak price periods; thus, cost savings are achieved by operating the pump during mid-peak and off-peak periods.

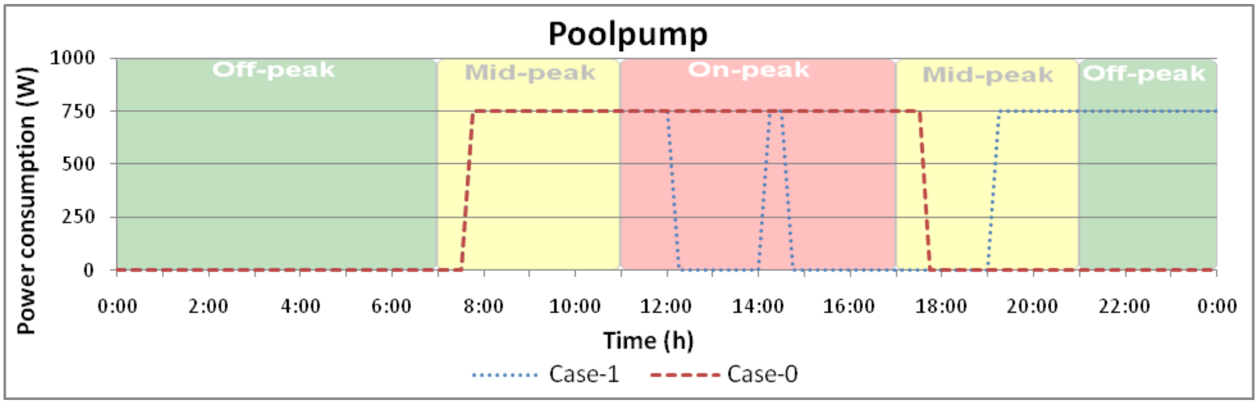

Figure 4-11: Comparison of operational schedule of pool pump in Case 1 and Case 0.

Energy Storage Device

Figure 4-12 demonstrates the operation of energy storage device including battery discharge, solar PV panel generation and battery storage levels at each interval. The model tries to maximize the battery discharge in order to sell power to the grid, while maintaining a minimum level of battery storage. Since the energy price is fixed, the schedules are independent of TOU price. No discharge is observed during the night, since the model has to preserve the battery charge at its minimum level; once the solar panel generation is available, the energy storage device starts to export power to the grid.

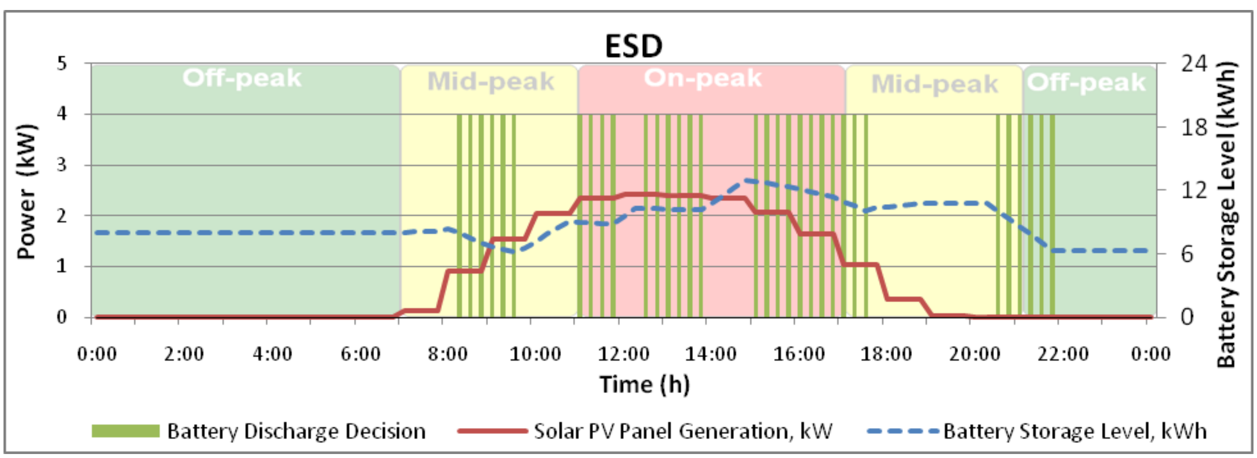

Figure 4-12: Operational schedule of ESD in Case 1.

4.2.1.2 Winter

Furnace

Figure 4-13 and 4-14 depicts the simulation results of the furnace with a programmable thermostat. The temperature set points and allowed variation from the set point are based on a typical customer's behavior. Since the house is usually empty during the day, the temperature is set to a lower value from 9:00 AM till 4:00 PM, and for rest of the time, the set point is preset to ensure customer's comfort. Note from these figures that similar operation of the furnace is observed in Case 0 and Case 1, as in the case of the air conditioner in the summer.

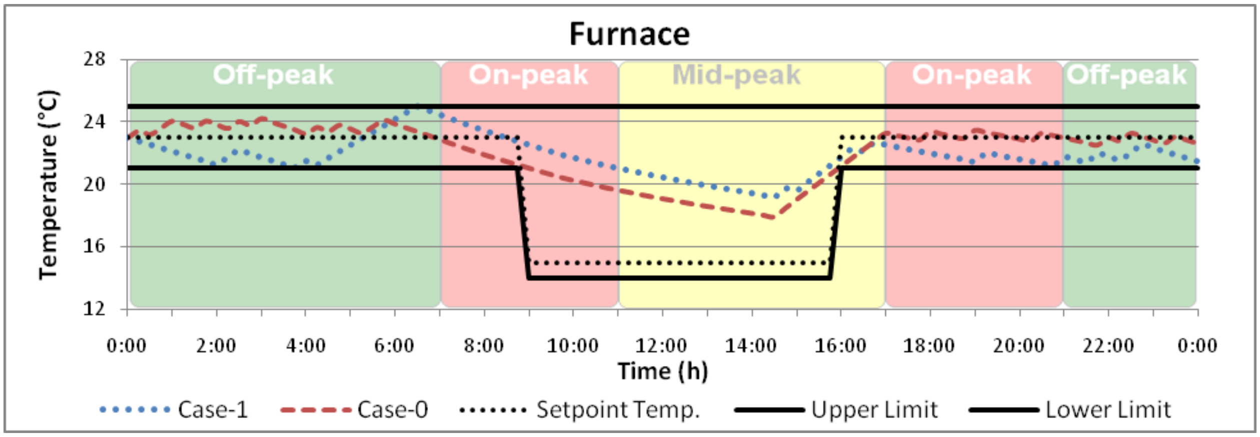

Figure 4-13: Comparison of indoor temperature of Case 0 and Case 1.

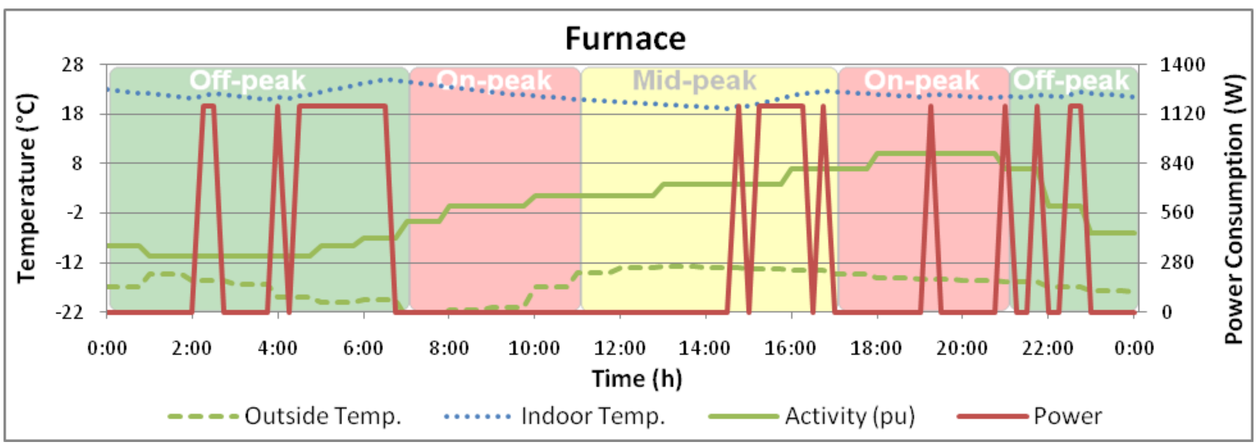

Figure 4-14: Operational schedule of the furnace in Case 1.

Fridge

Figure 4-15 presents the comparison between the inside fridge temperature for Case 1 and Case 0 and Figure 4-16 shows the operational schedule of the fridge in Case 1. Observe that results are not similar to the summer since the TOU prices are different for winter.

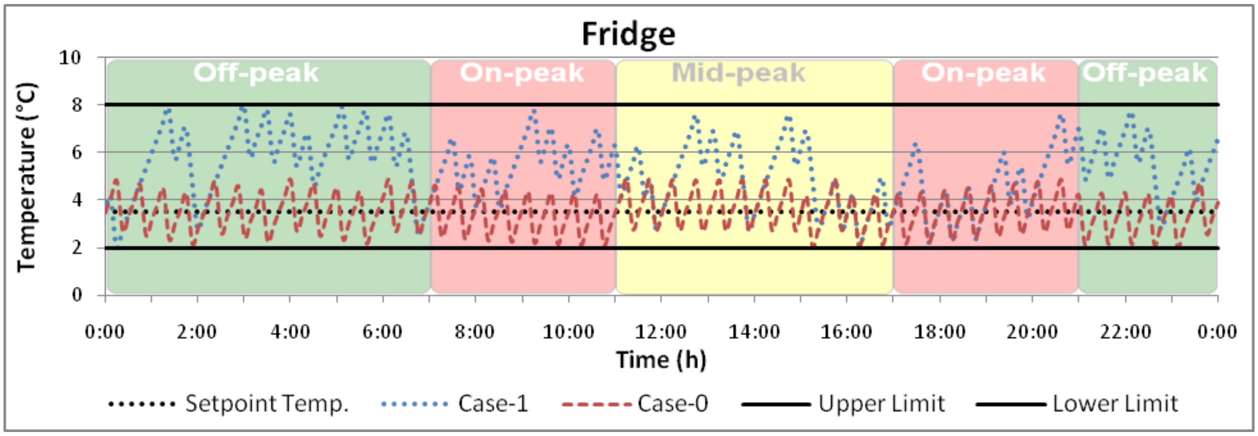

Figure 4-15: Comparison of inside fridge temperature in Case 1 and Case 0.

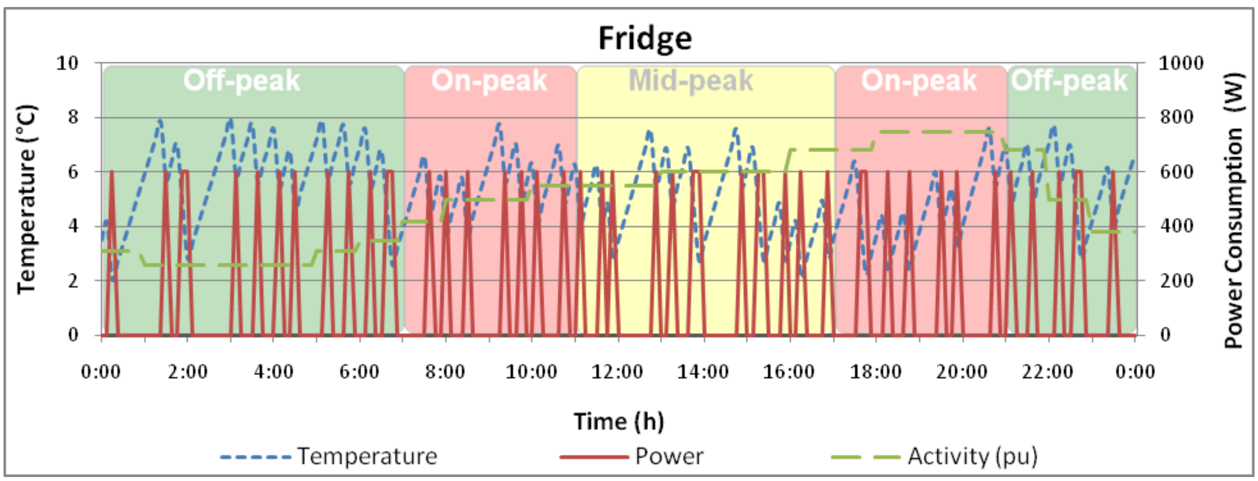

Figure 4-16: Operational schedule of fridge in Case 1.

Water heater

Figure 4-17 shows a comparison of the water temperature output for Case 1 and Case 0 while, Figure 4-18 depicts the operational schedule of the water heater and hot water usage. The results are different from the summer because of winter TOU prices.

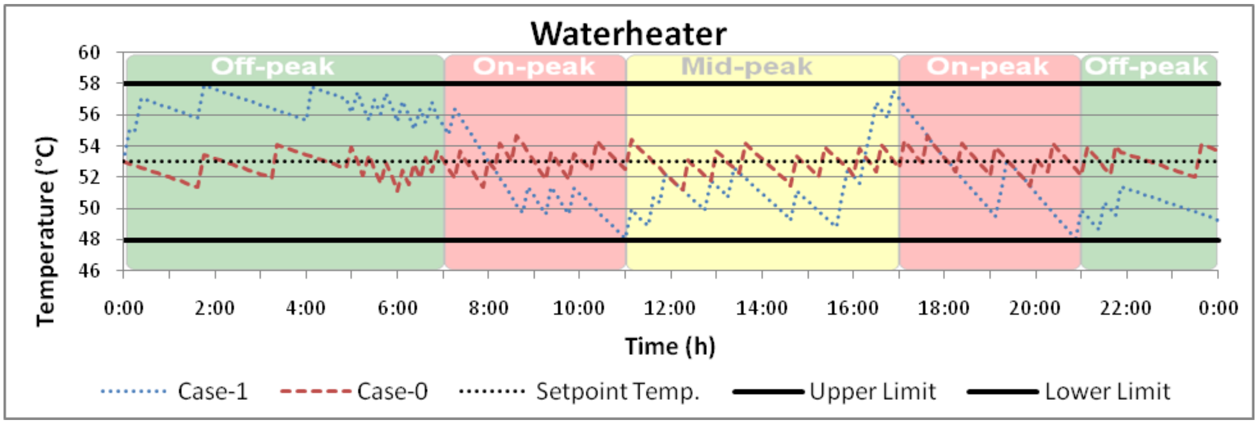

Figure 4-17: Comparison of water temperature in Case 1 and Case 0.

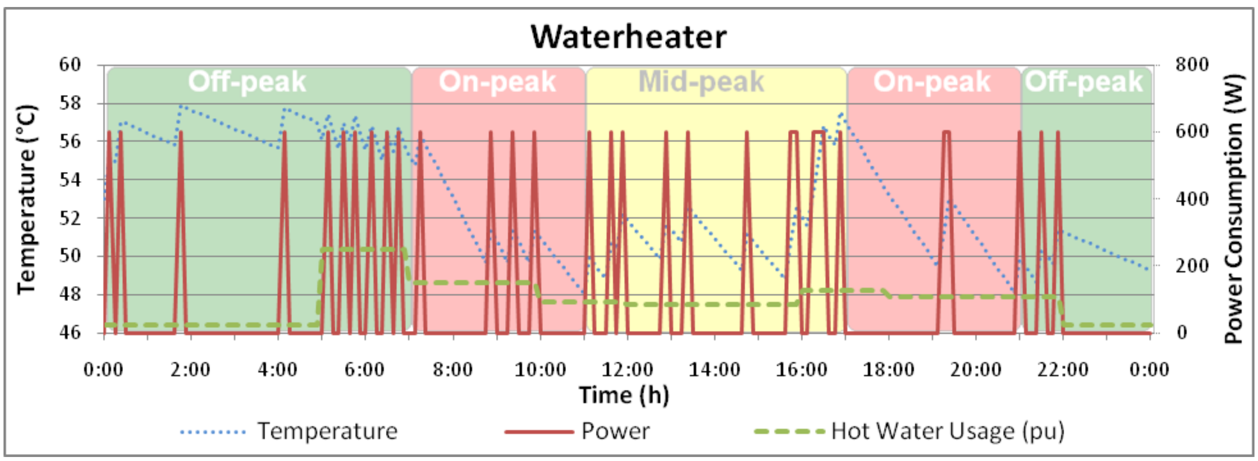

Figure 4-18: Operational schedule of water heater in Case 1.

Lighting

Figure 4-19 compares the illumination levels achieved in Case 1 and Case 0 for the lighting model. The operational schedules, outdoor illumination level and minimum required indoor illumination for a winter day are presented. The results show that the operational schedule is dependent on the minimum required illumination levels. Thus, a similar schedule to summer is observed but with a higher energy cost because of the different TOU prices in winter.

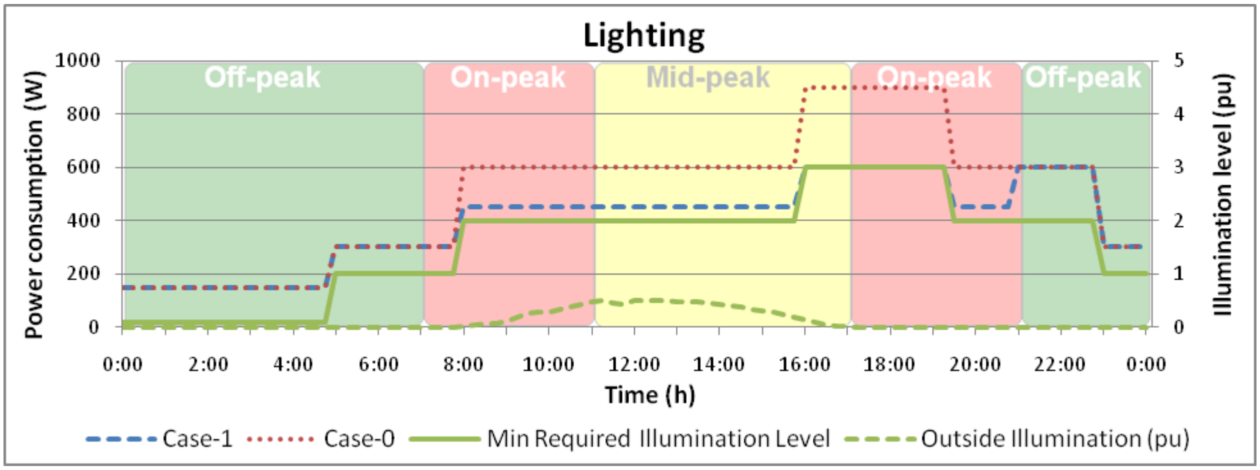

Figure 4-19: Comparison of operational schedule of lighting in Case 1 and Case 0.

Dishwasher

Figure 4-20 presents the operational schedule for the dishwasher. It is observed that Case 0 schedules the dishwasher during first available operational hours through mid-peak and on-peak periods while in Case 1 the dishwasher operations are observed during the off-peak period, as in the case of the summer day.

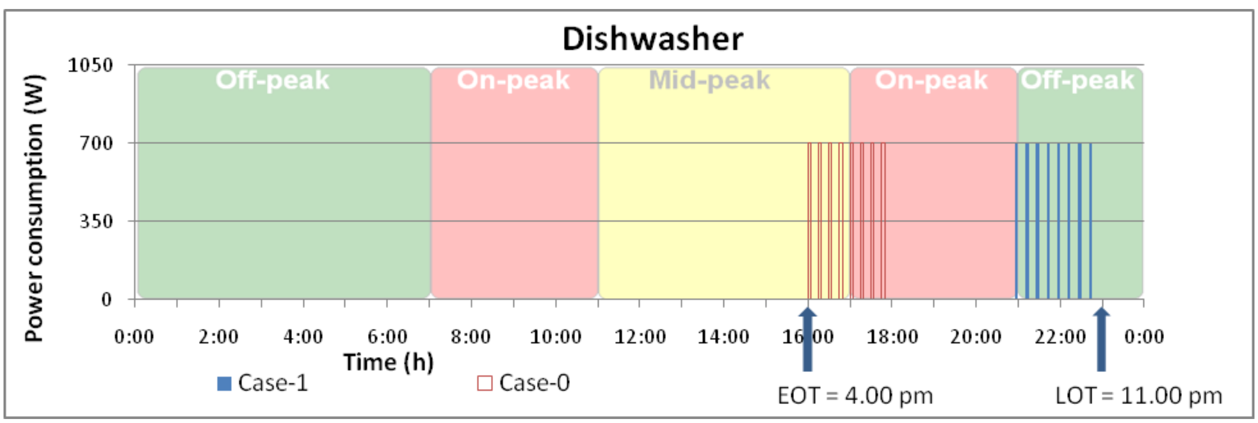

Figure 4-20: Comparison of operational schedule of dishwasher in Case 1 and Case 0.

Cloth washer and dryer

A comparison of the operational schedules of the cloth washer and dryer is presented in Figures 4-21 and 4-22. The cloth washer is scheduled during peak-price period in Case 1, while Case 0 starts operating it during the mid-peak price period. This is due to the fact that the operation of the cloth washer and dryer are inter-dependent; and hence in Case 1 the cloth washer is scheduled during on-peak price period, so that the dryer is scheduled during off-peak price period to minimize total cost.

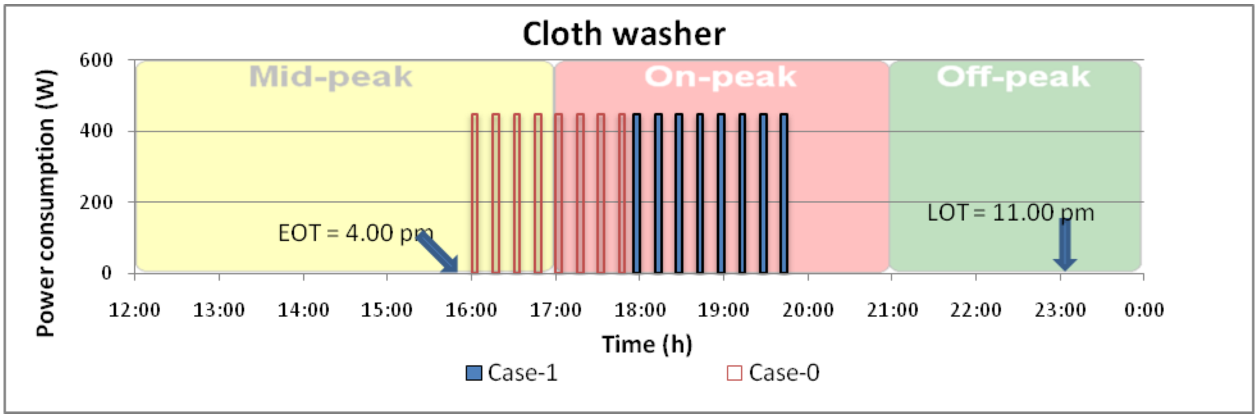

Figure 4-21: Comparison of operational schedule of cloth washer in Case 1 and Case 0.

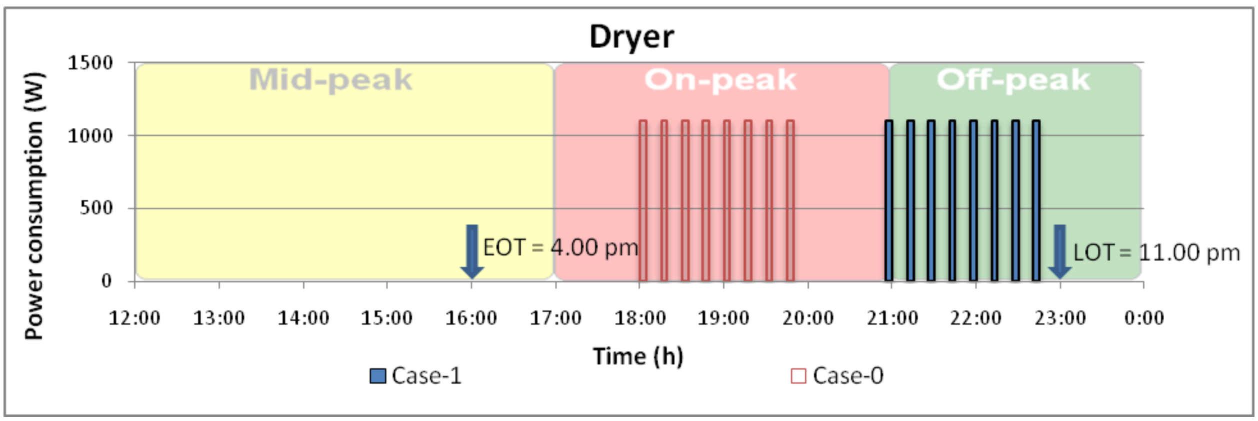

Figure 4-22: Comparison of operational schedule of dryer in Case 1 and Case 0.

Energy Storage Device

Figure 4-23 presents the operation of the energy storage device for a winter day. Because of low levels of power generation from the PV panels in winter, the battery discharge is much less than in a summer day.

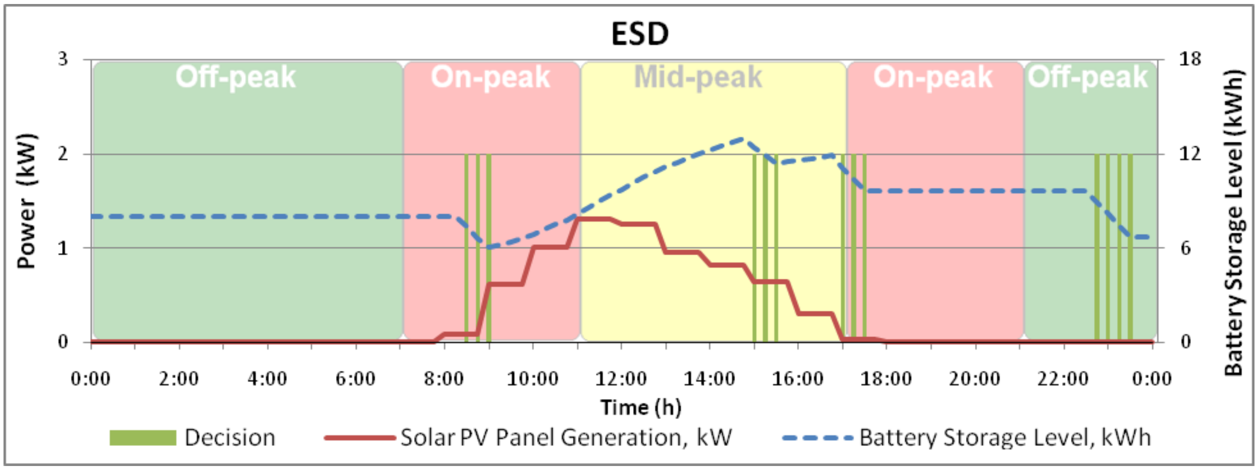

Figure 4-23: Operational schedule of ESD.

4.2.2 Cost and Energy Comparison

Comparison of energy costs, energy consumption, gas consumption and emissions for the energy hub as a whole and for individual devices is presented in Table 4-2 for summer day conditions. Results from the model in Case 1 are compared to Case 0 with programmable thermostat and fixed temperature settings. Observe that the total energy cost in Case 1 is reduced by 19.3% and 20.9% w.r.t. the base case for the programmable thermostat and fixed temperature settings, respectively.

Although the objective in Case 1 is to minimize the energy cost, the total energy consumption and emissions are reduced as well as expected. The revenue from the energy storage device is higher than in the base case, i.e. the optimization model fully utilizes the available energy while satisfying the energy storage device constraints. Since there is no limit on peak-power levels, the model schedules rest of the appliances during off-peak price periods, which results in higher peak demand in Case 1 as compared to Case 0.

Amongst the appliances, the air conditioner unit accrues the highest savings when compared to other devices. It shows a 24.1% reduction in daily cost when compared to the base case with fixed temperature settings. There is no change in the stove, dishwasher and cloth washer/dryer energy consumption; however these devices are optimally rescheduled to lower energy price periods. A similar comparison between Case 1 and Case 0 for a winter day is presented in Table 4-3.

Table 4-2: Comparison of cost, energy consumption and emissions in Case 1 with Case 0 for a summer day.

Item	Case-1	Case-0			
		Programmable Thermostat	Change (%)	Fixed Temperature	Change (%)
Energy Cost in $	5.03	6.24	19.3	6.37	20.9
Energy Consumption in kWh	49.96	56.91	12.2	58.56	14.7
Gas Cost in $	1.35	1.44	6.0	1.44	6.0
Gas Consumption in cu.m	4.60	4.90	6.1	4.90	6.1
ESD Revenue in $	19.85	16.84		16.84	
ESD Energy Supply in kWh	24.75	21.00		21.00	
Emission Cost in $	0.40	0.50		0.51	
Emission in kg	3.98	4.96	19.8	5.07	21.6
Peak Demand in kW	14.90	14.20		12.10	

Device		Case-1		Case-0: Programmable Thermostat		Change (%)		Case-0: Fixed Temperature		Change (%)	
		Energy Consumption (kWh)	Energy Cost ($)	Energy Consumption (kWh)	Energy Cost ($)	Energy Consumption Change (%)	Energy Cost Change (%)	Energy Consumption (kWh)	Energy Cost ($)	Energy Consumption Change (%)	Energy Cost Change (%)
Furnace (75 kBtu/hr)	Electricity	0	0	0	0			0	0		
	Gas in cu.m	0	0	0	0			0	0		
Air Conditioner (2.2 kW)		18.15	1.86	20.90	2.28	13.2	18.6	22.55	2.45	19.5	24.1
Waterheater (42 kBtu/hr)	Electricity	2.30	0.23	2.45	0.26	6.1	9.1	2.45	0.26	6.1	9.1
	Gas in cu.m	4.60	1.35	4.90	1.44	6.0	6.1	4.90	1.44	6.0	6.1
Fridge (0.6 kW)		3.45	0.35	3.53	0.36	2.1	2.6	3.53	0.36	2.1	2.6
Lighting (0.15 kW)		8.44	0.88	12.04	1.32	29.9	32.9	12.04	1.32	29.9	32.9
Stove (1.5 kW)		4.50	0.46	4.50	0.50	0.0	7.4	4.50	0.49	0.0	6.5
Dishwasher (0.7 kW)		1.40	0.11	1.40	0.16	0.0	31.6	1.40	0.16	0.0	31.6
Washer (0.45 kW)		0.90	0.10	0.90	0.10	0.0	0.0	0.90	0.10	0.0	0.0
Dryer (1.1 kW)		2.20	0.17	2.20	0.18	0.0	5.5	2.20	0.18	0.0	5.5
TubWaterheater (1.5 kW)		1.13	0.09	1.50	0.17	25.0	48.7	1.50	0.15	25.0	42.9
Poolpump (0.75 kW)		7.50	0.78	7.50	0.91	0.0	14.9	7.50	0.90	0.0	13.2

Table 4-3: Comparison of cost, energy consumption and emissions in Case 1 with Case 0 for a winter day.

Item	Case-1	Case-0			
		Programmable Thermostat	Change (%)	Fixed Temperature	Change (%)
Energy Cost in $	3.18	3.95	19.5	4.00	20.6
Energy Consumption in kWh	32.18	36.43	11.7	37.01	13.1
Gas Cost in $	4.96	5.48	9.4	5.79	14.3
Gas Consumption in cu.m	16.88	18.63	9.4	19.70	14.3
ESD Revenue in $	7.82	4.81		4.81	
ESD Energy Supply in kWh	9.75	6.00		6.00	
Emission Cost in $	0.67	0.75		0.77	
Emission in kg	6.67	7.54	11.6	7.69	13.3
Peak Demand in kW	11.50	10.13		9.33	

Device		Energy Consumption (kWh)	Energy Cost ($)	Energy Consumption (kWh)	Energy Cost ($)	Energy Consumption Change (%)	Energy Cost Change (%)	Energy Consumption (kWh)	Energy Cost ($)	Energy Consumption Change (%)	Energy Cost Change (%)
Furnace	Electricity	6.71	0.62	7.58	0.74	11.5	16.4	8.16	0.83	17.9	25.3
(75 kBtu/hr)	Gas in cu.m	12.28	3.61	13.88	4.08	11.5	11.5	14.95	4.39	17.9	17.9
Air Conditioner (2.2 kW)		0		0				0			
Waterheater	Electricity	2.30	0.23	2.38	0.26	3.1	9.4	2.38	0.25	3.1	8.1
(42 kBtu/hr)	Gas in cu.m	4.60	1.35	4.75	1.40	3.1	3.1	4.75	1.40	3.1	3.1
Fridge (0.6 kW)		3.45	0.36	3.53	0.37	2.1	2.9	3.53	0.37	2.1	2.9
Lighting (0.15 kW)		9.60	1.04	12.08	1.34	20.5	22.4	12.08	1.34	20.5	22.4
Stove (1.5 kW)		4.50	0.45	4.50	0.50	0.0	10.5	4.50	0.52	0.0	13.7
Dishwasher (0.7 kW)		1.40	0.11	1.40	0.17	0.0	35.3	1.40	0.17	0.0	35.3
Washer (0.45 kW)		0.90	0.11	0.90	0.11	0.0	-5.4	0.90	0.11	0.0	0.0
Dryer (1.1 kW)		2.20	0.17	2.20	0.28	0.0	38.6	2.20	0.20	0.0	13.6
TubWaterheater (1.5 kW)		1.13	0.09	1.88	0.19	40.0	53.0	1.88	0.21	40.0	58.9
Poolpump (0.75 kW)		0		0				0			

4.3 Case 2: Minimization of Energy Consumption

In this case, the objective function seeks to minimize the total daily energy consumption of the household. This effectively results in minimization of the operational hours of each device over a period of 24 hours and maximizes the energy storage device operation. Separate simulations are carried out for summer and winter days. Although TOU energy pricing is used as in the previous case for the sake of continuity, the pricing scheme has no effect on the optimum decisions.

4.3.1 Appliance Scheduling and Performance

A summary of the scheduling and performance of appliances follows:

- In the case of the air conditioner (for summer), no pre-cooling is observed during off-peak period since the optimization decisions are independent of varying energy prices during the day. Most of the decisions are observed when activity level and outside temperature are high, and hence the air conditioner is scheduled during on-peak and mid-peak hours, which results in higher energy cost.
- The inside temperature of the fridge remains close to the upper limit, so that the number of operations are minimized irrespective of the varying energy cost during the day. In the evening, the raised activity level yields more compressor operations to keep the fridge temperature within limits or near the set point value.
- The water temperature and operation schedule of the water heater is similar to the fridge, and most of the decisions are observed when HWU is at its maximum.
- The operational schedule of devices like the stove, dishwasher, cloth washer/dryer and pool pump do not show any energy consumption reduction, as they are required to operate for fixed number of hours during the day.
- In the case of the furnace (for winter), most of the time the indoor temperature stays at its lower limit in order to minimize furnace operations. The furnace shows more frequent operation when the outdoor temperature is very low and activity level is high.

4.3.2 Cost and Energy Comparison

Table 4-4 compares the energy cost, energy consumption, gas consumption and emissions, as a whole and for individual devices between Case 2 and Case 0, for summer day conditions. The results show an energy consumption reduction of 13.2% and 15.6% in Case 2 compared to Case 0 for a programmable thermostat and fixed temperature settings, respectively. Although the objective in this case is to minimize energy consumption, savings in energy cost, gas consumption and emissions are also achieved as expected. The revenue generated from the energy storage device is considerably higher than in Case 0, indicating that the optimization model is fully utilizing the available energy while satisfying the battery constraints. The peak demand is lower as compared to the base case, which shows that Case 2 may result in peak demand reductions as well.

Amongst the appliances, the air conditioner and lighting load accrue most of the savings when compared to other devices. The air conditioner shows a 15.8% and 22% reduction in daily energy consumption when compared to base case for a programmable thermostat and fixed temperature settings, respectively. The stove, dishwasher, cloth washer/dryer and pool pump show no change in their energy consumption, but an increase in energy costs is observed for these devices instead of savings; therefore, implementation of Case 2 may result in increased energy costs for some devices.

Similar set of comparative studies are also carried out for a winter day in Table 4-5, with the same trend being observed.

Table 4-4: Comparison of Case 2 with Case 0 for a summer day.

Item	Case-2	Case-0			
		Programmable Thermostat	Change (%)	Fixed Temperature	Change (%)
Energy Cost in $	5.46	6.24	12.5	6.37	14.2
Energy Consumption in kWh	49.41	56.91	13.2	58.56	15.6
Gas Cost in $	1.35	1.44	6.0	1.44	6.0
Gas Consumption in cu.m	4.60	4.90	6.0	4.90	6.0
ESD Revenue in $	19.85	16.84		16.84	
ESD Energy Supply in kWh	24.75	21.00		21.00	
Emission Cost in $	0.43	0.50		0.51	
Emission in kg	4.27	4.96	13.9	5.07	15.9
Peak Demand in kW	12.09	14.20		12.10	

Device		Energy Consumption (kWh)	Energy Cost ($)	Energy Consumption (kWh)	Energy Cost ($)	Energy Consumption Change (%)	Energy Cost Change (%)	Energy Consumption (kWh)	Energy Cost ($)	Energy Consumption Change (%)	Energy Cost Change (%)
Furnace (75 kBtu/hr)	Electricity	0		0				0			
	Gas in cu.m	0		0				0			
Air Conditioner (2.2 kW)		17.60	2.07	20.90	2.28	15.8	9.0	22.55	2.45	22.0	15.2
Waterheater (42 kBtu/hr)	Electricity	2.30	0.24	2.45	0.26	6.1	5.9	2.45	0.26	6.1	5.9
	Gas in cu.m	4.60	1.35	4.90	1.44	6.0	6.1	4.90	1.44	6.0	6.1
Fridge (0.6 kW)		3.45	0.36	3.53	0.36	2.1	1.6	3.53	0.36	2.1	1.6
Lighting (0.15 kW)		8.44	0.88	12.04	1.32	29.9	32.9	12.04	1.32	29.9	32.9
Stove (1.5 kW)		4.50	0.51	4.50	0.50	0.0	-2.0	4.50	0.49	0.0	-3.0
Dishwasher (0.7 kW)		1.40	0.17	1.40	0.16	0.0	-5.7	1.40	0.16	0.0	-5.7
Washer (0.45 kW)		0.90	0.11	0.90	0.10	0.0	-5.7	0.90	0.10	0.0	-5.7
Dryer (1.1 kW)		2.20	0.25	2.20	0.18	0.0	-38.2	2.20	0.18	0.0	-38.2
TubWaterheater (1.5 kW)		1.13	0.09	1.50	0.17	25.0	48.7	1.50	0.15	25.0	42.9
Poolpump (0.75 kW)		7.50	0.78	7.50	0.91	0.0	14.4	7.50	0.90	0.0	12.7

Table 4-5: Comparison of Case 2 with Case 0 for a winter day.

Item	Case-2	Case-0			
		Programmable Thermostat	Change (%)	Fixed Temperature	Change (%)
Energy Cost in $	3.51	3.95	11.0	4.00	12.3
Energy Consumption in kWh	32.18	36.43	11.7	37.01	13.1
Gas Cost in $	4.96	5.48	9.4	5.79	14.3
Gas Consumption in cu.m	16.88	18.63	9.4	19.70	14.3
ESD Revenue in $	7.82	4.81		4.81	
ESD Energy Supply in kWh	9.75	6.00		6.00	
Emission Cost in $	0.65	0.75		0.77	
Emission in kg	6.50	7.54	13.8	7.69	15.4
Peak Demand in kW	7.73	10.13		9.33	

Device		Energy Consumption (kWh)	Energy Cost ($)	Energy Consumption (kWh)	Energy Cost ($)	Energy Consumption Change (%)	Energy Cost Change (%)	Energy Consumption (kWh)	Energy Cost ($)	Energy Consumption Change (%)	Energy Cost Change (%)
Furnace	Electricity	6.71	0.68	7.58	0.74	11.5	8.2	8.16	0.83	17.9	18.0
(75 kBtu/hr)	Gas in cu.m	12.28	3.61	13.88	4.08	11.5	11.5	14.95	4.39	17.9	17.9
Air Conditioner (2.2 kW)		0		0				0			
Waterheater	Electricity	2.30	0.25	2.38	0.26	3.1	3.3	2.38	0.25	3.1	1.9
(42 kBtu/hr)	Gas in cu.m	4.60	1.35	4.75	1.40	3.12	3.13	4.75	1.40	3.12	3.1
Fridge (0.6 kW)		3.45	0.36	3.53	0.37	2.1	1.6	3.53	0.37	2.1	1.6
Lighting (0.15 kW)		9.60	1.04	12.08	1.34	20.5	22.4	12.08	1.34	20.5	22.4
Stove (1.5 kW)		4.50	0.50	4.50	0.50	0.0	-1.3	4.50	0.52	0.0	2.3
Dishwasher (0.7 kW)		1.40	0.17	1.40	0.17	0.0	-0.3	1.40	0.17	0.0	-0.3
Washer (0.45 kW)		0.90	0.11	0.90	0.11	0.0	0.0	0.90	0.11	0.0	5.1
Dryer (1.1 kW)		2.20	0.28	2.20	0.28	0.0	0.0	2.20	0.20	0.0	-40.7
TubWaterheater (1.5 kW)		1.13	0.12	1.88	0.19	40.0	35.9	1.88	0.21	40.0	44.0
Poolpump (0.75 kW)		0		0				0			

4.4 Case 3: Minimization of Emissions

This case seeks to minimize the CO_2 emissions contribution of a household customer in Ontario. The EHMS for the residential customer generates optimum schedules for the appliances based on a 24-hour forecast of Ontario's emissions profile as discussed in Chapter 2. At the same time, the model seeks to maximize the energy storage device operations so as to increase the customer's contribution towards reducing emissions by injecting emissions free electricity to the grid. TOU pricing is used in these simulations, but this has no effect on device performances. Separate simulations are carried out for summer and winter days.

4.4.1 Appliance Scheduling and Performance

A summary of the scheduling and performance of appliances follows:

- Air conditioner operation decisions are based on the emissions profile in Ontario. Similar to Case 1, pre-cooling is observed in the early hours when emissions are relatively low. In the evening, the indoor temperature stays at the upper limit so that the air conditioner minimizes its operation to avoid higher emissions period. The air conditioner mainly operates around 4:00 AM when the emissions are low, and in the evening when activity levels and outdoor temperatures are both high.
- In case of the water heater, the water temperature is close to its upper limit during the first half of the day, since emissions are lower in this period. For the next half of the day, the temperature is close to its lower limit since emissions are high during this time.
- Inside fridge temperature has a very similar trend as of the water heater's. The temperature stays close to the lower limit in the morning and afternoon, and then starts to drift upwards in the evening when emissions are relatively higher.
- In winter, the furnace is turned off from 9:00 AM to 2:00 PM, since the temperature limit range is wider during this period. The furnace primarily operates during early morning and evening periods.

4.4.2 Emissions, Cost and Energy Comparison

Table 4-6 presents a comparison of CO_2 emissions, energy cost, electricity and gas consumption between Case 3 and Case 0, for summer day conditions. The results show a 23-25% reduction in the customer's contributions to Ontario emissions with savings in energy cost and energy consumption as well. The contribution of the energy storage device towards emissions reduction is the same as in Case 1 and 2. The total energy cost is very close to that in Case 1 because the low emissions hours are similar as the off-peak price periods in a weekday; however this might not be necessarily the case always since emissions profiles may vary significantly from day to day depending on the total energy demand in the province. Peak demand in Case 3 is higher than in the base case for both summer and winter seasons as in Case 1.

Observe that the, air conditioner and water heater show greater reductions in emissions, i.e. 28% and 13.1%, respectively, when compared to the base case. Although the stove, dishwasher, cloth washer/dryer and pool pump show no change in their energy consumption, considerable savings in emissions are observed.

A similar comparison for a winter day's CO_2 emissions is presented in Table 4-7. An interesting observation in this case is that the energy cost of the stove, dishwasher and cloth washer increases in the winter. Therefore, minimizing CO_2 emissions may prove to increase costs to the customer under certain conditions.

Table 4-6: Comparison of Case 3 with Case 0 for a summer day.

Item	Case-3	Case-0			
		Programmable Thermostat	Change (%)	Fixed Temperature	Change (%)
Energy Cost in $	5.05	6.24	19.1	6.37	20.7
Energy Consumption in kWh	49.96	56.91	12.2	58.56	14.7
Gas Cost in $	1.35	1.44	6.0	1.44	6.0
Gas Consumption in cu.m	4.60	4.90	6.0	4.90	6.0
Emissions Cost in $	0.38	0.50	23.3	0.51	25.0
Emissions in kg	3.80	4.96	23.3	5.07	25.0
ESD Revenue in $	19.85	16.84		16.84	
ESD Energy Supply in kWh	24.75	21.00		21.00	
ESD Emission Savings in kg	2.60	2.15		2.08	
Peak Demand in kW	14.30	14.20		12.10	

Device		Emissions (kg)	Energy Consumption (kWh)	Energy Cost ($)	Emissions (kg)	Energy Consumption (kWh)	Energy Cost ($)	Emison Change (%)	Energy Consumption Change (%)	Energy Cost Change (%)	Emissions (kg)	Energy Consumption (kWh)	Energy Cost ($)	Emission Change (%)	Energy Consumption Change (%)	Energy Cost Change (%)
Furnace (75 kBtu/hr)	Electricity	0	0		0	0					0	0				
	Gas in cu.m	0	0		0	0					0	0				
Air Conditioner (2.2 kW)		1.38	18.15	1.86	1.77	20.90	2.28	21.8	13.2	18.2	1.92	22.55	2.45	28.0	19.5	23.8
Waterheater (42 kBtu/hr)	Electricity	0.18	2.30	0.24	0.21	2.45	0.26	13.7	6.1	8.0	0.21	2.45	0.26	13.1	6.1	8.0
	Gas in cu.m		4.60	1.35		4.90	1.44		6.0	6.1		4.90	1.44		6.0	6.1
Fridge (0.6 kW)		0.27	3.45	0.35	0.28	3.53	0.36	3.9	2.1	2.4	0.28	3.53	0.36	4.0	2.1	2.4
Lighting (0.15 kW)		0.69	8.44	0.88	1.05	12.04	1.32	34.3	29.9	32.9	1.05	12.04	1.32	34.3	29.9	32.9
Stove (1.5 kW)		0.34	4.50	0.46	0.40	4.50	0.50	14.5	0.0	7.4	0.40	4.50	0.49	14.6	0.0	6.5
Dishwasher (0.7 kW)		0.08	1.40	0.11	0.13	1.40	0.16	39.5	0.0	31.6	0.13	1.4	0.16	38.9	0.0	31.6
Washer (0.45 kW)		0.08	0.90	0.10	0.08	0.90	0.10	1.1	0.0	0.0	0.08	0.90	0.10	1.1	0.0	0.0
Dryer (1.1 kW)		0.12	2.20	0.17	0.13	2.20	0.18	5.3	0.0	5.5	0.13	2.20	0.18	5.3	0.0	5.5
TubWaterheater (1.5 kW)		0.04	1.13	0.09	0.15	1.50	0.17	71.4	25.0	48.7	0.13	1.50	0.15	66.4	25.0	42.9
Poolpump (0.75 kW)		0.62	7.50	0.78	0.76	7.50	0.91	19.2	0.0	14.7	0.75	7.50	0.90	17.5	0.0	12.9

Table 4-7: Comparison of Case 3 with Case 0 for a winter day.

Item	Optimizer	Without Optimizer			
		Programmable Thermostat	Change (%)	Fixed Temperature	Change (%)
Energy Cost in $	3.55	3.95	10.1	4.00	11.4
Energy Consumption in kWh	32.18	36.43	11.7	37.01	13.1
Gas Cost in $	4.96	5.48	9.4	5.79	14.3
Gas Consumption in cu.m	16.88	18.63	9.4	19.70	14.3
Emissions Cost in $	0.65	0.75	14.1	0.77	15.7
Emissions in kg	6.48	7.54	14.1	7.69	15.7
ESD Revenue in $	7.82	4.81		4.81	
ESD Energy Supply in kWh	9.75	6.00		6.00	
ESD Emission Savings in kg	2.17	1.37		1.36	
Peak Demand in kW	11.33	10.13		9.33	

Device		Emissions (kg)	Energy Consumption (kWh)	Energy Cost ($)	Emissions (kg)	Energy Consumption (kWh)	Energy Cost ($)	Emisison Change (%)	Energy Consumption Change (%)	Energy Cost Change (%)	Emissions (kg)	Energy Consumption (kWh)	Energy Cost ($)	Emission Change (%)	Energy Consumption Change (%)	Energy Cost Change (%)
Furnace	Electricity	1.33	6.71	0.68	1.54	7.58	0.74	13.8	11.5	8.2	1.68	8.16	0.83	20.8	17.9	18.0
(75 kBtu/hr)	Gas in cu.m		12.28	3.61		13.88	4.08		11.5	11.5		14.95	4.39		17.9	17.9
Air Conditioner (2.2 kW)		0	0		0	0					0	0				
Waterheater	Electricity	0.46	2.30	0.25	0.49	2.38	0.26	6.7	3.1	2.2	0.49	2.38	0.25	6.6	3.1	0.8
(42 kBtu/hr)	Gas in cu.m		4.60	1.35		4.75	1.40		3.1	3.1		4.75	1.40		3.1	3.1
Fridge (0.6 kW)		0.71	3.45	0.36	0.73	3.53	0.37	2.8	2.1	1.3	0.73	3.53	0.37	2.8	2.1	1.3
Lighting (0.15 kW)		2.00	9.60	1.04	2.51	12.08	1.34	20.6	20.5	22.4	2.51	12.08	1.34	20.6	20.5	22.4
Stove (1.5 kW)		0.90	4.50	0.55	0.95	4.50	0.50	5.4	0.0	-11.1	0.93	4.50	0.52	3.5	0.0	-7.1
Dishwasher (0.7 kW)		0.28	1.40	0.18	0.29	1.40	0.17	3.5	0.0	-5.4	0.29	1.40	0.17	3.5	0.0	-5.4
Washer (0.45 kW)		0.18	0.90	0.11	0.19	0.90	0.11	1.6	0.0	-5.4	0.18	0.90	0.11	-2.0	0.0	0.0
Dryer (1.1 kW)		0.44	2.20	0.28	0.44	2.20	0.28	0.2	0.0	0.0	0.46	2.20	0.20	5.8	0.0	-40.7
TubWaterheater (1.5 kW)		0.20	1.13	0.09	0.41	1.88	0.19	50.7	40.0	53.0	0.42	1.88	0.21	51.7	40.0	58.9
Poolpump (0.75 kW)		0	0		0	0					0	0				

4.5 Case 4: Minimization of Cost Subject to Peak Power Constraint

It was observed earlier that the minimization of energy cost in Case 1 resulted in a higher peak demand in the household. Therefore in this case an additional cap is applied to hourly energy consumption; an analysis is carried out to find the minimum allowable cap for a feasible solution. The operation of devices in this case becomes inter-dependent. However, the energy storage device is not affect by a peak power constraint, since it exports power directly to the grid.

Figure 4-24 and 4-25 represent the effect of a peak power constraint on household demand for a summer and winter day respectively. The comparison is carried out among the base case, Case 1 and Case 4. Two sub-cases for Case 4 are presented; one with intermediate and another with minimum feasible peak demand limits. Observe in these figures that in Case 1, peak demand occurs during off-peak periods, whereas the power consumption profile of Case 4 indicates that load has been shifted to mid-peak and on-peak price periods to avoid higher power demand in the off-peak period. This case is of interest to LDCs since it can be used to reduce the peak load of the system during on-peak hours. It was observed from the power consumption profile that the peak power can be clipped up to 7.1 kW (48% of Case 1) in summer and up to 5.6 kW (49% of Case 1) in winter (see Table 4-8 and 4-9); below these limits, the optimization problem becomes infeasible.

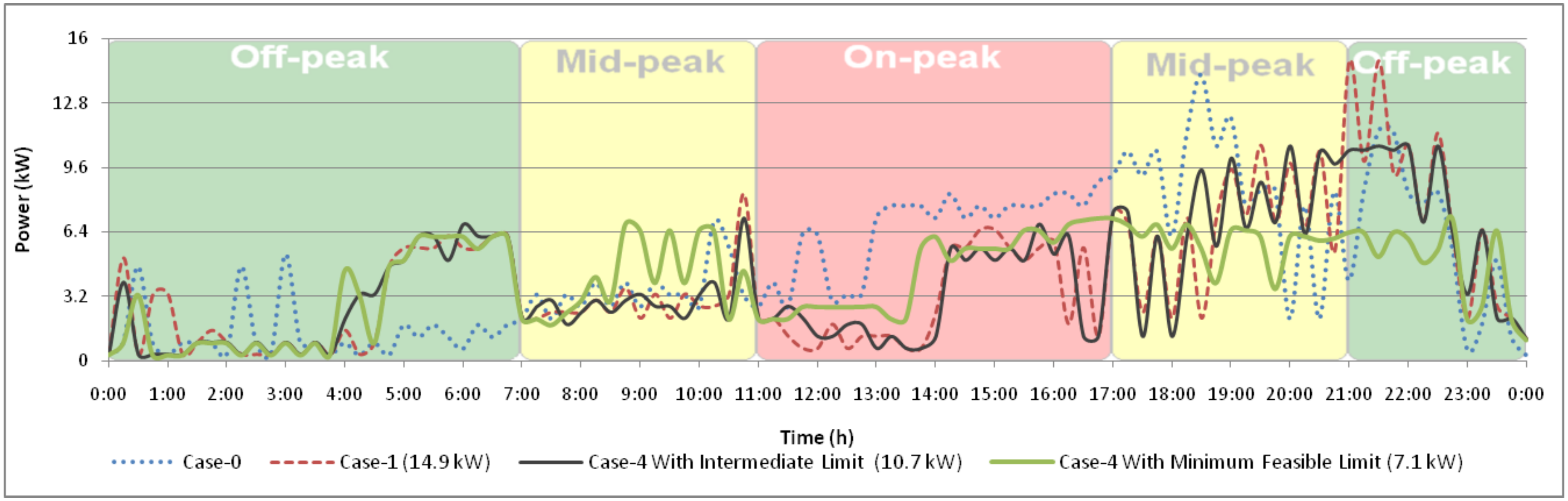

Figure 4-24: Effect of peak power constraint on household demand for a summer day.

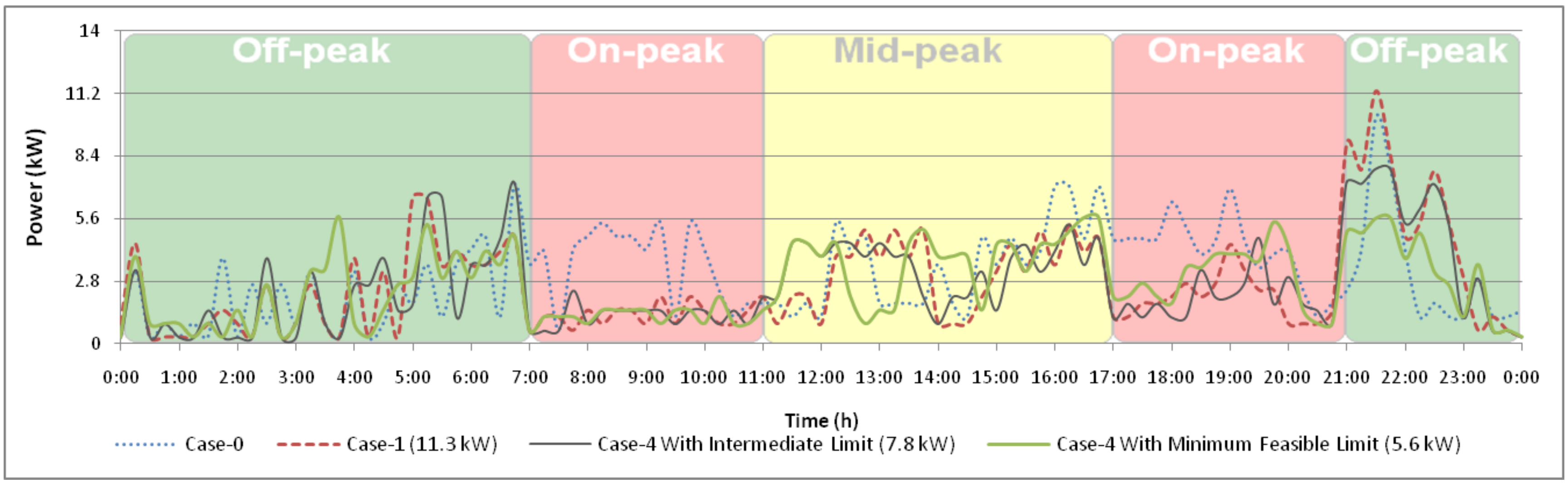

Figure 4-25: Effect of peak power constraint on household demand for a winter day.

4.5.1 Comparison of Peak Demand, Cost and Energy Consumption

Constraining the peak demand influences the performance and schedule of individual devices. Table 4-8 presents the results obtained for Case 4 with intermediate peak power cap and the minimum feasible peak power cap for a summer day. In summer, the air conditioner shows a rise in its energy cost and energy consumption in Case 4. The energy cost of dishwasher, water heater and pool pump increases, since these devices are scheduled during higher price periods. In winter, the energy consumption of all devices remains the same with a rise in energy cost observed for the stove and dishwasher.

Observe that these results show that peak demand can be significantly reduced without any major reduction in total energy cost and energy consumption.

Table 4-8: Comparison of Case 4 with Case 0 for a summer day.

Item		Case-1		Case-4 with intermediate limit		Case-4 with minimum feasible limit	
Energy Cost in $		5.03		5.07		5.32	
Energy Consumption in kWh		49.96		49.96		50.51	
Gas Cost in $		1.35		1.35		1.35	
Gas Consumption in cu.m		4.60		4.60		4.60	
ESD Revenue in $		19.85		19.85		19.85	
ESD Energy Supply in kWh		24.75		24.75		24.75	
Peak Demand in kW		14.90		10.70		7.10	
Device		Energy Consumption (kWh)	Energy Cost ($)	Energy Consumption (kWh)	Energy Cost ($)	Energy Consumption (kWh)	Energy Cost ($)
Furnace (75 kBtu/hr)	Electricity	0		0		0	
	Gas in cu.m	0		0		0	
Air Conditioner (2.2 kW)		18.15	1.86	18.15	1.88	18.70	1.99
Waterheater (42 kBtu/hr)	Electricity	2.30	0.23	2.30	0.23	2.30	0.24
	Gas in cu.m	4.60	1.35	4.60	1.35	4.60	1.35
Fridge (0.6 kW)		3.45	0.35	3.45	0.35	3.45	0.36
Lighting (0.15 kW)		8.44	0.88	8.44	0.88	8.44	0.88
Stove (1.5 kW)		4.50	0.46	4.50	0.47	4.50	0.49
Dishwasher (0.7 kW)		1.40	0.11	1.40	0.11	1.40	0.17
Washer (0.45 kW)		0.90	0.10	0.90	0.10	0.90	0.10
Dryer (1.1 kW)		2.20	0.17	2.20	0.17	2.20	0.18
TubWaterheater (1.5 kW)		1.13	0.09	1.13	0.09	1.13	0.09
Poolpump (0.75 kW)		7.50	0.78	7.50	0.78	7.50	0.83

Table 4-9: Comparison of Case 4 with Case 0 for a winter day.

Item	Case-1	Case-4 with intermediate limit	Case-4 with minimum feasible limit
Energy Cost in $	3.18	3.20	3.31
Energy Consumption in kWh	32.18	32.18	32.18
Gas Cost in $	4.96	4.96	4.96
Gas Consumption in cu.m	16.88	16.88	16.88
ESD Revenue in $	7.82	7.82	7.82
ESD Energy Supply in kWh	9.75	9.75	9.75
Peak Demand in kW	11.50	7.80	5.63

Device		Case-1		Case-4 with intermediate limit		Case-4 with minimum feasible limit	
		Energy Consumption (kWh)	Energy Cost ($)	Energy Consumption (kWh)	Energy Cost ($)	Energy Consumption (kWh)	Energy Cost ($)
Furnace (75 kBtu/hr)	Electricity	6.71	0.62	6.71	0.62	6.71	0.62
	Gas in cu.m	12.28	3.61	12.28	3.61	12.28	3.61
Air Conditioner (2.2 kW)		0.00		0.00		0.00	
Waterheater (42 kBtu/hr)	Electricity	2.30	0.23	2.30	0.23	2.30	0.23
	Gas in cu.m	4.60	1.35	4.60	1.35	4.60	1.35
Fridge (0.6 kW)		3.45	0.36	3.45	0.36	3.45	0.36
Lighting (0.15 kW)		9.60	1.04	9.60	1.04	9.60	1.04
Stove (1.5 kW)		4.50	0.45	4.50	0.47	4.50	0.47
Dishwasher (0.7 kW)		1.40	0.11	1.40	0.11	1.40	0.11
Washer (0.45 kW)		0.90	0.11	0.90	0.11	0.90	0.11
Dryer (1.1 kW)		2.20	0.17	2.20	0.17	2.20	0.28
TubWaterheater (1.5 kW)		1.13	0.09	1.13	0.09	1.13	0.09
Poolpump (0.75 kW)		0		0		0	

4.6 Case 5: Minimization of Cost, Energy Consumption and Emissions

In this case, a multi-objective function is defined, which minimizes energy cost, energy consumption and emissions as discussed in Chapter 3. The model assumed TOU prices and a forecasted Ontario's hourly emissions profile. Separate simulations are carried out for summer and winter. The user can give precedence to any particular objective function by changing the weights in the objective function. The operation of the energy storage device is not affected in this case, since the objective is to maximize its operations, showing similar revenues.

4.6.1 Appliance Scheduling and Performance

In all study cases the operational schedule of air conditioner is very similar to Case 1, as pre-cooling is carried out in the morning off-peak period. During the afternoon, the air conditioner is turned off most of the time, since both emissions and energy price are high. The operation of the air conditioner is effected by a higher activity level in the evening. The inside temperature of the fridge and water temperature of water heater show similar trend as observed in Case 1. In the case of the furnace, no pre-heating is observed, with the temperature following the lower limits throughout the day to minimize number of operations.

4.6.2 Energy Cost, Energy Comparison and Emissions Comparison

Table 4-10 and 4-11 presents a comparison of Case 5 and Case 0 for summer and winter days, respectively. Reductions in energy cost, energy consumption and emissions in Case 5, are compared to Case 0, are evident from these tables. However, the total energy cost, energy consumption and emissions are higher as compared to their corresponding values in Case 1, Case 2 and Case 3. Since Case 5 seeks to minimize all objectives, the peak demand increases as it is not limited in this case.

The dishwasher, washer, dryer and pool pump do not show any change in energy consumption as in previous cases, but their corresponding emissions and cost have changed. In winter, the dishwasher and dryer show a slight increase in emissions.

Table 4-10: Comparison of Case 5 with Case 0 for a summer day.

Item	Case-5	Case-0			
		Programmable Thermostat	Change (%)	Fixed Temperature	Change (%)
Energy Cost in $	5.04	6.24	19.3	6.37	20.9
Energy Consumption in kWh	49.96	56.91	12.2	58.56	14.7
Gas Cost in $	1.35	1.44	6.0	1.44	6.0
Gas Consumption in kWh	4.60	4.90	6.0	4.90	6.0
Emissions Cost in $	0.38	0.50	23.0	0.51	24.7
Emissions in kg	3.82	4.96	23.0	5.07	24.7
ESD Revenue in $	19.85	16.84		16.84	
ESD Energy Supply in kWh	24.75	21.00		21.00	
Power Demand in kW	15.49	14.20		12.10	

Device		Case-5 Emissions (kg)	Case-5 Energy Consumption (kWh)	Case-5 Energy Cost ($)	Programmable Thermostat Emissions (kg)	Programmable Thermostat Energy Consumption (kWh)	Programmable Thermostat Energy Cost ($)	Change (%) Emisison Change (%)	Change (%) Energy Consumption Change (%)	Change (%) Energy Cost Change (%)	Fixed Temperature Emissions (kg)	Fixed Temperature Energy Consumption (kWh)	Fixed Temperature Energy Cost ($)	Change (%) Emission Reduction (%)	Change (%) Energy Consumption Change (%)	Change (%) Energy Cost Change (%)
Furnace (75 kBtu/hr)	Electricity	0	0		0	0					0	0				
	Gas in cu.m	0	0		0	0					0	0				
Air Conditioner (2.2 kW)		1.41	18.15	1.86	1.77	20.90	2.28	20.5	13.2	18.2	1.92	22.55	2.45	26.8	19.5	23.8
Waterheater (42 kBtu/hr)	Electricity	0.18	2.30	0.23	0.21	2.45	0.26	12.9	6.1	10.1	0.21	2.45	0.26	12.2	6.1	10.1
	Gas in cu.m		4.60	1.35		4.90	1.44		6.0	6.1		4.90	1.44		6.0	6.1
Fridge (0.6 kW)		0.27	3.45	0.35	0.28	3.53	0.36	3.2	2.1	2.6	0.28	3.53	0.36	3.2	2.1	2.6
Lighting (0.15 kW)		0.69	8.44	0.88	1.05	12.04	1.32	34.3	29.9	32.9	1.05	12.04	1.32	34.3	29.9	32.9
Stove (1.5 kW)		0.34	4.50	0.46	0.40	4.50	0.50	14.5	0.0	7.4	0.40	4.50	0.49	14.6	0.0	6.5
Dishwasher (0.7 kW)		0.08	1.40	0.11	0.13	1.40	0.16	39.5	0.0	31.6	0.13	1.40	0.16	38.9	0.0	31.6
Washer (0.45 kW)		0.08	0.90	0.10	0.08	0.90	0.10	1.1	0.0	0.0	0.08	0.90	0.10	1.1	0.0	0.0
Dryer (1.1 kW)		0.12	2.20	0.17	0.13	2.20	0.18	5.3	0.0	5.5	0.13	2.20	0.18	5.3	0.0	5.5
TubWaterheater (1.5 kW)		0.04	1.13	0.09	0.15	1.50	0.17	71.4	25.0	48.7	0.13	1.50	0.15	66.4	25.0	42.9
Poolpump (0.75 kW)		0.61	7.50	0.78	0.76	7.50	0.91	20.3	0.0	14.9	0.75	7.50	0.90	18.7	0.0	13.2

Table 4-11: Comparison of Case 5 with Case 0 for a winter day.

Item	Case-5	Case-0: Programmable Thermostat	Case-0: Change (%)	Case-0: Fixed Temperature	Case-0: Change (%)
Energy Cost in $	3.18	3.95	19.4	4.00	20.5
Energy Consumption in kWh	32.18	36.43	11.7	37.01	13.1
Gas Cost in $	4.96	5.48	9.4	5.79	14.3
Gas Consumption in kWh	16.88	18.63	9.4	19.70	14.3
Emissions Cost in $	0.66	0.75	12.5	0.77	14.2
Emissions in kg	6.60	7.54	12.5	7.69	14.2
ESD Revenue in $	7.82	4.81		4.81	
ESD Energy Supply in kWh	9.75	6.00		6.0	
Power Demand in kW	11.33	10.13		9.33	

Device		Case-5			Case-0: Programmable Thermostat			Case-0: Change (%)			Case-0: Fixed Temperature			Case-0: Change (%)		
		Emissions (kg)	Energy Consumption (kWh)	Energy Cost ($)	Emissions (kg)	Energy Consumption (kWh)	Energy Cost ($)	Emisison Change (%)	Energy Consumption Change (%)	Energy Cost Change (%)	Emissions (kg)	Energy Consumption (kWh)	Energy Cost ($)	Emission Reduction (%)	Energy Consumption Change (%)	Energy Cost Change (%)
Furnace (75 kBtu/hr)	Electricity	1.34	6.71	0.62	1.54	7.58	0.74	13.1	11.5	15.9	1.68	8.16	0.83	20.2	17.9	24.9
	Gas in cu.m		12.28	3.61		13.88	4.08		11.5	11.5		14.95	4.39		17.9	17.9
Air Conditioner (2.2 kW)		0	0		0	0					0	0				
Waterheater (42 kBtu/hr)	Electricity	0.47	2.30	0.23	0.49	2.38	0.26	4.7	3.1	9.4	0.49	2.38	0.25	4.6	3.1	8.1
	Gas in cu.m		4.60	1.35		4.75	1.40		3.1	3.1		4.75	1.40		3.1	3.1
Fridge (0.6 kW)		0.71	3.45	0.36	0.73	3.53	0.37	2.6	2.1	2.9	0.73	3.53	0.37	2.6	2.1	2.9
Lighting (0.15 kW)		2.00	9.60	1.04	2.51	12.08	1.34	20.6	20.5	22.4	2.51	12.08	1.34	20.6	20.5	22.4
Stove (1.5 kW)		0.94	4.50	0.45	0.95	4.50	0.50	1.1	0.0	10.5	0.93	4.50	0.52	-0.9	0.0	13.7
Dishwasher (0.7 kW)		0.30	1.40	0.11	0.29	1.40	0.17	-3.9	0.0	35.3	0.29	1.40	0.17	-3.9	0.0	35.3
Washer (0.45 kW)		0.18	0.90	0.11	0.19	0.90	0.11	3.6	0.0	0.0	0.18	0.90	0.11	0.1	0.0	0.0
Dryer (1.1 kW)		0.47	2.20	0.17	0.44	2.20	0.28	-7.5	0.0	38.6	0.46	2.20	0.20	-1.5	0.0	13.6
TubWaterheater (1.5 kW)		0.20	1.13	0.09	0.41	1.88	0.19	50.7	40.0	53.0	0.42	1.88	0.21	51.7	40.0	58.9
Poolpump (0.75 kW)		0	0		0	0					0	0				

4.7 Comparison of All Case Studies

The following can be observed in the Table 4-12:

- Case 0 has the highest energy cost, energy consumption and emissions among all cases.
- In terms of energy cost, Case 1 and Case 5 yield almost identical savings.
- Energy consumption is minimum in Case 2, however, overall energy consumption for all the cases is very similar except for Case 0. Therefore, Case 2 is not significant, since costs and emissions are higher with respect to all cases.
- Case 1 and Case 5 have approximately the same amount of total emissions, which are the lowest among all cases.
- Case 4, which has a maximum peak power constraint, results in a 50% reduction in peak demand as compared to Case 1, while the total energy cost, energy consumption and emissions are higher than Case 1.
- The revenue obtained from exporting energy to the grid is larger in all cases with respect to Case 0, since the optimization model maximizes the revenue from ESD operations.

Figure 4-26 shows a comparison of total energy cost, electricity consumption, gas consumption and emissions for all cases for a summer day. Energy cost in Case 1, Case 3 and Case 5 are very close to each other because the peak emissions and peak price periods are occurring approximately during the same time intervals. Electricity consumption in all cases remains almost the same but considerably lower than Case 0, while gas consumption is slightly less in all cases when compared to Case 0. Case 3 and Case 5 show approximately equal emissions, which are less than all other cases and significantly smaller than Case 0.

Similar comparison of energy costs, electricity consumption, gas consumption and emissions for a winter day are presented in Table-4-13 and Figure 4-27.

Table 4-12: Summary comparison of all cases for a summer day.

Item	Case-0	Case-1	Case-2	Case-3	Case-4 with minimum feasible peak power constraint	Case-5
Energy Cost in $	6.24	5.03	5.46	5.05	5.32	5.04
Energy Consumption in kWh	56.91	49.96	49.41	49.96	50.51	49.96
Gas Cost in $	1.44	1.35	1.35	1.35	1.35	1.35
Gas Consumption in cu.m	4.90	4.60	4.60	4.60	4.60	4.60
ESD Revenue in $	16.84	19.85	19.85	19.85	19.85	19.85
ESD Energy Supply in kWh	21.00	24.75	24.75	24.75	24.75	24.75
Emissions Cost in $	0.50	0.40	0.42	0.38	0.42	0.38
Emissions in kg	4.96	3.98	4.25	3.80	4.23	3.82
Peak Demand in kW	14.20	14.90	12.09	14.30	7.10	15.49

Device		Case-0 Energy Consumption (kWh)	Case-0 Energy Cost ($)	Case-0 Emission (kg)	Case-1 Energy Consumption (kWh)	Case-1 Energy Cost ($)	Case-1 Emission (kg)	Case-2 Energy Consumption (kWh)	Case-2 Energy Cost ($)	Case-2 Emission (kg)	Case-3 Energy Consumption (kWh)	Case-3 Energy Cost ($)	Case-3 Emission (kg)	Case-4 Energy Consumption (kWh)	Case-4 Energy Cost ($)	Case-4 Emission (kg)	Case-5 Energy Consumption (kWh)	Case-5 Energy Cost ($)	Case-5 Emission (kg)
Furnace (75 kBtu/hr)	Electricity	0			0			0			0			0			0		
	Gas in cu.m	0			0			0			0			0			0		
Air Conditioner (2.2 kW)		20.90	2.28	1.77	18.15	1.86	1.50	17.60	2.07	1.55	18.15	1.86	1.38	18.70	1.99	1.75	18.15	1.86	1.41
Waterheater (42 kBtu/hr)	Electricity	2.45	0.26	0.21	2.30	0.23	0.18	2.30	0.24	0.19	2.30	0.24	0.18	2.30	0.24	0.19	2.30	0.23	0.18
	Gas in cu.m	4.90	1.44		4.60	1.35		4.60	1.35		4.60	1.35		4.60	1.35		4.60	1.35	
Fridge (0.6 kW)		3.53	0.36	0.28	3.45	0.35	0.28	3.45	0.36	0.28	3.45	0.35	0.27	3.45	0.36	0.28	3.45	0.35	0.27
Lighting (0.15 kW)		12.04	1.32	1.05	8.44	0.88	0.69	8.44	0.88	0.69	8.44	0.88	0.69	8.44	0.88	0.69	8.44	0.88	0.69
Stove (1.5 kW)		4.50	0.50	0.40	4.50	0.46	0.36	4.50	0.51	0.40	4.50	0.46	0.34	4.50	0.49	0.36	4.50	0.46	0.34
Dishwasher (0.7 kW)		1.40	0.16	0.13	1.40	0.11	0.08	1.40	0.17	0.14	1.40	0.11	0.08	1.40	0.17	0.08	1.40	0.11	0.08
Washer (0.45 kW)		0.90	0.10	0.08	0.90	0.10	0.08	0.90	0.11	0.09	0.90	0.10	0.08	0.90	0.10	0.08	0.90	0.10	0.08
Dryer (1.1 kW)		2.20	0.18	0.13	2.20	0.17	0.12	2.20	0.25	0.20	2.20	0.17	0.12	2.20	0.18	0.12	2.20	0.17	0.12
TubWaterheater (1.5 kW)		1.50	0.17	0.15	1.13	0.09	0.07	1.13	0.09	0.05	1.13	0.09	0.04	1.13	0.09	0.06	1.13	0.09	0.04
Poolpump (0.75 kW)		7.50	0.91	0.76	7.50	0.78	0.61	7.50	0.78	0.65	7.50	0.78	0.62	7.50	0.83	0.61	7.50	0.78	0.61

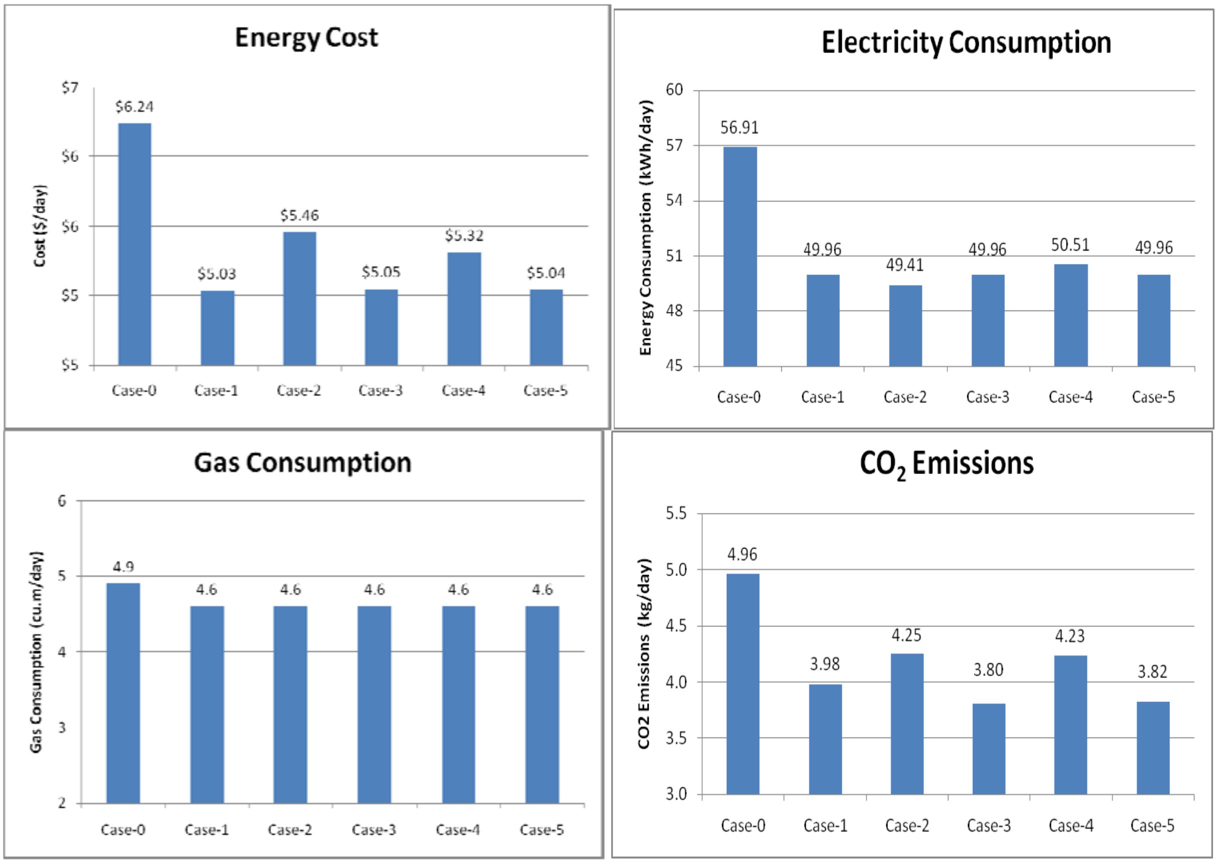

Figure 4-26: Comparison of energy cost, energy consumption, gas consumption and emissions for a summer day from all cases.

Table 4-13: Summary comparison of all cases for a winter day.

Item	Case-0	Case-1	Case-2	Case-3	Case-4 with minimum feasible peak power	Case-5
Energy Cost in $	3.95	3.18	3.51	3.55	3.31	3.18
Energy Consumption in kWh	36.43	32.18	32.18	32.18	32.18	32.18
Gas Cost in $	5.48	4.96	4.96	4.96	4.96	4.96
Gas Consumption in cu.m	18.63	16.88	16.88	16.88	16.88	16.88
ESD Revenue in $	4.81	7.82	7.82	7.82	7.82	7.82
ESD Energy Supply in kWh	6.00	9.75	9.75	9.75	9.75	9.75
Emissions Cost in $	0.75	0.67	0.66	0.65	0.67	0.66
Emissions in kg	7.54	6.67	6.64	6.48	6.66	6.60
Peak Demand in kW	10.13	11.50	7.73	11.33	5.63	11.33

Device		Case-0			Case-1			Case-2			Case-3			Case-4 with minimum feasible peak power			Case-5		
		Energy Consumption (kWh)	Energy Cost ($)	Emission (kg)	Energy Consumption (kWh)	Energy Cost ($)	Emission (kg)	Energy Consumption (kWh)	Energy Cost ($)	Emission (kg)	Energy Consumption (kWh)	Energy Cost ($)	Emission (kg)	Energy Consumption (kWh)	Energy Cost ($)	Emission (kg)	Energy Consumption (kWh)	Energy Cost ($)	Emission (kg)
Furnace (75 kBtu/hr)	Electricity	7.58	0.74	1.54	6.71	0.62	1.35	6.71	0.68	1.37	6.71	0.68	1.33	6.71	0.62	1.36	6.71	0.62	1.34
	Gas in cu.m	13.88	4.08		12.28	3.61		12.28	3.61		12.28	3.61		12.28	3.61		12.28	3.61	
Air Conditioner (2.2 kW)		0		0.00	0.00		0.00	0.00			0.00		0.00	0.00		0.00	0.00		0
Waterheater (42 kBtu/hr)	Electricity	2.38	0.26	0.49	2.30	0.23	0.47	2.30	0.25	0.47	2.30	0.25	0.46	2.30	0.23	0.47	2.30	0.23	0.47
	Gas in cu.m	4.75	1.40		4.60	1.35		4.60	1.35		4.60	1.35		4.60	1.35		4.60	1.35	
Fridge (0.6 kW)		3.53	0.37	0.73	3.45	0.36	0.71	3.45	0.36	0.71	3.45	0.36	0.71	3.45	0.36	0.71	3.45	0.36	0.71
Lighting (0.15 kW)		12.08	1.34	2.51	9.60	1.04	2.00	9.60	1.04	2.00	9.60	1.04	2.00	9.60	1.04	2.00	9.60	1.04	2.00
Stove (1.5 kW)		4.50	0.50	0.95	4.50	0.45	0.97	4.50	0.50	0.93	4.50	0.55	0.90	4.50	0.47	0.99	4.50	0.45	0.94
Dishwasher (0.7 kW)		1.40	0.17	0.29	1.40	0.11	0.30	1.40	0.17	0.29	1.40	0.18	0.28	1.40	0.11	0.30	1.40	0.11	0.30
Washer (0.45 kW)		0.90	0.11	0.19	0.90	0.11	0.18	0.90	0.11	0.18	0.90	0.11	0.18	0.90	0.11	0.19	0.90	0.11	0.18
Dryer (1.1 kW)		2.20	0.28	0.44	2.20	0.17	0.47	2.20	0.28	0.47	2.20	0.28	0.44	2.20	0.28	0.44	2.20	0.17	0.47
TubWaterheater (1.5 kW)		1.88	0.19	0.41	1.13	0.09	0.21	1.13	0.12	0.22	1.13	0.09	0.20	1.13	0.09	0.21	1.13	0.09	0.20
Poolpump (0.75 kW)		0			0		0	0		0	0		0	0		0	0		0

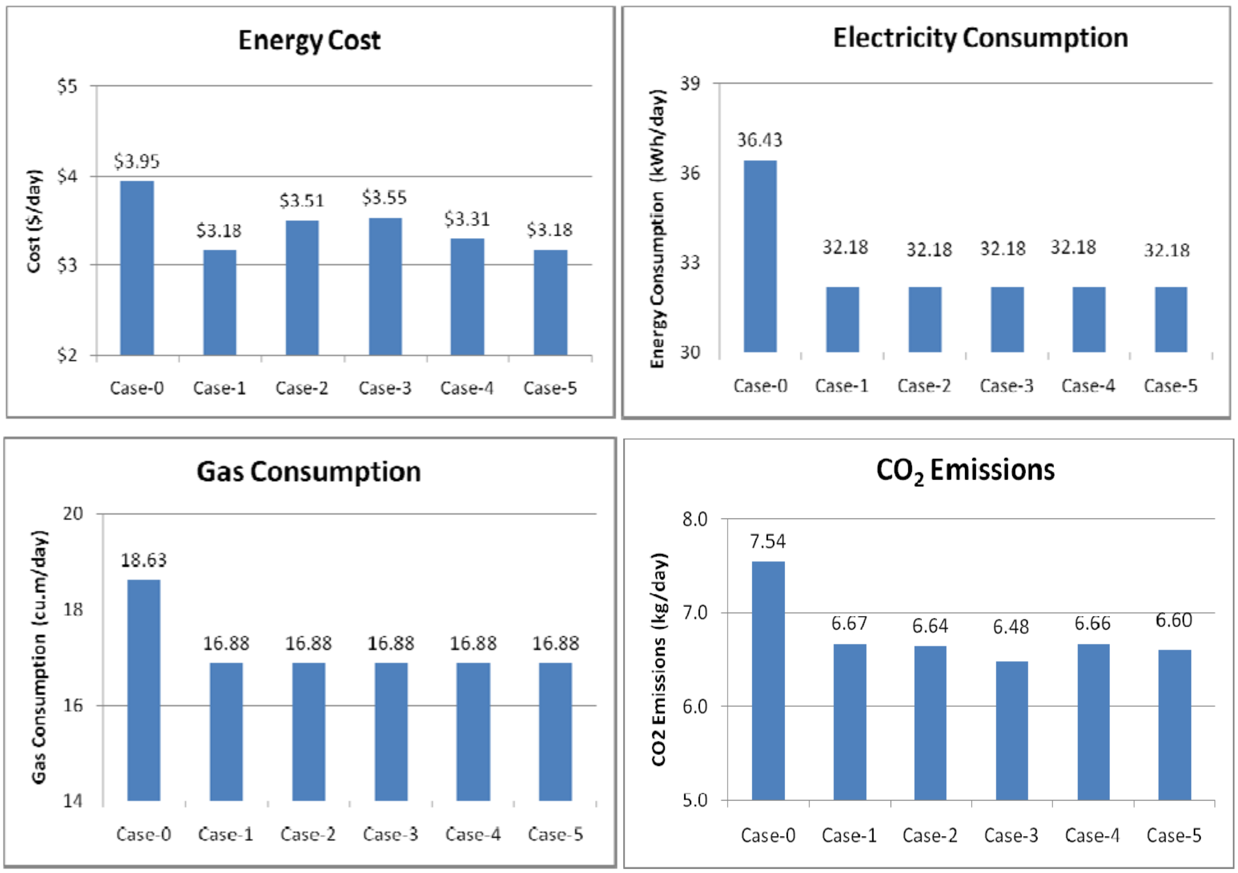

Figure 4-27: Comparison of energy cost, energy consumption, gas consumption and emissions for a winter day from all cases.

4.8 Energy Price Effect Studies

In this section, the performance and results for the EHMS residential model are studied under different energy price schemes in Ontario. For this, Case 1 is simulated using FRP and RTP prices. The results of energy cost, energy consumption and emissions for the whole system and for individual devices are compared with respect to Case 0 to analyze the savings. Monte Carlo simulations are also carried out subsequently to study the effect of fluctuating RTPs on the optimum decisions.

4.8.1 Summary Comparison

Table 4-18 and Figure 4-28 show the effects of using different pricing schemes, i.e. TOU, RTP and FRP, on the operational schedules of the devices for Case 1on a summer day. Note that energy cost is higher with TOU prices as compared to FRP; however, FRP results in the highest energy consumption among all energy prices. Gas consumption does not change in any case and the ESD revenue is independent of energy prices. Minimum emissions are obtained with TOU price but this may change for different emissions profile. Observe that the peak demand of the household is reduced significantly in the case of FRP as compared to TOU and RTP (notice that no peak demand constraints are used here).

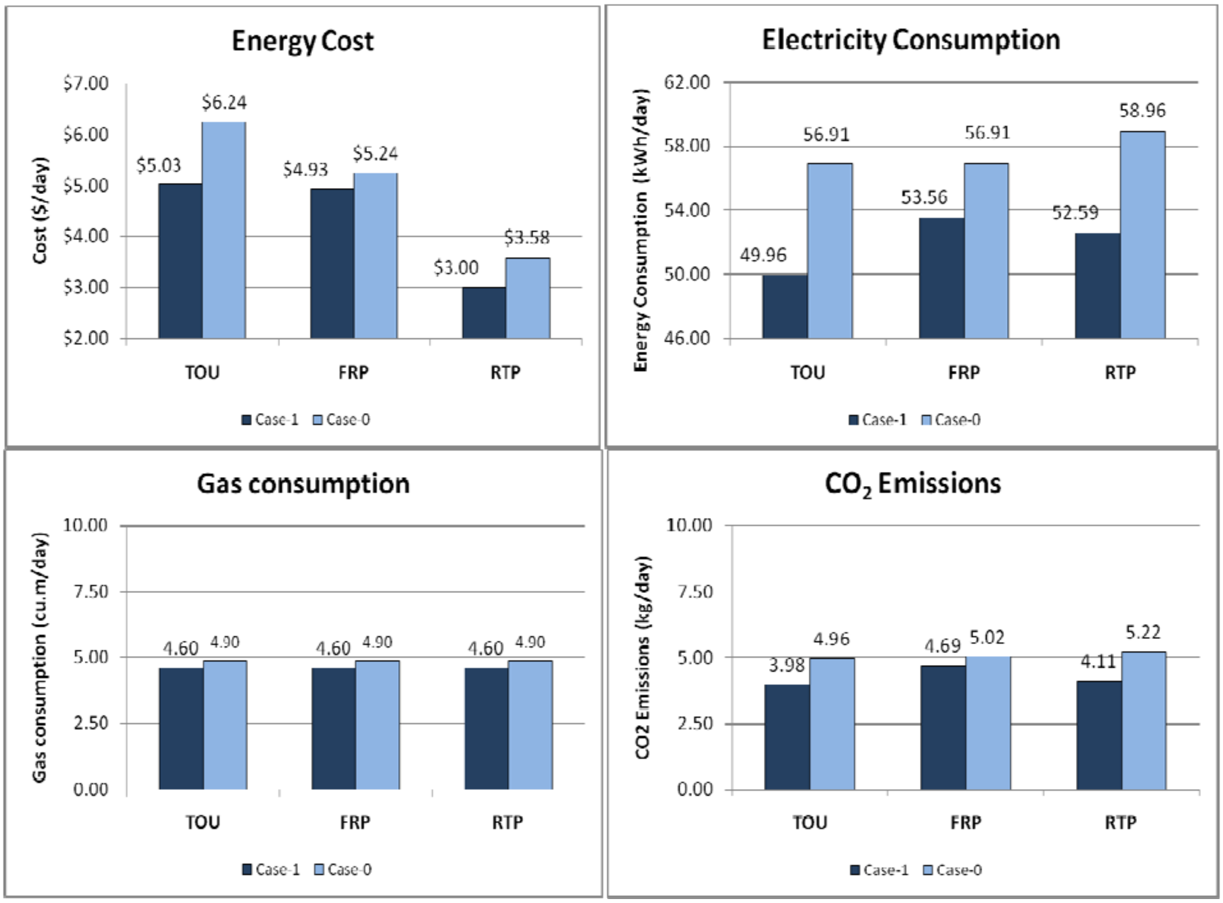

Figure 4-28: Comparison of energy cost, energy consumption, gas consumption and emissions for TOU, FRP and RTP prices for a summer day.

Table 4-14: Comparison of effect of different energy prices of summer in Case 1.

Item		Time Of Use (TOU)			Flat Rate (FRP)			Real Time Price (RTP)		
Energy Cost in $		5.03			4.93			3.00		
Energy Consumption in kWh		49.96			53.56			52.59		
Gas Cost in $		1.35			1.35			1.35		
Gas Consumption in kWh		4.60			4.60			4.60		
ESD Revenue in $		19.85			19.85			19.85		
ESD Energy Supply in kWh		24.75			24.75			24.75		
Emissions Cost in $		0.40			0.47			0.41		
Emissions in kg		3.98			4.69			4.11		
Peak Demand in kW		14.90			11.30			14.90		
Device		Energy Consumption (kWh)	Energy Cost ($)	Emission (kg)	Energy Consumption (kWh)	Energy Cost ($)	Emission (kg)	Energy Consumption (kWh)	Energy Cost ($)	Emission (kg)
Furnace	Electricity	0			0			0		
(75 kBtu/hr)	Gas in cu.m	0			0			0		
Air Conditioner (2.2 kW)		18.15	1.86	1.50	18.15	1.67	1.68	18.15	1.00	1.40
Waterheater	Electricity	2.30	0.23	0.18	2.30	0.21	0.19	2.30	0.13	0.18
(42 kBtu/hr)	Gas in cu.m	4.60	1.35		4.60	1.35		4.60	1.35	
Fridge (0.6 kW)		3.45	0.35	0.28	3.45	0.32	0.28	3.53	0.20	0.28
Lighting (0.15 kW)		8.44	0.88	0.69	12.04	1.11	1.05	10.99	0.66	0.94
Stove (1.5 kW)		4.50	0.46	0.36	4.50	0.41	0.40	4.50	0.26	0.37
Dishwasher (0.7 kW)		1.40	0.11	0.08	1.40	0.13	0.13	1.40	0.08	0.08
Washer (0.45 kW)		0.90	0.10	0.08	0.90	0.08	0.09	0.90	0.05	0.08
Dryer (1.1 kW)		2.20	0.17	0.12	2.20	0.20	0.20	2.20	0.13	0.12
TubWaterheater (1.5 kW)		1.13	0.09	0.07	1.13	0.10	0.05	1.13	0.04	0.04
Poolpump (0.75 kW)		7.50	0.78	0.61	7.50	0.69	0.62	7.50	0.45	0.61

Similar comparison is made among energy prices for a winter day, and the results are as shown in Figure 4-29 and Table 4-19. Observe that TOU results in higher energy costs than FRP as in summer. Electricity consumption is nearly equal for all price schemes. Gas consumption is also equal but this time with higher consumption than summer which is due to the gas furnace. Minimum emissions are obtained with TOU, as in the summer case.

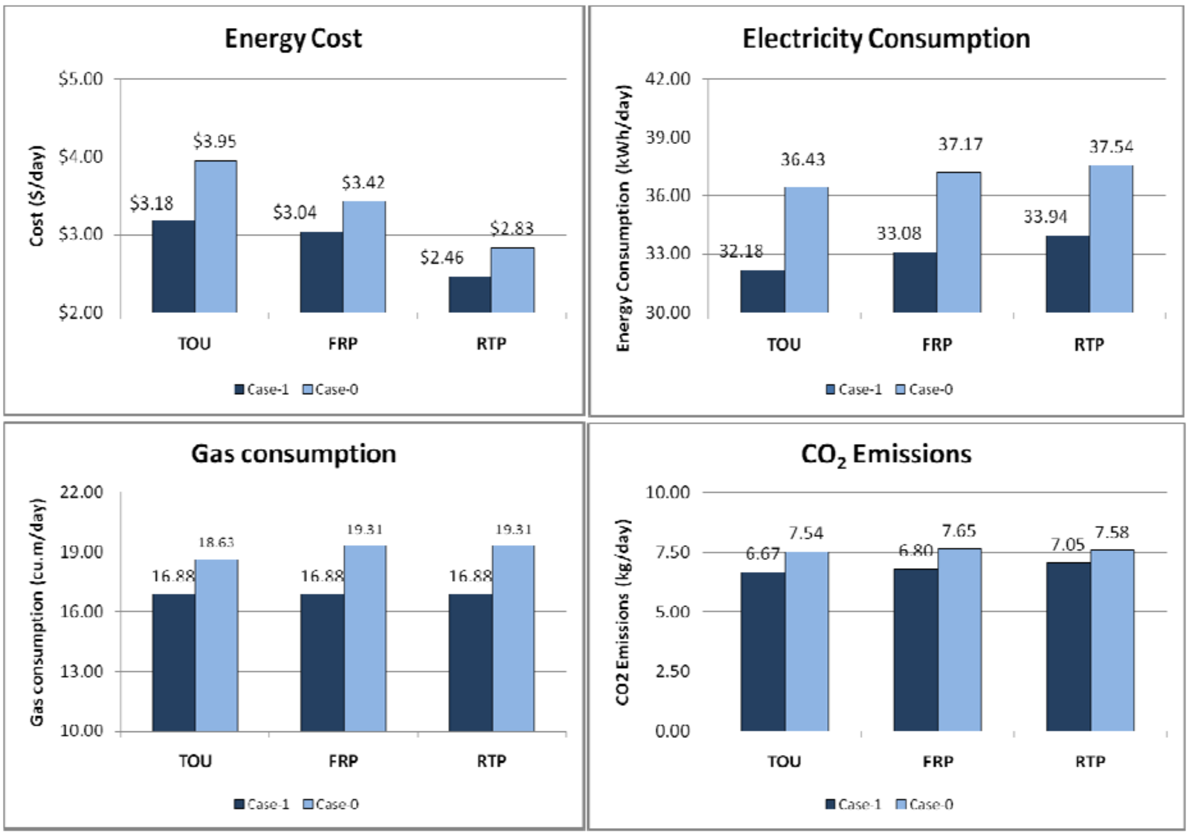

Figure 4-29: Comparison of energy cost, energy consumption, gas consumption and emissions for TOU, FRP and RTP prices for a winter day.

Table 4-15: Comparison of effect of different energy prices of winter in Case 1.

Item	Time Of Use (TOU)	Flat Rate (FRP)	Real Time Price (RTP)
Energy Cost in $	$3.18	$3.04	$2.46
Energy Consumption in kWh	32.18	33.08	33.94
Gas Cost in $	$4.96	$4.96	$4.96
Gas Consumption in kWh	16.88	16.88	16.88
ESD Revenue in $	$7.82	$7.82	$7.82
ESD Energy Supply in kWh	9.75	9.75	9.75
Emissions Cost in $	$0.67	$0.68	$0.71
Emissions in kg	6.67	6.80	7.05
Peak Demand in kW	11.5	8.03	8.93

Device		TOU Energy Consumption (kWh)	TOU Energy Cost ($)	TOU Emission (kg)	FRP Energy Consumption (kWh)	FRP Energy Cost ($)	FRP Emission (kg)	RTP Energy Consumption (kWh)	RTP Energy Cost ($)	RTP Emission (kg)
Furnace (75 kBtu/hr)	Electricity	6.71	$0.62	1.35	6.71	$0.62	1.37	6.71	$0.46	1.37
	Gas in cu.m	12.28	$3.61		12.28	$3.61		12.28	$3.61	
Air Conditioner (2.2 kW)		0		0	0		0	0		0
Waterheater (42 kBtu/hr)	Electricity	2.30	$0.23	0.47	2.30	$0.21	0.47	2.30	$0.16	0.48
	Gas in cu.m	4.60	$1.35		4.60	$1.35		4.60	$1.35	
Fridge (0.6 kW)		3.45	$0.36	0.71	3.45	$0.32	0.71	3.45	$0.25	0.71
Lighting (0.15 kW)		9.60	$1.04	2.00	10.50	$0.97	2.18	11.36	$0.85	2.36
Stove (1.5 kW)		4.50	$0.45	0.97	4.50	$0.41	0.93	4.50	$0.31	0.97
Dishwasher (0.7 kW)		1.40	$0.11	0.30	1.40	$0.13	0.28	1.40	$0.11	0.30
Washer (0.45 kW)		0.90	$0.11	0.18	0.90	$0.08	0.18	0.90	$0.08	0.18
Dryer (1.1 kW)		2.20	$0.17	0.47	2.20	$0.20	0.47	2.20	$0.17	0.47
TubWaterheater (1.5 kW)		1.13	$0.09	0.21	1.13	$0.10	0.21	1.13	$0.07	0.22
Poolpump (0.75 kW)		0		0	0		0	0		0

4.8.2 Monte Carlo Simulations for Price Variation Analysis

As mentioned earlier, RTPs are set every hour and fluctuate more than TOU prices. Thus, RTPs change hourly and therefore a study of the effects of variable rates on the optimization model's output are needed. The results from the HOEP forecaster developed by colleagues at Waterloo under Energent auspices are used to estimate possible range of variation of RTPs.

Monte Carlo simulations are carried out by generating normally distributed random samples of price inputs *Normal* (μ, σ). The flow chart of Monte Carlo simulation process is shown in Figure 4-30. The mean value for the distribution (μ) correspond to the deterministic value used, and the standard deviation (σ) is taken from the aforementioned price forecasting results; these values are:

Mean, μ = RTP values as shown in Figure 3-3

Standard Deviation, σ = 1.619 cents/kWh

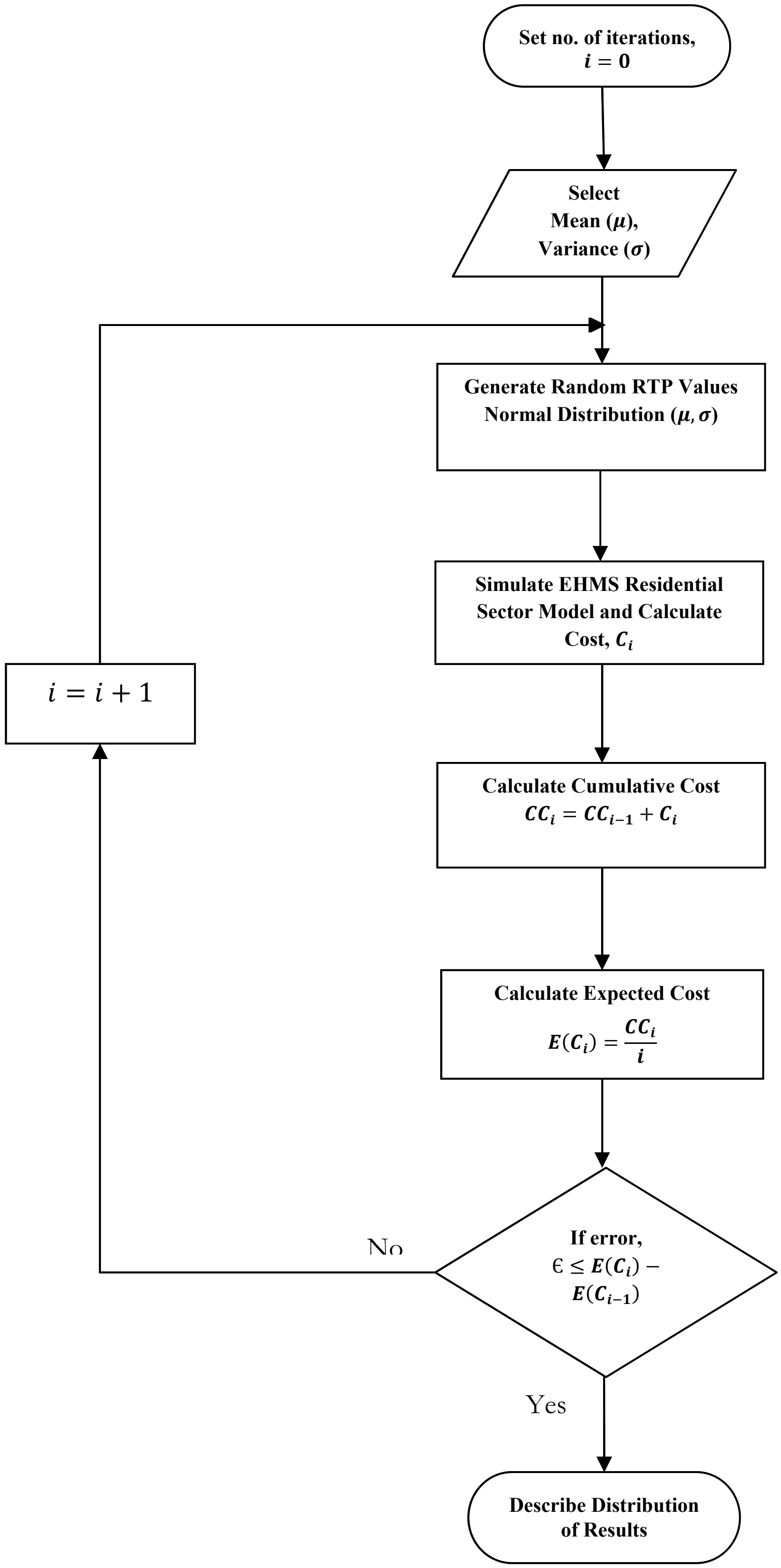

Figure 4-30: Monte Carlo Simulation Flow Chart.

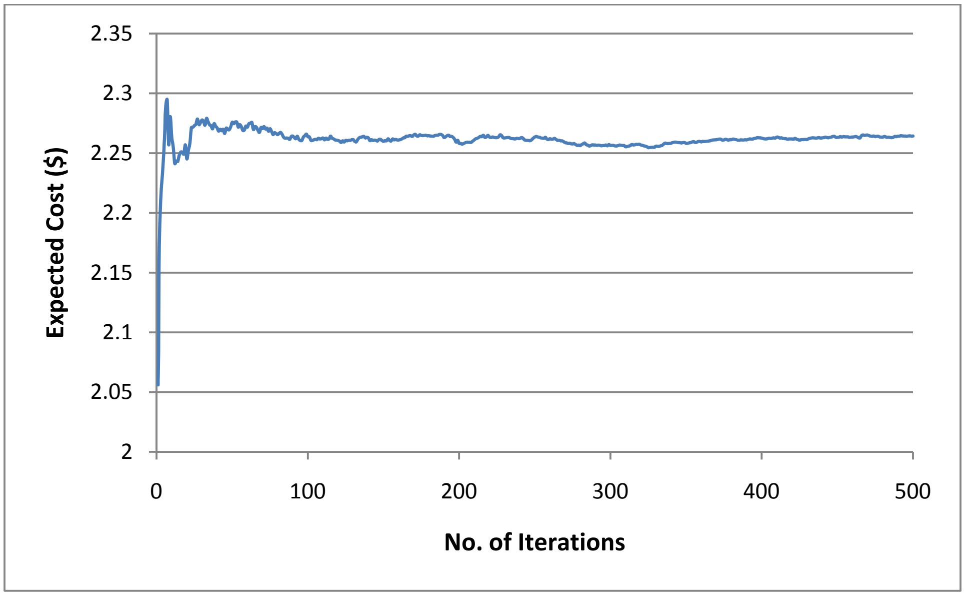

Figure 4-31: Expected cost from EHMS model.

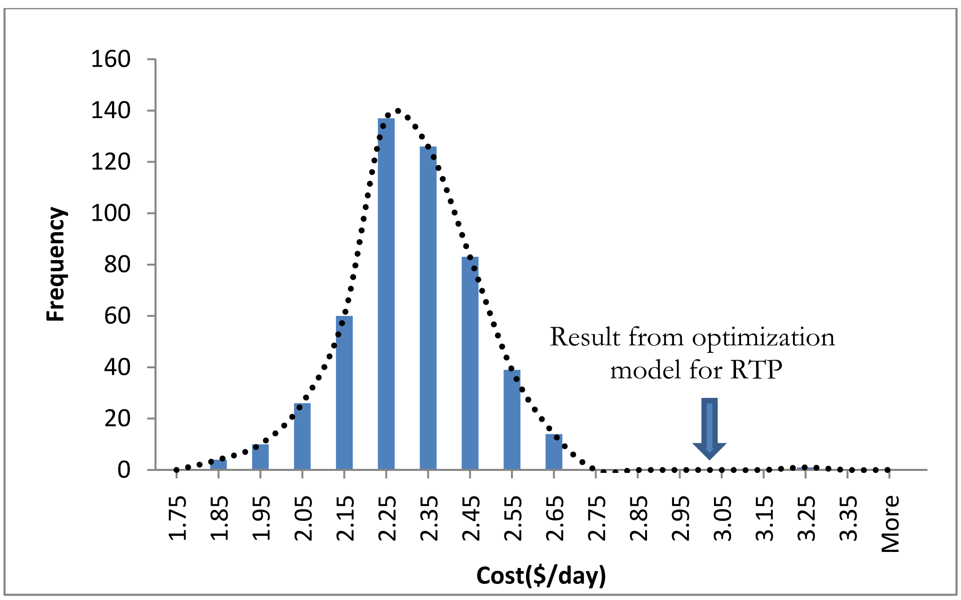

Figure 4-32: Frequency distribution of cost.

The result in Figure 4-31 show that the cumulative average cost after 500 iterations is \$2.25. The frequency distribution of expected cost in Figure 4-32 shows that the expected costs are less than the deterministic value of \$3.00 discussed in Section 4.8.1. This is an interesting and somewhat unexpected but positive result, which reflects the nonlinear behavior of the model with respect to electricity prices.

4.9 Summary

This chapter described the various realistic case-studies for the EHMS residential sector model. Different objective functions were considered as representative of customers' operating choices, and the corresponding results demonstrated the capability of the model to generate optimum operational schedules of devices to minimize energy costs, energy consumption and emissions based on user-defined constraints and preferences. An important conclusion of these studies is that there is considerable potential to reduce the peak demand of a household customer without major increases in energy costs, which should be of interest to LDCs. The results also show that the model can significantly reduce customer's contribution towards CO_2 emissions.

The analysis of using different energy prices in the model demonstrated that using TOU instead of FRP will result in a relatively higher energy bill. Also if RTP is used in place of TOU, the expected cost savings for the customer will be higher relative to the case without optimization and for the same respective rates. Finally, and in general, the results show that the implementation of the EHMS residential model to optimize operational schedule of devices should result in significant savings for residential customers.

Chapter 5

Conclusions

5.1 Summary and Conclusions

The present thesis dwelled upon validating the residential sector model of the EHMS to establish and quantify the benefits accrued from it. The validation exercise was carried out by conducting several case-studies representing various residential-customers' operational objectives. A detailed comparative analysis of the performance of individual appliances was presented. This research also investigated the contribution of a residential customer to CO_2 emissions in Ontario, and how the EHMS model could reduce these emissions; to this effect, a forecasting methodology to estimate day-ahead CO_2 emissions from power generation sector in Ontario was developed.

In Chapter 2, a mathematical model was developed, based on single-variable econometric time-series, to estimate power generation from coal-fired and gas-fired generating units and hence forecast the day-ahead CO_2 emissions profile for Ontario. This forecasted emissions profile was incorporated in the EHMS model, to optimize the residential customer's emissions contribution. The forecasting model is simple and based on data available from IESO website and can be readily integrated into the EHMS model.

Chapter 3 presented the EHMS residential sector model, which was modified to include CO_2 emissions of a household and, gas consumption of furnace and water heater models. This model was modified to simulate the behavior of a residential customer interested in maximizing comfort, based on fixed temperature set points. Realistic input data was presented and discussed for different energy pricing schemes, Ontario's emissions profiles, weather conditions and typical power ratings of home appliances to test the performance of the EHMS model under practical conditions that are to be experienced during the implementation phase of the EHMS project.

In Chapter 4, various case-studies were developed, considering different objectives of the customer, to demonstrate the capability of the EHMS model to generate appropriate optimum operational schedules. The results for minimization of energy costs, energy consumption and/or emissions subject to realistic user-defined constraints and preferences were presented and discussed in detail in this chapter.

A number of conclusions and important observations resulting from the presented work can be made, and are summarized next:

- The allowable indoor temperature deviation from set point depends on the customer's perception of comfort, and it is usually $\pm1°C$. The results show that more cost savings can be achieved if the temperature deviation is further relaxed.

- Minimization of energy usually results in a higher energy costs with respect to other minimization objectives, because the decisions are independent of the dynamically varying prices.

- An environment friendly customer can significantly reduce its contribution to Ontario's CO_2 emissions through appropriate optimal decisions. This may result in higher energy cost for some days, since peak-price and peak-emission periods may not coincide. Therefore in order to avoid higher energy cost while minimizing emissions, a customer may opt to minimize the energy cost and the emissions simultaneously, as discussed in Case-5.

- Savings in natural gas consumption is not considerable using the EHMS model, because of flat rate pricing of natural gas. However, according to the Canada Energy Outlook 2006 report, the natural gas prices are expected to raise three times, consequently savings could be expected to be significant using this model.

- Peak demand of a customer can be reduced significantly (up to 50%) without incurring major increase in energy costs.

- The analysis of using different energy prices in the EHMS model demonstrates that TOU prices will result in 2% to 4% increase in energy costs to the customers, as compared to FRP.

5.2 Thesis Contributions

The main contributions of this work in order of importance are:

1. The expected benefits of the EHMS optimization model for residential customers in Ontario are clearly evaluated and demonstrated.
2. A single-variable econometric time series forecasting model is developed to estimate Ontario's day-ahead hourly CO_2 emissions from the power generation sector, based on publically available data at the IESO website.
3. The thesis clearly identifies and models the current behavior of a typical residential customer.
4. Devices such as like furnaces and water heaters require representation of both natural gas and electricity supply balance constraints in the EHMS model. This thesis contributes to advancing the EHMS model by incorporating a detailed representation of these devices.
5. This research proposes a shorter scheduling period for the fridge and water heater (7.5 minute) than the one proposed in [9] (15 minute).

5.3 Future Work

- The emissions forecasting model uses the aggregate generation from power plants for ease of implementation. The forecasting model can be further improved by considering each generating units individually, and considering power imports and exports to/from Ontario to neighboring provinces and the US. Also using a week-ahead availability of power generators from IESO, the forecasting for weekends and public holidays could be improved. A similar forecasting strategy could be used in other sectors such as commercial and agricultural to forecast the generation from wind turbines and solar panels.
- The ESD model can be modified to consider wind turbine generation, net-metering and dynamic prices.

- The simulation considered the same peak power limits for each time interval; however, these limits could be applied in principle to only certain hours instead of the whole day, such as during peak hours. This would help LDCs to shift/control the load in a situation when power generation is somewhat intermittent due to wind and solar based generation.
- Similar studies to those presented here for the residential customer can be extended to the agriculture, commercial and industrial sectors before the implementation phase to validate their respective mathematical models and benefits.

Appendix

Table A-1: Historical values of Ontario's total market demand [25].

Ontario's Demand $X_{j,k}$ (MW)														
Time (h)	05-Jan	06-Jan	07-Jan	08-Jan	09-Jan	10-Jan	11-Jan	12-Jan	13-Jan	14-Jan	15-Jan	16-Jan	17-Jan	18-Jan
1	16771	17745	17662	17328	18981	18440	18456	18118	18047	19498	19802	20453	20062	19043
2	16826	17483	17157	17238	18722	18271	17826	17936	17272	19211	19609	20249	19919	18794
3	16860	17415	16772	16738	18613	18135	17628	17746	17131	19014	19593	20317	19936	18500
4	16962	17445	16425	16731	18116	18123	17578	17610	17414	19053	19463	20469	19755	18377
5	17175	17727	16971	17051	18232	18287	17517	17834	17306	19312	19596	20594	19647	18256
6	18061	18255	17640	17727	19172	18476	17406	18547	18235	20184	20420	21268	19897	18219
7	19588	20080	19737	19573	20847	18966	18294	20673	20049	22084	21568	22963	20479	18669
8	21362	21879	21115	21132	22654	19785	19261	22248	22392	23917	23620	24197	21311	19034
9	21583	22021	21685	21537	22950	20451	19642	22532	22677	24064	23713	23844	21569	19917
10	21309	21981	21651	21502	22600	21087	20106	22517	22208	23856	23740	24076	22338	20552
11	21787	22096	21938	21950	22175	21256	20090	22584	22275	23338	23262	24063	22768	21150
12	21569	22000	21752	22763	22273	21210	20125	22629	22630	23202	23618	23703	22634	21171
13	21009	21865	21700	22200	22217	21278	20387	22167	22487	22843	23553	23429	22849	21186
14	21288	21928	21405	21713	21683	21191	20380	22062	22499	22851	23325	23836	22670	21052
15	21271	21044	21306	21303	21241	21301	20353	22059	22471	22631	23188	23673	21787	20939
16	21414	21462	21309	21796	21508	21444	20674	22303	22323	22819	22807	23781	22176	21232
17	22080	22527	21660	22385	22385	21604	21597	22470	22727	23821	23886	24031	22598	21449
18	23160	23332	22312	23602	23683	23043	23309	23280	24089	24805	24555	24541	22965	23028
19	23489	22990	22685	23389	22987	22620	22711	23269	24428	24733	24298	24867	23019	22591
20	23318	22496	22300	23286	22935	22517	22272	23307	23868	23900	23861	24438	22469	22400
21	22716	21640	21670	22684	22175	21684	21903	22943	23492	23496	23516	24124	22098	21965
22	21859	20803	20658	22046	21042	21215	20929	21810	22324	22681	22860	23165	21665	21271
23	20412	19210	19381	21484	20234	20742	20390	20691	20867	21317	22469	22162	20810	20148
24	18540	18124	18329	20156	19047	19520	19007	19234	19525	20179	21265	20950	19750	19055

Table A-2: Historical values of power output from coal-fired plants [26].

Power Output of Coal-fired Units $Y_{j,k}$ (MW)														
Time (h)	05-Jan	06-Jan	07-Jan	08-Jan	09-Jan	10-Jan	11-Jan	12-Jan	13-Jan	14-Jan	15-Jan	16-Jan	17-Jan	18-Jan
1	630	1921	2174	1369	3082	2418	729	2298	2026	3524	3932	4226	2854	2664
2	371	1360	1830	1530	2868	2583	595	2259	1106	3552	4041	4170	2975	2641
3	344	1282	1244	1484	3071	2338	522	2151	1139	3576	4001	4180	3028	2615
4	352	1462	1108	1481	2772	2444	530	2013	1230	3435	3990	4164	2925	2602
5	446	1946	1914	1534	2720	2659	430	2360	1502	3478	3874	3923	2831	2501
6	772	2204	2270	1978	2944	2868	416	2392	1821	3298	3787	3873	2737	2352
7	1336	2878	3191	2692	3403	2551	416	3255	2543	4042	3693	3972	2702	2423
8	1870	3232	3570	3208	3776	2415	421	3760	3958	4596	4023	4179	2408	1989
9	2121	3330	3560	3590	3725	2710	432	3699	4105	4506	4106	4155	2048	2010
10	1954	2963	3190	3235	3623	2627	485	3641	3894	3510	4178	4102	2473	2482
11	2212	3142	3275	3400	3179	2737	714	3598	3987	3297	4009	4065	2920	2986
12	1987	3100	3396	3664	3336	2765	1023	3670	4373	3455	4098	3987	2818	3077
13	1748	3050	3439	3489	3290	2746	1166	3405	4488	3691	4048	3648	2746	3221
14	1999	3371	3107	2992	2985	2676	1316	3576	4593	3766	3954	3935	2597	3034
15	2077	3243	3248	2714	2681	2737	1492	3869	4476	3805	4090	3803	2559	2972
16	2092	3441	3062	2960	2796	2832	1605	3708	4268	4090	3819	3617	2929	2925
17	2517	3570	2905	3059	2820	2731	2350	3801	3911	4392	3876	3492	3110	2780
18	2998	3737	3301	3450	3007	3086	2742	3816	4425	4463	3818	3035	3016	3008
19	3383	3618	3339	3434	2829	3166	2556	4028	4534	4398	3936	3077	3072	2905
20	3325	3337	3341	3348	2774	3350	2010	3971	4248	4298	3926	3045	2951	2859
21	3228	2940	3172	3568	2764	3315	2118	3867	4208	4330	3973	3062	2945	3065
22	3307	2779	2966	3461	3041	3464	1398	3594	4164	4349	3866	3049	2923	2951
23	3004	2195	2296	3265	3070	3429	764	2978	4075	3930	4113	3022	2717	2420
24	2422	2332	2188	2959	2816	3336	638	2570	3523	3966	4089	2889	2454	2408

Table A-3: Historical values of power output from gas-fired plants [26].

Power Output of Gas-fired Units $Y_{j,k}$ (MW)														
Hour	05-Jan	06-Jan	07-Jan	08-Jan	09-Jan	10-Jan	11-Jan	12-Jan	13-Jan	14-Jan	15-Jan	16-Jan	17-Jan	18-Jan
1	1373	1044	1075	1083	1109	1176	1101	1023	1050	1036	1265	1412	1338	885
2	1383	1048	1092	1070	1102	1121	1045	1025	1044	1019	1260	1216	1131	851
3	1410	1046	1072	990	1102	1064	1046	1029	992	1027	1256	1213	1201	847
4	1415	958	1053	985	1035	969	972	1028	1105	1141	1374	1335	1197	847
5	1357	964	980	987	1015	940	959	959	1188	1519	1455	1423	1191	846
6	1419	1019	1036	1025	1077	952	959	1037	1426	1994	1889	1766	1357	963
7	1679	1372	1386	1294	1434	1076	1116	1355	1815	2134	2461	1924	1481	1009
8	2321	1858	1973	1707	2009	1109	1213	1860	2118	2722	3000	1920	1807	1373
9	2359	2178	2516	1922	2499	1417	1753	1930	2320	2939	2960	2025	2169	1617
10	2343	2458	2486	1980	2544	1670	2269	1917	2156	3125	2647	2194	2074	1617
11	2481	2465	2617	2093	2548	1861	2497	2319	2133	3210	3108	2377	1971	1620
12	2779	2449	2507	2549	2540	1974	2524	2387	2313	3144	3387	2593	2186	1640
13	2875	2471	2625	2515	2536	2124	2522	2348	2204	2759	3453	2723	2285	1644
14	2877	2572	2625	2473	2529	2209	2524	2128	2310	2875	3190	2928	2279	1678
15	2697	2359	2377	2166	2220	2195	2524	1831	2343	2758	3071	2889	1820	1835
16	2571	2240	2133	1991	2005	2192	2525	1684	2298	2833	2942	2748	1703	1989
17	2580	2324	2142	1996	2008	2141	2331	1686	2351	2951	2958	2717	1729	2020
18	2681	2455	2441	2194	2318	2320	2300	1686	2750	3137	2927	2635	1763	2384
19	2773	2587	2544	2505	2297	2031	2197	1689	3009	3177	2992	2763	1794	2258
20	2702	2424	2474	2376	2267	2034	1805	1694	2814	2974	2798	2657	1699	2272
21	2676	2273	2314	2266	2272	1859	1808	1596	2782	2875	2392	2477	1660	2230
22	2125	2283	1701	1899	1974	1940	1300	1379	2329	2559	2356	2370	1519	2094
23	1756	1671	1353	1570	1612	1262	1040	1382	1655	1746	2310	2326	1427	1903
24	1114	1124	1117	1148	1279	1127	1026	1103	1211	1302	2051	2114	1054	1187

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