WIND ALLOCATION METHODS FOR IMPROVING ENERGY SECURITY IN RESIDENTIAL SPACE AND HOT WATER HEATING

by

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DEDICATION

I dedicate this thesis to my beloved mother, my sister, and my wife who continuously supported me in each step of my life. Thank you for your faith in me.

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ABSTRACT

Worldwide, wind energy added to the energy mix of electricity suppliers may be seen as way of improving energy security and reducing greenhouse gas emissions. However, due to wind's variability wind electricity cannot be used to meet demands which require a continuous supply of electricity. One solution to the variability problem is to adopt services that are capable of storing energy for use at a later time.

Five new wind-allocation methods are considered to maximize its use of wind-electricity while at the same time reducing emissions.

Simulations results, show that households benefit from an annual savings of about 30% to 36% with an estimated payback period ranging between 3.5 and 5.5 years. Emissions reduction in the off-peak scenarios is between 32% and 35% and about 86% in the anytime scenario. Heating demands satisfied ranges between 75% and 96% and total wind used for heating is between 3%-4%.

LIST OF ABBREVIATIONS USED

AMI	Advanced Metering Interface
AEHD	Allowable ETS Heating Demand
ADHD	Allowable DHW Heating Demand
BES	Battery energy storage
CO2	Carbon dioxide
CO2e	Carbon Dioxide Equivalent
CAES	Compressed air energy storage
DHW	Domestic Hot Water
DOE	Department of Energy
DR	Demand response
DG	Distributed generation
DES	Distributed energy storage
DER	Distributed energy resource
ETS	Electric Thermal Storage
ERGREG	European Regulators Group for Electricity and Gas
EMINENET	Early Market Introduction of New Energy Technologies
fSHL	Space Heating Load Fraction
GHG	Greenhouse Gas
GDP	Gross Domestic Product
HCR	Hourly Charge Rate
HDH	Heating Degree Hours

HSD	Hourly System Demand
IEA	International Energy Agency
LFO	Light fuel Oil
MCFC	Molten-carbonate fuel cells
MSC	Maximum storage Capacity
MDC	Maximum DHW Capacity
MIC	Maximum input charge
MDR	Maximum Discharge Rate
MIN	Minimum Recharge Method
MAX	Maximum Recharge Method
MIX	Mixture Recharge Method
DIS	Discharge Recharge Method
MOSES	Model of Short-Term Energy Security
NEMS	National Energy Modeling System
NB	New Brunswick
NRCan	National Resource Canada
OEE	Office of Energy Efficiency
OECD	Organization for Economic Cooperation and Development
OPEC	Organization of the Petroleum Exporting Countries
OE	Office of Electricity Delivery & Energy Reliability
OT	Outdoor Temperature
P.E.I	Prince Edward Island
PHES	Pumped Hydro energy storage

PCT	Programmable communicating thermostat
PHEV	Plug-in hybrid electric vehicles
PEV	Plug-in electric vehicles
PCM	Phase change material
SEETSS	Summerside Electric Energy Transmission Scheduling System
SESUG	Summerside Electric Smart Utility Grid
SHL	Space Heating Load
SOC	State of charge
SD	System Demand
SIT	Set Indoor Temperature
TSPMI	Tantalus Single Phase Meter Interface
TDH	Total Degree Hours
VBA	Visual Basic for Applications
WWEA	World Wind Energy Association
^{o}C	Degree Centigrade
^{o}F	Degree Fahrenheit
CO_2e	Carbon dioxide equivalent
GWh	Gigawatt-hour
GW	Gigawatt
Gt	Gigatonne
Gb/s	Gigabyte per second
kWh	Kilowatt-hour
kg	Kilogram

ms^{-1}	Meter per second
m	Meter
MW	Megawatt
TW	Terawatt

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CHAPTER 1 INTRODUCTION

Ever since the oil-embargos of the 1970s, there has been a growing awareness amongst individuals, academics, policymakers, and politicians of the unsustainable nature of our existing use of energy: both in terms of its long-term availability and affordability, as well as its environmental acceptability. In response, many energy-importing jurisdictions, especially those in the European Union, have instituted programs that encourage the adoption of energy sources and processes that are more secure and less damaging to the environment. In North America, the City of Summerside in the Canadian province of Prince Edward Island is another such example.

Energy security, the "the uninterrupted physical availability at a price which is affordable, while respecting environment concerns" (IEA, 2010), is essential for the social and economic wellbeing of any society (World Bank, 2005). The evolution of energy security in a jurisdiction can be observed by measuring the different flows of energy within the system in terms of changes to their availability ("the uninterrupted physical availability"), affordability ("at a price which is affordable"), and environmental acceptability ("respecting environmental concerns") (Hughes, 2011).

The extensive use of fossil fuels has led to an increase in greenhouse gas concentrations which has serious effects on the environment (EPA, 2012) and factors like price volatility and depletion rate of fossil fuels has raised concerns over a jurisdictions energy security (Hughes, 2009). Worldwide fossil fuels are mainly used to meet three basic services: electricity generation, heating and cooling and transportation (IEA, 2011a).

Many jurisdictions have adopted policies and standards to counter the twin challenges of maintaining or improving energy security and mitigating climate change by the introduction of low carbon technologies, notably wind, into their energy mix resulting in an increase in electricity generation. This increase in electricity generation coupled with wind intermittency issues has made many jurisdictions reconsider the use of wind electricity by integrating wind electricity into services that do not demand a continuous supply of electricity by storing wind electricity and using it to meet the service demand when required. Heating and cooling demand is one such service that does not demand a continuous supply of electricity if a storage option is available. By using Electric Thermal Storage (ETS) systems wind electricity and its intermittency can be exploited by storing wind electricity in the form of heat and meeting the space heating demands when required (Hughes, 2010b).

1.1 Summerside Project

Summerside, with an estimated population of 14,500, had an annual electrical consumption of about 126 GWh and a peak load of 23MW in 2010. Prior to late 2009, 76.5% of its electricity demand was met by NB Power (generated primarily from imported, fossil-energy sources and some domestic hydroelectricity), while the remaining 23.5% came from the West Cape Energy wind farm located in West Cape, P.E.I. (City of Summerside, 2011). The city's heavy reliance on imported electricity placed it in a fragile state exposing itself to affordability issues in terms of price fluctuations due to volatile energy markets, availability issues in terms of secondary energy usage, and acceptability issues in terms of making it a contributor of secondary greenhouse gas emissions, thereby compromising its energy security.

Summerside began addressing its energy security challenges in December 2009 with the installation of a 12 MW wind farm consisting of four V-90 (3MW) wind turbines. The addition of the wind farm (henceforth referred to as the Summerside Wind Park) meant that Summerside's electrical demand can be met from grid-electricity (that is, thermal and hydroelectric sources supplied by NB Power), a combination of grid-electricity and wind-electricity (from NB Power, West Cape, and Summerside), or wind-electricity alone (West Cape or Summerside, or both). At the end of 2010, the first full year of the Wind Park's operation, 51.7% of the city's electricity was met by NB Power while the remainder (48.3%) came from wind energy (City of Summerside, 2010). In some situations, all of Summerside's electricity was met by the Wind Park, and on occasion, there has been a surplus of wind-generated electricity (wind-electricity) that was exported to NB Power. Annual wind-electricity surplus (from both Summerside and West Cape) is estimated to be about 15%. Although the export and sale of wind-electricity generates revenues between \$0.03 and \$0.05 per kWh for Summerside Electric, the city made a strategic and innovative decision to employ the surplus wind-electricity for local use in residential energy services other than traditional electricity services (i.e., lighting and appliances) to further enhance its energy security.

The energy demand of Summerside's two principal energy services—transportation and heating—are met almost exclusively from refined petroleum products. In fact, more than three-quarters of P.E.I.'s secondary energy demands are met from imported refined petroleum products such as gasoline and light fuel oil. Of the total petroleum available to the province, about 38% is used for space and water heating in the residential, commercial and institutional, and industrial sectors (Natural Resource Canada/Office of Energy Efficiency, 2011). Events, both local and global, that cause supply disruptions, increase the price of crude oil, or a requirement on the reduction in greenhouse gas emissions will all have a detrimental effect on Summerside's energy security in terms of energy availability, affordability, and acceptability.

In 2011, driven in part by the desire to reduce the city's greenhouse gas emissions, Summerside began to implement a Green Municipal Fund sponsored wind-heating pilot program intended to show how wind-electricity could meet residential space and water heating needs to reduce greenhouse gas emissions. The program creates two new, "smart" electrical loads consisting of 100 electric-thermal storage (ETS) units and 100 domestic hot water (DHW) units. The city's plans are to maximize its use of wind-electricity, allocating it effectively to meet the heating demand of the participating households, thereby reducing greenhouse gas emissions and improving energy security. Central to these plans is a city-wide smart grid.

Physically, a smart grid is an electrical grid which also supports bi-directional communications between the customer-end's smart devices and the electricity provider; it also employs an Advanced Metering Infrastructure (or AMI) which consists of the smart meter (an interval meter) allowing the provider to know the customer's electrical consumption at any moment in time (via the smart meter) and a control system monitoring the various smart devices. A smart grid is the merging of two networks, namely a power network and a communication network.

Summerside's project, known as the Summerside Smart-Grid Pilot Program, consists of three components: the Wind Park, the smart heating units (i.e., the ETS and DHW units), and a smart grid. The smart grid allows Summerside Electric (the electricity provider) to know the state-of-charge of, and to control the charging of, each household's ETS and DHW units. In order to maximize the use of wind-electricity, the AMI can control charging the ETS and DHW units (via device-specific communication protocols): when wind is available and during NB Power's low-rate periods, residential electric thermal storage units and hot water heaters are to be charged from the wind and grid, while during the high-rate periods, on-demand electricity is to be met from the wind.

1.2 Current Practice

In most jurisdictions, ETS units are charged during the off-peak overnight hours (11:00 PM to 7:00 AM) and anytime during weekends and holidays; to encourage their use, the cost of off-peak, weekend, and holiday electricity is typically less than the cost at other times. An alternative approach (any-time charging) proposed charging the ETS system if wind-electricity was available (Hughes, 2010b) and directing any excess (or surplus) electricity to meet the on-demand electricity needs.

There are two types of charging scenarios:

- Off-peak charging: In this scenario, the ETS and DHW units are charged only during the off-peak hours. A combination of wind electricity and grid electricity is used to charge the ETS and DHW units and priority to charge with wind electricity is given over grid electricity based on the availability of wind electricity.
- Any time charging: Here, the ETS and DHW units are charged any time of the day if wind electricity is available. During on-peak hours no grid electricity is used for the charging of the ETS and DHW units.

Although the two approaches worked as energy dumps and managed to meet the space heating demands by storing electricity in form of heat, little was offered in terms of flexibility or control of the variable supply of wind electricity to manage it efficiently. Wind, being intermittent and unpredictable, makes it very difficult for any wind farm to predict the next hour's electricity output. In order to meet a dedicated demand, utilities have to do load balancing and precisely indicate the amount of electricity required to meet that demand. If there is any shortfall of electricity from the various sources available to meet this demand, utilities tend to import electricity to meet this demand. Utilities have to ensure that they do not import excess and create a energy spill and pay a penalty. Although any expansion in the production of wind-electricity will generate more electricity, the underlying challenge of addressing the variability of wind remains. Any wind electricity allotted to meet a particular hourly demand has to be consumed within that hour otherwise it creates an excess which needs to be dumped. Excess electricity can be reduced if wind allocation is efficiently managed, and the excess can be used to meet other demands. In order to avoid such problems utilities have to decide on how to allocate variable electricity (wind electricity) to meet a particular demand.

1.3 Thesis Objective

The primary objective of this thesis is to develop a set of wind-allocation methods that can handle wind variability by attempting to maximize the use of wind-electricity by allocating it effectively to improve energy security in residential space and hot water heating.

To demonstrate the viability of the objective, the thesis:

- analyzes and compares the wind allocation methods based on different wind conditions, notably zero wind, maximum wind and average wind.
- applies the developed methods to the Summerside Smart Grid program and analyzes the effects on energy security in terms of availability of the wind heating program to meet the heating demands, affordability of the wind heating

program and the acceptability of the wind heating program during the 2010-2011 heating season.

The development of these wind allocation methods gives flexibility to the system in controlling the variable load effectively and efficiently allocating wind electricity to charge the ETS and DHW systems, thereby addressing wind variability issues and energy security issues. The research includes a cost analysis in terms of customer cost and savings and supplier benefits to study the effects of energy security in terms of affordability to the customer and the utility provider. This research includes an emissions analysis to study the effects of energy security in terms of acceptability by evaluating the amount of fossil or grid backup required to charge the ETS and DHW units and meet the heating demands when wind electricity is insufficient. The research also includes a system reliability analysis to study the effects of energy security in terms of availability of wind electricity in meeting the heating demand.

The five wind allocation methods developed are Minimum (MIN) recharge method, Maximum (MAX) recharge method, Mixture (MIX) recharge method, Discharge (DIS) recharge method and On-peak discharge method. Of the five methods the DIS method is used only on weekends and holidays. The on-peak method is set as the default method to be used during on peak hours. The MIN, MIX and MAX methods can be used for any off-peak hours. Based on the heating demands and available wind electricity different combinations (MINMIN, MINMIX, MINMAX or MINDIS, MIXDIS, MAXDIS) of the methods can be implemented to suit the utilities requirements.

1.4 Thesis Organisation

The remaining chapters of the thesis are organised as follows:

Chapter 2 presents an outline of energy security and the tools and method used to analyse a jurisdiction's energy security, followed by an introduction to energy systems and their functions. It also presents a brief outlook of renewable energy and how wind energy and storage can be coupled to solve wind intermittency issues. Finally the chapter concludes by defining smart grids and their functions.

Chapter 3 presents the wind allocation methods developed to analyse the potential impact of wind heating system on a jurisdiction's energy security. Also, the implementation of the simulation model with the necessary software tools is discussed.

Chapter 4 presents a case study to examine the proposed methods. Furthermore it explains selection of the case study locale and date acquired for the research.

Chapter 5 discusses the simulation results based on customer cost, supplier balance, ETS vs. Non-ETS and Wind Usage.

Finally, Chapter 6 presents the concluding remarks of this thesis and outlines some of its recommendations and limitations and suggests related future work.

CHAPTER 2 LITERATURE REVIEW

2.1 Energy Security

Over the past 50 years, most jurisdictions in the world have grown increasingly dependent on three primary energy sources to meet their energy security needs: crude oil, coal, and natural gas (IEA, 2011a). However, resource depletion, environmental degradation, and price instability is resulting in a decline in energy security and an increase in economic and social difficulties in many of these same jurisdictions. Maintaining and improving energy security in the face of these problems and the global economic downturn will be one of the major challenges facing politicians, policymakers, and the public in the 21st century (IEA, 2011b).

According to the IEA's New Policies Scenario, world energy demand is expected to grow by 40% by 2035 of which 90% is expected to occur in non-OECD countries. The growth in energy demand is, in part, due to the rate of growth in world GDP, with a projected average annual increase of 3.6% between 2009 and 2035, making it a fundamental driver of energy demand. World population growth is assumed to increase by 26%, reaching 8.6 billion in 2035, and will also contribute to the increase in world energy demand. As production and consumption in energy demand increases in non-OECD countries, the OECD share of inter-regional fossil-fuel trade is expected to decline from 42% in 2009 to 29% in 2035. OPEC oil production is predicted to reach half the world total required in 2035. This growth in demand will contribute to an increase in global energy infrastructure requirements totaling $38 trillion which is an estimate for the period 2011 to 2035. Energy prices for oil, natural gas and coal are expected to increase and have an effect on the demand and supply patterns.

The ever-increasing demand for energy has raised global energy-related greenhouse gas emissions (GHG) to 30.4 Gt in 2010 and is anticipated to reach an unprecedented 36.4 Gt in 2035; an emissions trajectory consistent with a long-term global temperature increase of more than 3.5°C by 2035 (Asif & Muneer, 2005). Around 45% of these emissions are already locked in, coming from capital stock which already exists or will be in operation in 2035 (IEA, 2011b). At present the dependency on fossil fuels has led to four major concerns: depletion of fossil fuel reserves, global warming, rising energy costs, and energy security concerns (Asif & Muneer, 2005).

Energy security has been one of the main focuses of public policy, coexisting and often competing with economic development and environmental protection. This issue is of paramount importance to the global economy because energy is essential for the basic energy services of transportation, heating and cooling, and electrical services that are indispensible for the functioning of any jurisdiction. Normally, energy security concerns relate to energy supply and demand, in particular to external supply sources over which there is less control than domestic supply (Verrastro & Ladislaw, 2010).

Since economies of all countries, in particular developed countries, depend on a secure supply of energy, the uninterrupted availability of sufficient energy at an affordable price must prevail over the long term if energy is to contribute to sustainable development. Due to the growing reliance of most countries on imported energy sources the energy supply can become more vulnerable giving more critical importance to energy security (Asif & Muneer, 2005).

Of the trillion barrels of proven oil reserves, which is sufficient to meet 54.2 years of global production, almost 66% of oil reserves are distributed among Middle Eastern countries. Annual global oil production increased by 1.3% in 2010, and virtually all of the net growth was in OPEC with large increase in Saudi Arabia, UAE, Kuwait and Iraq. World natural gas consumption grew by 2.2% and production grew by 3.1% (BP, 2012). Oil and gas reserves in the non-Middle Eastern countries are depleting at a faster rate than those in the Middle Eastern countries and if production continues at the current rate, many countries will cease to be relevant players as an energy contributor. In less than two decades many countries will be dependent for energy sources on a single region which is politically unstable. The geopolitical situation in the Middle Eastern region has given rise to serious reservations regarding the production and supply of crude oil; with such conditions, it is not possible to guarantee secure supplies of energy (Asif & Muneer, 2005).

Energy security concerns continue to be determined mainly by supply security concerns, as fossil fuels remains the dominant energy source, accounting for 90% of global energy demand (Global challenges in energy, 2005). Concerns regarding dramatically higher energy prices, regional supply shortfalls, and new predictions of imminent depletion of oil reserves suggest (Asif & Muneer, 2005) the need for strong and effective policies in the area of energy security and has prompted policymakers and raise the issue of energy independence (Verrastro & Ladislaw, 2010).

According to the IEA, energy security has many aspects: long-term energy security is mainly linked to timely investments to supply energy in line with economic developments and environmental needs. On the other hand, short-term energy security is the ability of an energy system to react promptly to sudden changes in supply and demand. Another way to look at energy security is to study the different energy sources (coal, oil, gas, and renewable), intermediate means (electricity, refineries) and transportation modes (grids, pipelines, ports, ships). All of these have risks of supply interruptions or failures, challenging the security of undisturbed energy supply (IEA, 2012).

Although oil supply security remains an important concern, energy security policies must address a broader range of risk that address a variety of natural, economic and political factors, that affect all energy sources and infrastructure which could potentially identify threats to energy security. Based on current energy security risk, understanding vulnerabilities requires a comprehensive analysis. Tools like Model of Short-Term Energy Security (MOSES), assist to evaluate short-term security of energy supply. MOSES' approach is to combine and interpret indicators related to various aspects of energy security in a systematic, transparent and policy-relevant way (IEA, 2011).

MOSES takes an energy systems approach in analyzing energy security and does not aim to rank the countries on their basis of energy security. Instead it identifies 'energy security profiles' of individual countries based on their risks and resilience capacities. Energy systems analysis deals with all parts of the energy system from energy supply to transformation and distribution to end-use energy services. Some of the limitations of MOSES are:

- Focuses only on short term physical security of primary sources and secondary fuels
- Economic or affordability dimensions of energy security are not captured
- Long term issues such as environmental impact are not assessed
- Cannot be used to compare overall energy security of jurisdictions or countries as it does not provide an overall energy security index
- Since the overall focus is on energy supply, security of energy services are not analysed

Rather than looking on the security of energy supply to evaluate energy security the four R's method can be applied to the energy service of a jurisdiction to improve its energy security and develop energy policies (Hughes, 2009). The method consists of four R's which are Review (understanding the problem), reduce (using less energy), replace (shifting to secure sources) and restrict (limiting new demand to secure sources) which explains the implications and importance of energy security and how it can be improved. This method can be applied to any energy security problem and can be used as an educational tool or as a tool to develop improved energy security policies. Limitation of the tool include lack of visualization tools to indicate the current energy security status of a jurisdiction and indicating pathways for improved energy security (Hughes, 2009).

Although several tools like EMINENET (Early Market Introduction of New Energy Technologies), NEMS (National Energy Modeling System) and EnergyPLAN; have been developed to analyse energy security, all have limitations which range from tools developed for specific jurisdiction to tools developed to analyse specific types of energy (Connolly, Lund, Mathiesen, & Leahy, 2009).

2.2 Energy Systems

All jurisdictions have an energy system of one or more energy chains composed of conversion or transportation processes. This system converts and transports energy flows from its suppliers in order to meet the needs of its various energy services. The jurisdiction's energy security can be impacted by anything affecting the flows of energy through a process within the system. A generic framework has been developed by integrating the International Energy Agency's definition of energy security with structured systems analysis techniques. Three energy security indicators with a process-flow energy systems model applicable to those energy systems, which can be defined as processes that convert or transport flows of energy to meet the energy-demand flows from downstream processes, have been created using this framework. The energy security level can be determined, in terms of availability, affordability, and acceptability. This is accomplished by measuring the various flows of energy within the energy system (Hughes, 2011).

An energy system comprises of one or more energy chains, linking energy sources to an energy service. The chain's complexity level is determined by its energy inputs and demand. Smaller jurisdictions, which have limited energy resources, and rely upon energy imports, as a secondary source rather than primary, will have shorter less complex chains. Each process within the energy chain, regardless of it handling a conversion or distribution, is associated with six flows, as shown in Figure **1**; the flows are defined as follows (Hughes, 2011):

- The $Demand_{IN}$ flow is the result of a downstream process or energy service calling for energy from this process; it indicates the quantity of energy required.
- Upon receipt of the $Demand_{IN}$ flow, the process attempts to meet the demand with the quantity of energy specified; this is indicated by the $Energy_{OUT}$ flow.
- The process requires a supply of energy to meet $Demand_{IN}$; this energy is supplied by an upstream process and the amount of energy of energy required is specified in $Demand_{OUT}$.
- The upstream process is expected to supply the process with a flow of energy, specified as $Energy_{IN}$; the quantity supplied should meet the quantity requested in $Demand_{OUT}$.

- No process is perfect, it will always exhibit some degree of inefficiency and, as a result, is associated with emissions or losses, or both, that are released to the environment; these are specified in the process's $Environment_{OUT}$ flow. For example, a wood stove does not transfer all of the energy in the wood to the stove-top for heating: heat can be lost up the chimney and insufficient air-supply can result in inefficient combustion; while all stoves are associated with varying quantities of ash, smoke, and atmospheric pollutants. Even an electrical distribution grid has losses to the environment in the form of heat. Because of these inefficiencies, $Energy_{IN}$ is always greater than $Energy_{OUT}$.
- Finally, most jurisdictions (or organizations responsible for the process) have regulations intended to control the actions of the process; these regulations are specified in the $Policy_{IN}$ flow.

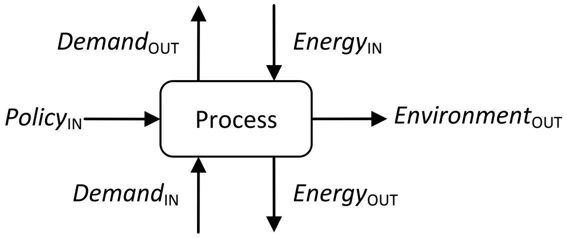

Figure 1: A generic energy process (Hughes, 2011)

According to (Hughes, 2011) "The energy system, its energy chains, and energy supply are intended to meet the energy demands of the jurisdiction's energy services. Ideally, they do; however, the loss of an energy supply or the failure of a process within a chain can result in a deterioration of the jurisdiction's energy security". Any changes in flow can be measured using the three indicators (availability, affordability, and acceptability) and the level of energy security (i.e. improvement or deterioration) can be observed as follows (Hughes, 2011):

- **Availability:** When the energy output of a process, $Energy_{OUT}$, matches $Demand_{IN}$, the flow is available and can be considered secure. However, if $Energy_{OUT}$ is less than $Demand_{IN}$, there is a loss of availability, leading to a possible deterioration in energy security. The cause of the problem could be the process or the failure of the process's $\mathit{Energy}_{\mathrm{IN}}$ flow to meet $\mathit{Demand}_{\mathrm{IN}}$.

- **Affordability:** Each energy flow in a chain is associated with a cost determined by the initial $\mathit{Energy}_{\mathrm{IN}}$ and any intervening processes; these costs affect the affordability of the energy flow. As the cost of a flow increases, it can become less affordable and hence less secure; conversely, if the cost declines, it can become more affordable and more secure. Subsidizing the cost of $\mathit{Energy}_{\mathrm{OUT}}$ can create the illusion of an improvement in affordability; however, the size and duration of the subsidy can adversely impact the jurisdiction.
- **Acceptability:** The acceptability indicator refers to the environmental acceptability of an energy flow; it can be measured by comparing $\mathit{Environment}_{\mathrm{OUT}}$ flows with standards specified in, for example, $\mathit{Policy}_{\mathrm{IN}}$. In some jurisdictions, acceptability also pertains to the social or political acceptability of an energy flow or process; examples of this include public perceptions regarding nuclear power and the extraction of tight natural-gas by fracking.

Based on the outcome of the level of energy security, policies can be developed to improve energy security if required. Policies tend to affect processes and in turn affect the flows associated with the processes. The success of any energy security policy can be measured by the above mentioned indicators.

2.3 A path towards renewable energy

Decreasing greenhouse gas emissions and generating more energy to meet the energy demand are two major issues that most countries face today. Equally daunting, is the energy security issue faced by energy importing countries. Many countries are being forced to find alternative energy solutions. Renewable and nuclear energy sources may supply some solutions for energy security and environmental depletion. Consequently, many countries have invested in these alternative energy sources to reduce their reliance on imported oil, increase the secure energy supply, reduce the unpredictability of the price associated with imported fossil fuels, and minimize greenhouse gas emissions (Apergis, Payne, Menyah, & Wolde-Rufael, 2010).

The International Energy Agency (IEA) statistics indicate that the current trend in the supply and use of energy is unsustainable – economically, environmentally and socially. Unless definitive action is taken, by the year 2050, energy-related CO_2 emissions will have grown two-fold, and the increased oil demand will intensify the concerns over energy security supplies (IEA, 2009).

In 2009 Stanford University performed a study that rated energy systems based on their environmental impacts. Study results indicated that energy systems driven by wind, water or sunlight (WWS), such as wind, solar, geothermal, tidal and hydroelectric power, were the optimum solution. The least favorable systems were nuclear power, oil, natural gas, coal with carbon capture, and ethanol. In addition, the study found that use of electric vehicles that were recharged by water, wind or sunlight would by and large eliminate pollution from the transportation sector (Jacobson & Delucchi, 2009).

Renewable energy offers significant opportunities for further growth that can facilitate the transition to a global sustainable energy supply by the middle of this century.

In 2009, 13.4% of the world's overall primary energy supply was a renewable energy source. Non-hydro emerging renewable energy sources such as wind, solar and geothermal energy show a rapid rate of increase, primarily in power generation (IEA, 2011a). By 2035, the amount of non-hydro renewable energy in the overall power output is predicted to rise 15%. This is a 12% increase from 2009. By 2050, the IEA predicts that renewable energy will account for 44% of the electricity generation mix. Furthermore, renewable energy will play a key role in meeting the global target for CO_2 by 30% by 2035. In comparison, nuclear energy is anticipated to only account for 6% of the target. This is mainly on account of long lead times, high capital costs, and public opposition. Even so, renewable and nuclear energy are anticipated to play a major role in both energy supplies and emissions reduction (IEA, 2011).

Approaches for developing sustainable energy typically include the following changes in technology: saving energy on the demand side, improving efficiency in energy production, and substituting fossil fuels with renewable energy resources. Hence, it is crucial to incorporate strategies for integration of the energy source in an intelligible energy system influenced by energy savings and efficiency measures for large-scale renewable energy implementation plans. Two main challenges for sustainable development of renewable energy approaches are the Integration of high shares of intermittent resources into the energy mix, and the inclusion of the transportation sector (Lund, 2007).

A region's level of development and accessibility of natural resources and technologies determines the relevance of the technological changes and their order of importance. OECD and developing countries have some key differences in their energy systems. OECD countries, at a very high stage of development, primarily follow the gains in energy efficiency approach. Whereas, in developing countries, where renewable sources (primarily biomass) are considerable (27.6%) but inefficiently used, the better approach to follow is the modernization of how the energy is used. Energy consumption in developing countries grows 2.5 times faster than in OECD countries. This speed of growth gives them a lot of opportunity for innovation as the energy system continues to grow. In both cases, the increased use of carbon free resources will contribute to CO_2 emission reduction, thereby mitigating climate change (Goldemberg, 2004).

Based on the energy [R]evolution scenario, it is predicted that by 2050, renewable sources will provide 77% of the electricity generated worldwide. In addition, the installed capacity of the technologies will grow from 1000 GW to 9100 GW. The architecture of the electricity generation differs considerably by region. In the Middle Eastern region, electricity demands will be met by using solar technology as the energy source. Whereas, in Latin America and OECD North America, 90% of the electricity needs will be met with a combination of wind, solar and hydro energy. Renewable electricity grown is predicted to be about 60 – 75%, in developing countries such as India and China. The amount of renewables used for supplying heat is expected to reach

71% of the overall global heating needs. In the transportation sector, the amount of bio fuels used is anticipated to reach 15%. Furthermore, renewable electricity will supply approximately 24% of the overall transport energy needs with the introduction of the electric vehicles. Factoring in the amount of renewable sources in the generation of electricity, 36% of transport energy requirements will be achieved by renewable sources (Krewitt, et al., 2009).

The primary issue with renewable energy sources is their uncertainties. Resource, technology and economic base are the three uncertainty classifications used to evaluate the energy resources. To evaluate and enhance the resources force in the energy mix, a grid cell level analysis, using availability of data and local variations, is performed to find the uncertainty criterion. A perfect example is the assessment of wind energy. In order to evaluate resource base factors such as average wind speed, roughness factor and land availability, technology base factors such as average turbine size, and conversion efficiency, and economic factors such as capital cost, interest rate and transportation/transmission need to be taken into account (Vriesa, Vuuren, & Hoogwijk, 2006).

2.4 Wind and Energy Storage

Wind energy, is one of the world's fastest growing sources of clean and renewable energy. Wind Energy plays a key role in reducing greenhouse gas emissions. (Saidur, Islam, Rahim, & Solangi, 2010). It is expected that wind energy could potentially supply 12% of global electricity needs by the year 2020. This is primarily on account of it being a source of energy that is easily accessible, widely available, non-polluting, and site dependant. (Omer, 2006). Wind energy, with speeds exceeding 6.9 ms^{-1} at 80 m, is capable of producing around 72 TW of power globally. This equates to five times the overall power produced, and 20 times electric power produced in the world. (Jacobson, 2008).

In 2010, the generation of global wind electricity was around 190 GW. Countries such as the United States, China, Germany and India shared approximately 74% of the global capacity. It is projected by the World Wind Energy Association (WWEA), that by the year 2015, the capacity of global wind-electricity production will rise to 600 GW, and by 2020, reach 1500 GW. The rise in installed capacities will help to reduce the cost of wind electricity. This is in comparison with electricity generation using fossil fuels. (WWEA, 2011). Government policies, and subsidies, representing about 44% of overall electricity production, are the driving forces behind the expansion of wind electricity generation (IEA, 2011).

Increased wind electricity generation to meet the rising electrical energy demands has important ramifications on the design of the electrical system. This is primarily due to the variable nature of the energy source. Additional costs are incurred by the electrical systems to guarantee the security of the supply. With the use of wind energy, the amount of flexible capacity needed to guarantee system adequacy, the ability to continuously meet electricity demands, is estimated to be 1MW for every 5MW wind generation capacity (IEA, 2011).

Granted, wind energy is a promising form of renewable energy. Nevertheless, the intermittent and variable nature of the output energy frequently prevents it from meeting the energy demands. This intermittency is not a serious technical constraint if the ratio of wind energy to total electrical supply is relatively low. With that said, in situations with high levels of wind energy penetration, the intermittency becomes more pronounced, resulting in the technological and economical necessity of some kind backup power (Anderson & Leach, 2004).

Wind generation is termed as non-dispatchable by utilities. This is due to the fact that it is intermittent, seasonal and variable in nature resulting in maximum generation and maximum energy demand not being matched. Forecasting challenges makes forecasting errors of about 20-50% and are not uncommon and may result in huge cost to the utilities for not meeting supply and demand. Thereby, making wind electricity unsuitable for base and peak load operations. Direct use of wind energy is possible where continuous use of electricity is not required and is therefore good for applications that do not require continuous use of electricity (Sovacool, 2008).

Intermittency, variability and connecting to large electrical grids are three key factors that affect the penetration of wind energy in the energy mix. As a result of these factors, wind electricity is considered to be not load following, and gives rise to instabilities within the grid. Energy storage is the solution to both these problems. It is not only technologically simple, but covers two basic needs, electrical generation and space heating (PeterJ.Hall, 2008).

One innovative method to resolving the intermittent nature of wind energy is by storing the energy. Energy storage is similar to backup power as it balances supply and demand, by providing power to the electric grid when wind power is minimal or insufficient. However, this is where the similarity ends. Its ability to provide supplementary storage for utilities when there is excessive wind power is an added advantage that backup power does not have (Kempton & Dhanju, 2006). In this day and age, it is pertinent for any jurisdiction, planning to include intermittent wind energy in large scale into their energy system, to develop an effective means of energy storage (Carlin, Laxson, & Muljadi, 2003).

In a recent study, Blarke evaluated the effectiveness of storage and relocation options in renewable energy systems (Blarke, 2008). The study suggests jurisdictions can store unconsumed wind generated electricity for later use, when the demand for energy is high. Hence, this technology provides the utilities with a solution that reduces wind variability in order to meet the supply and demand throughout the day constant. In addition, maximum utilization of wind energy is improved within the energy system. Pumped Hydro energy storage (PHES), compressed air energy storage (CAES), Electric thermal storage (ETS) and battery energy storage (BES) are a few of the major electric energy storage technologies in the market today (Ibrahim, Ilinca, & Perronb, 2008).

Both electrical and thermal energy may be stored using energy storage technologies (Baker, 2008). With Electrical energy storage, the electricity is converted from the power network to a form that is stored and converted back to electrical energy. This form of storage is used to store intermittent electricity and provide electricity during periods of high demand, high cost of generation, or when the generation of electricity is not possible (Chen, et al., 2008).

Storage technologies for electricity fall under four main categories which are: Electrical energy storage (Electrostatic energy storage including capacitors and super capacitors, Magnetic/current energy storage including SMES), Mechanical energy storage (Kinetic energy storage (flywheels), Potential energy storage (PHES and CAES)), Chemical energy storage (Electrochemical energy storage (conventional batteries such as lead-acid, nickel metal hydride, lithium ion and flow-cell batteries such as zinc bromine and vanadium redox), chemical energy storage (fuel cells, molten-carbonate fuel cells – MCFCs and Metal-Air batteries), thermo chemical energy storage (solar hydrogen, solar metal, solar ammonia dissociation–recombination and solar methane dissociation–recombination)) and Thermal energy storage (Low temperature energy storage (Aquiferous cold energy storage, cryogenic energy storage), High temperature energy storage (sensible heat systems such as steam or hot water accumulators, graphite, hot rocks and concrete, latent heat systems such as phase change materials) (Chen, et al., 2008).

Thermal energy storage is typically associated with time constants measured in hours, days or even months, to provide for seasonal storage capacity deployed with irregular energy sources such as wind. Technologies for thermal storage include those based on the sensible and latent heat capacity of materials. Systems based on sensible heat capacity of materials include bulk and smaller-capacity hot and cold water storage systems, underground thermal energy, or specific bespoke thermal storage media. Systems based on latent heat capacity of materials include a mature technology for ice storage, and the use of various bespoke phase change materials (PCMs) (Baker, 2008).

Space heating, followed closely behind with domestic hot water, are the dominant energy services in residential areas of many northern jurisdictions with lengthy heating seasons. Due to the growing concern over energy security and green house gas emissions, smaller jurisdictions, heavily dependent on imported fossil fuels to meet their space heating needs, are forced to rethink their strategy on the type of energy source used. An optimal alternative to fossil based heating is the use of locally available wind electricity to meet the space heating demands (Hughes, 2009).

Electric space heating technologies like baseboards heaters, electric furnaces or geothermal heat pumps (Lee & Lam, 2007) all require a continuous supply of electricity. With the intermittent nature of wind electricity this can be a problem for electricity suppliers and the use of Electric thermal storage (ETS) heaters has be demonstrated to work well with intermittent wind electricity. Electric Thermal Storage (ETS) technology converts the inexpensive off–peak electricity into latent heat to store it as thermal energy to meet end-user heating and domestic hot water demand (Hughes, 2010b). An alternative to using off-peak electricity is to charge ETS at anytime throughout the day from intermittent supplies of wind for meeting residential heating demand (Hughes, 2009).

ETS units are made up of a special type of material such as high density ceramic blocks or paraffin wax), and electric heating elements. Nine high density ceramic bricks make up each ETS heating unit. These bricks can be heated to a maximum of 1400 ^{o}F/760 ^{o}C, each unit measures 7” by 8” by 1-3/4” in height and 10 pounds in weight. During periods of high winds, the excess electricity generated, can be stored in the ETS unit for later use. This process is accomplished by using the excess electricity to heat the ETS unit electric elements (up to 1400 ^{o}F). The ceramic blocks will then be heated by the electric elements, which will pass through the blocks like an electric oven. Thus converting the electric energy to thermal energy. During times when heat is required, the air in the ceramic bricks is circulated and a thermostat is used to extract the energy. ETS units are capable of storing large amounts of heat, therefore they are able to meet the heating demands for an extended amount of time (SKRECC, 2009).

Two kinds of ETS Systems are room and central. Of these two systems, the first is only capable of heating a limited number of rooms in a home, while the latter, is built with the capacity to store enough thermal energy to heat the entire home. The method by which the Central ETS system provides heat to the home (i.e. air forced, or hydronic) further classifies the system. The following four conditions define how the ETS system functions (Hughes, Dhaliwal, Long, & Sheth, 2006):

Off: When the ETS system has heated the environment to the required temperature, it shuts off, saving its thermal energy until more heat is required. A fully charged ETS system can retain its heat for up to 10 days.

Charging: When electricity is available to heat the ceramic bricks, the ETS will supply heat to them. If the environment is at the required temperature, the ETS diverts all the electricity to heating the bricks.

Discharging: When there is no electricity available to heat the environment, the ETS releases some of its stored thermal energy. The discharging is done in a controlled manner to ensure that the environment does not exceed the maximum specified temperature; when the maximum is reached, the ETS system enters the "off" state.

Charging and discharging: When electricity is available to heat the ceramic bricks and the environment is in need of heat, the ETS system will both charge and discharge.

2.5 Smart Grid

Advances in communication and information technologies has paved the path for a reliable more secured and energy efficient power grids. The use of such technologies in the current grid system is more commonly called a "Smart Grid". Smart grids use modern technologies to transform the current grid to operate more intelligently to facilitate (Moslehi & Kumar, 2010):

- better situational awareness and operator assistance;
- autonomous control actions to enhance reliability by increasing resiliency against component failures and natural disasters, and by minimizing frequency and magnitude of power outages subject to regulatory policies, operating requirements, equipment limitations, and customer preferences;
- efficiency enhancement by maximizing asset utilization;
- improved resiliency against malicious attacks through better physical security and state-of-the-art cyber security to maintain data integrity, confidentiality, and

authenticity, and to facilitate non repudiation even in the presence of adversaries in parts of the system;

- integration of renewable resources including solar and wind at levels from consumer premises to centralized plants to advance global energy sustainability;
- integration of all types of energy storage and other resources to counter the variability of renewable resources and demand;
- two-way communication between the consumer and utility so that end users can actively participate and tailor their energy consumption based on individual preferences (price, environmental concerns, etc.);
- improved market efficiency via innovative bundled products of energy such as ancillary services, risks, made available to consumers and other market participants; and
- higher quality of service—free of voltage sags and spikes as well as other disturbances and interruptions—to power an increasingly digital economy.

Two schools of thought exist around the definition of a Smart Grid. The first used by the European Regulators Group for Electricity and Gas (ERGREG), defines the grid as “electricity networks that can intelligently integrate the behavior and actions of all users connected to it–generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies". The second, as defined by the United States Department of Energy’s (DOE’s) Office of Electricity Delivery & Energy Reliability (OE), specifies the aims assigned to the smart grid in greater detail. This approach, defines the smart grid as a system based on the following seven characteristics or performance-based functionalities: "self-healing from power disturbance events; enabling active participation by consumers in demand response; operating resiliently against physical and cyber attack; providing power quality for 21st century needs; accommodating all generation and storage options; enabling new products, services, and markets; optimizing assets and operating efficiently" (Clastres, 2011).

Examining the inadequacy's in the current grid system and improving functionality of the current grid system by incorporating any missing technologies is another approach in the defining a smart grid. Based on this approach the smart grid must be (Sioshansi, 2011):

- more reliable;
- more integrated;
- more accommodating of growing intermittent recourses;
- facilitating the integration of more distributed generation;
- acting as a flexible two-way conduit between generation and load; and
- enabling the ''prices-to devices'' revolution, now in its infancy, to permeate beyond the meter.

The key component of any smart grid system is its Advanced Metering Infrastructure, which is essentially a smart meter capable of two way communication between the service provider and the meter. Such communications enables utilities to provide dynamic pricing to the consumer offering advantageous rates depending on time of use. A typical example could be a programmable communicating thermostat (PCT) which would be capable of automatically modifying the set point temperature when the electricity rate exceeds a pre-defined threshold, thus reducing the cost to the customer. Smart meters and dynamic pricing has also opened the door to the "prices to devices" concept. A concept, used by smart appliances to operate effectively based on the available electricity price data. Some future aspects of the smart grid include technological additions such as smart distribution networks, distributed generation and storage and plug-in hybrid electric vehicles (PHEVs) (Hledik, 2009).

Smart grid and advanced metering infrastructure was first implemented to improve demand side management. Demand response (DR), distributed generation (DG), and distributed energy storage (DES) are important ingredients of the emerging smart grid technology and are collectively referred to a distributed energy resource (DER). Smart grid technology along with DER makes it possible to offer useful controllable load resources like thermal storage and plug-in electric vehicles (PEV) to effectively manage power supply load control. DER, an important ingredient of smart grid technology, enhances both market efficiency and operational reliability. If implemented correctly, it helps curb supply market power via supply scarcity conditions, and improves operational reliability via profusion of variable generation (Rahimi & Ipakchi, 2010).

Weather driven and non-scheduled renewable energy sources are differentiate from a conventional generating facility in the manner in which they are controlled. Higher penetration levels of renewable energy sources requires far more advanced control of the power system in order to maintain system dependability. The effective use of transmission, through demand response and smart energy storage, allows the smart grid to maintain system reliability. Xcel Energy's SmartGridCity, suggests that the use of advanced energy storage coupled with the smart grid technology helps to reduce the variability associated with renewable energy. This is done by increasing the shares of renewable energy on the grid, thereby cutting down on emissions. The biggest source of variability on the power system is high level wind energy penetration. As a result, forecasting becomes crucial for effective smart grid operations, and improving system efficiency (Potter, Archambault, & Westrick, 2009).

2.6 Summary

In this chapter, previous works related to energy security and energy systems were reviewed. The role of renewable energy sources—notably wind—as an energy source in the generation of electricity, and its variability and use of storage has been studied. Further, an overview of the smart gird and its functions has been presented. This review has highlighted that storage has the ability to maximize the utilization of the locally available wind-electricity into a jurisdiction's energy system and to improve energy security.

CHAPTER 3 METHODS AND IMPLEMENTATION

This chapter develops wind-allocation methods that can effectively handle wind variability and maximize the use of wind-electricity by allocating it effectively to improve energy security in residential space and hot water heating.

3.1 Variables

Maximum Storage Capacity (MSC): Maximum storage capacity is the size of an ETS unit. It is the maximum allowable amount of energy that any individual system can store (kWh).

Maximum DHW Capacity (MDC): MDC is the maximum allowable amount of energy that any individual DHW system can store to maintain a particular hot water temperature and depends on the size of the hot water tank (kWh).

State of charge (SOC): SOC is the amount of energy left in an individual ETS or DHW system at any given hour (kWh).

Maximum Input Charge (MIC): MIC is the maximum amount of energy that can be applied to recharge an individual ETS or DHW system at any given hour (kWh).

Hourly Charge Rate (HCR): HCR is the minimum amount of energy required by an individual ETS system every hour to maintain a steady state of recharge so that by the end of the period (off-peak hour period) the system will attain its maximum capacity (kWh); and can be calculated as shown in equation (1).

$$HCR = (MSC - SOC \div Number\ of\ hours\ left\ in\ the\ period) \tag{1}$$

Maximum Discharge Rate (MDR): MDR is the maximum amount of energy that can be discharged from an individual ETS system in any given hour to maintain a steady state of discharge so that at the end of the period (peak hour period) the SOC is maintained at its minimum and the stored energy is used effectively (kWh); and can be calculated as shown in equation (2).

$$MDR = (SOC \div Number\ of\ hours\ left\ in\ the\ period) \tag{2}$$

Set Indoor Temperature (SIT): The air temperature in degrees Celsius (°C) that has to be maintained inside the household.

Outdoor Temperature (OT): The current average hourly outdoor temperature in degrees Celsius (°C).

Heating Degree Hours (HDH): Heating degree-hours for a given day refers to the number of Celsius degrees that the mean temperature is below 18°C. If the temperature is equal to or greater than SIT, then the number will be zero. For example, an hour with a mean temperature of 15.5°C has 2.5 heating degree-hours if the set indoor temperature is 18°C; an hour with a mean temperature of 20.5°C has zero degree-hours. Heating degree-hours are used primarily to estimate the heating requirements of buildings (hours); it can be calculated as shown in equation (3).

$$HDH = (SIT - OT) \tag{3}$$

Total Degree Hours (TDH): TDH is the sum of all individual heating degree hours and is calculated as shown in equation (4).

$$TDH = \sum_{0}^{8760} HDH \tag{4}$$

Allowable ETS Heating Demand (AEHD): The amount of discharge possible form an ETS system at any given hour to meet the space heating requirements by simultaneously charging and discharging the ETS. AEHD cannot exceed maximum input charge of the ETS system (kWh); and can be calculated as shown in equation (5).

$$AEHD = MIC - HCR \tag{5}$$

Allowable DHW Heating Demand (ADHD): The amount of discharge required from a DHW system at any given hour to meet the DHW heating requirements. All DHW systems are assumed to be fully charged at the start of any given hour and ADHD cannot exceed maximum input charge of the DHW system (kWh); and can be calculated as shown in equation (6).

$$ADHD = DHW\ Load \tag{6}$$

System Demand (SD): The System Demand is the electricity requirement set by the wind heating system for recharging the individual ETS and DHW systems and at the same time discharging energy to meet the heating demands (kWh); and can be calculated as shown in equation (7).

$$SD = (HCR + AEHD + ADHD) \tag{7}$$

During peak hours and off-peak weekend hours the amount of grid electricity and/or the amount of wind electricity required to meet the heating demands will be added to SD

Hourly System Demand (HSD): HSD for any given hour is the sum of individual ETS and DHW system demand (kWh); and can be calculated as shown in equation (8).

$$HSD = \sum_{0}^{number\ of\ units} SD \tag{8}$$

Space Heating Load Fraction (fSHL): Fraction of hourly space heating load allotted to households based on dwelling type and size. Three types of dwelling size used in this research: small, medium and large households. The percentage of space heating load for small households are 75% of the annual space heating load, 100% for medium households and 125% for large households.

3.2 Hourly Space Heating Load Estimation (SHL)

Space heating load is a measurement of how much heat is required per hour to heat a given space, and to maintain a desired temperature. Annual heating load varies by household size and location and can be calculated by software programs like RETScreen (NRCan, 2012). SHL is expressed in kWh can be calculated as shown in equation (9).

$$SHL = ((Annual\ Heating\ Load\ per\ Household \div TDH) \times HDH) \tag{9}$$

3.3 Hourly Domestic Hot Water Load Estimation (DHW)

Hourly hot water demand can be calculated based on the fraction of the daily hot water demand and can vary depending upon the number of people in a household, usage and capacity of the hot water storage tank. Annual domestic hot water heating load can be calculated by software programs like RETScreen (NRCan, 2012). Figure 2 shows the DHW consumption based on the study by (Perlman & Mills, 1985).

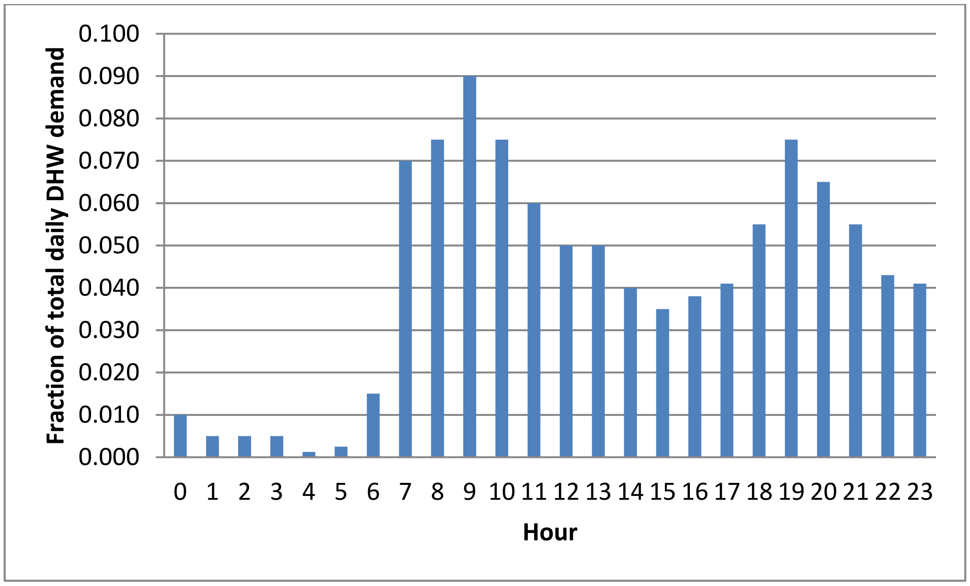

Figure 2: Daily Hot water consumption profile

The allowable DHW load per hour based on the storage tank capacity to meet the hot water heating demands is expressed in kWh and can be calculated as shown in equation (10).

$$DHW = Fraction\ of\ daily\ DHW\ demand\ for\ given\ hour \times MDC \quad \textbf{(10)}$$

3.4 Methods

When wind-electricity is available, it can be allocated in some combination to a household's ETS unit, its space heating load, or the DHW. A total of five allocation methods have been developed: minimum, maximum, and mixture for any off-peak period (weekday, weekend, or holiday), discharge (weekends and holidays only), and on-peak discharge to handle on-peak hour recharging. Off-peak hours can be classified into weekday off-peak hours, weekend off-peak hours and holidays off-peak hours. Weekday off-peak hours are from 11:00 pm to 7:00 am (8 hours) Monday to Friday. Week end off-peak hours are from Friday 11:00 pm to Sunday 11:00 pm (48 hours). Holiday off-peak hours are from 11:00 pm previous day to 11:00 pm next day (24 hours). Peak hours are from 7:00 am to 11:00 pm (16 hours) during the weekdays.

All allocation methods were limited by the availability of wind and had to follow a fixed set of rules and conditions.

The following conditions dictate the application of wind to the ETS and DHW units:

- Available wind-electricity is greater than the total system demand; that is, the sum of the demand of the individual ETS and DHW units in the system.
- Available wind-electricity is less than the total system demand.
- There is no wind-electricity available.

The following rules are applied to each allocation method:

- Available wind is first used to meet the ETS demand, any remaining is used to meet the DHW demand.
- At the end of off-peak, all ETS and DHW units should be at their maximum capacity.
- Units cannot be charged beyond their maximum input charge.
- Hourly charge rate to be maintained so that at the end of the off-peak hour, the ETS and DHW units are fully charged.
- Discharge based on space heating demand is possible only if charging ETS is more than the sum of hourly discharge and hourly charge rate.
- If demand for ETS is zero, then discharge is possible only to meet space heating demand if same amount can be charged back to the ETS system.
- ETS discharge should not be greater than space heating demand.
- Hourly DHW demand has to be met through discharge.
- Charging from the grid during peak hours is done only to meet hourly DHW charging rates and to satisfy the DHW demands when there is insufficient wind.

The five different allocation methods are now described. In every case each ETS is associated with a maximum combined hourly discharge and recharge volume. An ETS has a minimum hourly demand, obtained by dividing the available storage volume by the hours remaining in the recharge period; for example, at midnight, during the off-peak hours of 11:00 PM to 7:00 AM, the divisor is seven.

3.4.1 Minimum (MIN) recharge method

In this method, the available wind-electricity is first used to recharge the ETS unit to meet its minimum hourly demand; if there is insufficient wind-electricity, then grid-electricity is used to make up the difference. If the minimum demand is met, the remaining wind-electricity is applied to the space heating demand; any shortfalls are met by the backup. Any excess wind electricity is directed towards the DHW unit to meet its hourly demand, supplemented by grid-electricity if necessary. Any excess wind-electricity is used to meet the demand of other electrical services.

The basis of the design of this method is such that, of the available wind electricity, only the minimum wind electricity is used to meet the hourly demands and the rest of the wind electricity is made available to meet the demands of other services. This method is designed to ensure that other electrical services will not be deprived of the available wind electricity. This method is expected to work well when there are periods of low wind availability or when wind availability is zero.

STEPS FOR ETS Allocation

1. Every hour check wind availability
2. Calculate Hourly Space heating load (SHL) based on (fSHL)
3. Obtain Maximum Input Charge for the ETS (MIC)
4. Obtain Sate of charge (SOC)
5. Calculate Hourly charge rate (HCR)
6. Calculate Hourly System Demand (HSD)
7. If wind electricity available is greater than system demand (HSD) then recharge ETS by hourly charge rate (HCR)
    a. Use excess wind to meet Space heating load (SHL) by simultaneously charging and discharging the ETS, such that discharge should not be greater than AEHD
    b. If Heating demand cannot be met then use other sources of energy to supplement the difference
8. If wind electricity available is less than system demand (HSD) but greater than hourly charge rate (HCR) then recharge ETS to Hourly charge rate (HCR)

    a. Use excess wind to meet Space heating load (SHL) by simultaneously charging and discharging the ETS, such that discharge should not be greater than AEHD
    b. If Heating demand cannot be met then use other sources of energy to supplement the difference
9. If wind electricity available is less than hourly charge rate (HCR) then charge ETS based on maximum potential energy available for recharge.
    a. Use grid electricity to reach the Hourly charge rate (HCR)
    b. Use other sources of energy to meet the heating demand

STEPS FOR DHW Allocation

1. Check wind electricity available after meeting the ETS demand
2. Calculate hot water requirements (ADHD)
3. Obtain maximum input charge for the DHW system (MIC)
4. Obtain Sate of charge (SOC)
5. Calculate Hourly charge rate (HCR) based on DHW requirement; here, HCR = SOC-ADHD
6. If wind electricity is greater than hourly charge rate (HCR) then use balance of wind to simultaneously recharge and discharge from the DHW system to meet the hot water demands. Discharge cannot be greater than (MIC) for the DHW system
7. Excess wind electricity is treated as spill
8. If balance of wind electricity is insufficient, then use grid electricity to simultaneously recharge and discharge from the DHW system to meet the hot water demands, do not exceed the maximum hourly recharge (MIC)
9. Do not exceed DHW capacity (MDC)

The DHW allocation is the same for all the methods.

3.4.2 Maximum (MAX) recharge method

This method begins with the available wind recharging the ETS unit up to its hourly maximum. If there is insufficient wind, grid-electricity is used for charging. Once the ETS unit is fully charged, the available wind-electricity is applied to the space heating demand, supplemented by grid-electricity; if the demand exceeds the allowable ETS recharge rate, the backup is used.[1] The DHW unit is recharged with wind-electricity if space heating demand has been met; like the ETS, if there is insufficient wind, grid-

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[1] Unless otherwise indicated, the backup is always light-fuel oil (LFO).

electricity is used. As in all other cases, any remaining wind-electricity is applied to other electrical services.

The basis of the design of this method is such that, the available wind electricity is utilized to its maximum benefit to meet the ETS and DHW demands for that hour. The emphasis of this method is to ensure the ETS and DHW are fully charged when wind electricity is available. This method is expected to work well during periods of high wind variability.

STEPS FOR ETS ALLOCATION

1. Every hour check wind availability
2. Calculate Hourly Space heating load (SHL) based on (fSHL)
3. Obtain Maximum Input Charge for the ETS (MIC)
4. Obtain Sate of charge (SOC)
5. Calculate Hourly charge rate (HCR)
6. Calculate Hourly System Demand (HSD)
7. If wind electricity available is greater than system demand (HSD) then recharge ETS up to its maximum input charge (MIC).
    a. No discharge to meet the space heating demands until ETS attains Maximum Capacity (MSC)
    b. If Heating demand cannot be met then use other sources of energy to supplement the difference
    c. If ETS is charged to its maximum capacity then Excess wind electricity is used to meet the heating demands. Meet the space heating load (SHL) by simultaneously charging and discharging the ETS, such that discharge should not be greater than AEHD
8. If wind electricity available is less than system demand (HSD) but greater than hourly charge rate (HCR) charge ETS to Hourly charge rate (HCR)
    a. No discharge possible through the ETS
    b. Heating demands are met by other sources of energy
9. If wind electricity available is less than hourly charge rate (HCR) then charge ETS based on maximum potential energy available for recharge.
    a. Use grid electricity to reach the Hourly charge rate
    b. Use other sources of energy to meet the heating demands

3.4.3 Mixture (MIX) recharge method

The third method is a mix of the minimum and maximum recharge methods in which the available wind-electricity is first applied to meet the minimum ETS recharge; this can be supplemented from grid-electricity if necessary. Any wind-electricity not required to meet the ETS demand is used for space heating, supplemented by the backup as required. If wind is still available, it is directed towards the ETS unit to recharge up to its maximum. The DHW unit demand is met by any remaining wind-electricity; if there is insufficient wind-electricity, the DHW draws electricity from the grid to meet its hourly demand. Any excess wind-electricity is directed towards other electrical services.

The basis of the design of this method is such that, the available wind electricity is utilized meet the ETS and space heating demands for that hour. The emphasis of this method is to ensure the ETS gets the priority over other services when wind electricity is available. This method is expected to work well when wind electricity availability is moderate and consistent over longer periods of time.

STEPS FOR ETS ALLOCATION

1. Every hour check wind availability
2. Calculate Hourly Space heating load (SHL) based on (fSHL)
3. Obtain Maximum Input Charge for the ETS (MIC)
4. Obtain Sate of charge (SOC)
5. Calculate Hourly charge rate (HCR)
6. Calculate Hourly System Demand (HSD)
7. If wind electricity available is greater than system demand (HSD) then recharge ETS by hourly charge rate (HCR)
    a. Use excess wind electricity to meet Space heating load (SHL) by simultaneously charging and discharging the ETS, such that discharge should not be greater than AEHD
    b. Use remaining wind electricity to recharge the ETS up to its Maximum recharge limit (MIC).
8. If wind electricity available is less than system demand (HSD) but greater than hourly charge rate (HCR) then recharge ETS to Hourly charge rate (HCR)

    a. Use excess wind electricity to meet Space heating load (SHL) by simultaneously charging and discharging the ETS, such that discharge should not be greater than AEHD
    b. If Heating demand cannot be met then use other sources of energy to supplement the difference
9. If wind electricity available is less than hourly charge rate (HCR) then charge ETS based on maximum potential energy available for recharge.
    a. Use grid electricity to reach the Hourly charge rate if wind electricity is insufficient
    b. Use other sources of energy to meet the space heating load

3.4.4 Discharge (DIS) recharge method

This method is employed during the weekends and holidays only. It starts by discharging the energy stored in the ETS to meet the household's space-heating demand. If the demand cannot be met by the ETS, it is simultaneously recharged and discharged from any available wind-electricity to meet the space-heating demand. Any remaining demand is met from grid-electricity simultaneously recharging and discharging the ETS. If the ETS can still be recharged and there is wind available, the ETS unit is recharged to its maximum. Any excess wind electricity is used to meet the DHW's hourly demand. If there is insufficient wind-electricity for this purpose, the DHW unit is charged from the grid. Any remaining wind-electricity is made available for other electrical services.

This method is an off-peak method but is used explicitly during weekends and holidays only. The basis of the design of this method is such that, the available wind electricity is fully utilized to meet the space heating demands for that hour. The emphasis of this method is to ensure the space heating gets the priority over other services when wind electricity is available. Since the method focuses on meeting the heating demands, this approach aims to keep the ETS SOC to a minimum. This method is expected to work well during weekend hours when wind electricity availability is high.

STEPS FOR ETS ALLOCATION

1. Every hour check wind availability

2. Calculate Hourly Space heating load (SHL) based on (fSHL)
3. Obtain Maximum Input Charge for the ETS (MIC)
4. Obtain Sate of charge (SOC)
5. Calculate maximum discharge rate (MDR)
6. Discharge MDR to meet the heating demands.
7. If heating demands are not met and if wind electricity is available use wind electricity to meet the heating demands (SHL) by simultaneously charging and discharging the ETS, such that SOC after discharge should not be less than initial SOC-MDR
8. If still needed use grid electricity to meet the heating demands
9. If excess wind electricity is available recharge ETS to its maximum potential recharge limit (MIC).

3.4.5 On-peak discharge method

In this method, any wind-electricity available during the weekday on-peak is used to meet the space heating demands for each household by simultaneously discharging and recharging its ETS unit. If insufficient wind-electricity is available, the energy stored in the ETS unit is used to meet the space heating demand; any remaining demand is met with the backup. If wind is still available, it recharges the ETS unit to its maximum. After the demand and ETS recharging has been taken care of, any remaining wind-electricity is applied to meet the DHW unit's hourly demand; any DHW demand not met from the wind is supplied by the grid. Finally, if wind-electricity is still in excess, then it is directed towards other electrical services.

This method is the default on-peak method used during weekday hours between 7:00 AM to 11:00 PM. The basis of the design of this method is such that the available wind electricity is fully utilized to meet the space heating demands and on peak recharging of the ETS during the peak hours of the weekdays. The emphasis of this method is to ensure the space heating gets the priority over other services when wind electricity is available. This method is expected to work well during weekday hours when wind electricity availability is high. During peak hours the focus of the wind allocation algorithm is to satisfy the heating demands through ETS discharge.

STEPS FOR ETS ALLOCATION

1. Every hour check wind availability
2. Calculate Hourly Space heating load (SHL) based on (fSHL)
3. Obtain Maximum Input Charge for the ETS (MIC)
4. Obtain State of charge (SOC)
5. Calculate maximum discharge rate (MDR)
6. If wind electricity is available then apply wind electricity to meet the heating demand (SHL) by simultaneously charging and discharging the ETS, such that SOC after discharge should not be less than initial SOC-MDR.
7. If Excess wind electricity is available then recharge the ETS up to its potential maximum recharge limit (MIC).
8. If heating demands are not met then discharge ETS to Maximum discharge rate (MDR) to meet the heating demands
9. If heating demands are still not met then use other energy source to meet the heating demand

3.5 Comparative analysis of the methods

For the purpose of this thesis and to show the functionality and capabilities of the different methods a comparative analysis of the different methods were performed based on zero wind conditions, maximum (available wind more than system demand) wind conditions and average wind conditions. The time frame for this analysis was taken as eight hours and a total of one ETS unit and one DHW unit were included for the analysis. The ETS units and DHW units were considered to be empty at the start of the analysis. Simulations were performed applying each method and the outcome is discussed below.

The following initial assumptions were made for the demonstration of the methods as shown in Table 1.

Table 1: Initial Assumption for wind Allocation

	ETS	DHW
Total number ETS units	1	1
Maximum Input Charge	6 kWh	4.5 kWh
Fraction of space heating Load	100%	NA
Heating Demand/hour	2.5 kWh	0.2 kWh
Initial SOC	0	15 kWh
Capacity	33.8 kWh	15 kWh
Amount of wind electricity	Zero	
Period	Weekday Off-peak	

In the following examples, a single hour's output is shown as it is assumed that the same conditions apply for all eight hours of the simulation, thereby allowing a comparison of the methods in a controlled environment. During the entire year's simulation, the conditions vary from hour-to-hour, resulting in different hourly results although the same method is used for the entire year. If the methods were available to an electricity supplier, the methods could change in response to expected wind conditions.

3.5.1 Zero-wind condition

As the name suggests, no wind electricity was made available during the time frame of the analysis. Simulation was conducted for eight hour time period on all three off-peak methods (MIN, MIX and MAX) and allocation results for a given hour are as shown in Table 2.

Table 2 : Allocation results for zero wind condition for a weekday off-peak hour

	Wind Allocation Methods		
	MIN	***MIX***	***MAX***
System demand (kWh)	4.4	4.4	4.4

Excess wind (kWh)	0.0	0.0	0.0
ETS SOC (kWh)	4.2	4.2	4.2
SH met (kWh)	0.0	0.0	0.0
ETS Grid (kWh)	4.2	4.2	4.2
ETS Wind (kWh)	0.0	0.0	0.0
Equivalent Oil Backup (kWh)	2.5	2.5	2.5
DHW Met (kWh)	0.2	0.2	0.2
DHW Grid (kWh)	0.2	0.2	0.2
DHW Wind (kWh)	0.0	0.0	0.0

From Table 2 it can be seen that under zero wind conditions all methods showed the same characteristics in terms of allocation technique. The amount of grid electricity used to charge the ETS and DHW units was similar. The space heating load was purely met by oil backup in all three cases. Since the availability of wind is zero all three methods chose to recharge the ETS to its HCR. The domestic hot water demand was purely met by using grid electricity.

The initial assumptions were slightly changed to analyse the effectiveness of the off-peak methods (MIN, MIX and MAX) during weekend period when compared to the weekend discharge recharge method (DIS). The SOC of the ETS was assumed to be maximum (i.e. 100% full) and all other initial assumption remained unchanged. Simulation was conducted for eight-hour time period and allocation results for a given hour are as shown in Table 3

Table 3: Allocation results for zero wind condition for one weekend off-peak hour

	Methods	
	MIN/MIX/MAX	***DIS***
System demand (kWh)	0.2	1.9
Excess wind (kWh)	0.0	0.0
ETS SOC (kWh)	33.8	33.0
SH met (kWh)	0.0	2.5
ETS Grid (kWh)	0.0	1.7
ETS Wind (kWh)	0.0	0.0
Equivalent Oil Backup (kWh)	2.5	0.0
DHW Met (kWh)	0.2	0.2
DHW Grid (kWh)	0.2	0.2
DHW Wind (kWh)	0.0	0.0

As it can be seen from Table 3 the MIN, MIX and MAX methods showed the same characteristics in terms of allocation strategy. The space heating load was purely met by backup sources which could potentially increase emission levels depending on the back up source used. On the other hand the DIS method proved its effectiveness by totally eliminating the use of back up sources to meet the SHL demand. All space heating demand was satisfied by partly discharging ETS and partly using grid electricity to meet the demand. The DIS method has the edge over the other methods during weekend periods as it was able to meet all of the heating demand. In all of the wind allocation methods the DHW demand was purely met by grid electricity. Overall acceptability of the DIS method depends upon the grid emission levels.

3.5.2 Maximum wind condition

As the name suggests, maximum wind electricity (available wind electricity is greater than system demand) was made available during the time frame of the analysis. All initial assumption made remained the same except wind availability and Space heating load. Wind availability was assumed 10kWh and SHL was assumed 0.5 kWh. Simulation was conducted for eight hour time period on all three off-peak methods (MIN, MIX and MAX) and allocation results for a given hour are as shown in Table 4.

Table 4: Allocation results for maximum wind condition for one weekday off-peak hour

	Methods		
	MIN	**MIX**	**MAX**
System demand (kWh)	4.9	6.2	6.2
Excess wind (kWh)	5.1	3.8	3.8
ETS SOC (kWh)	4.2	5.5	6.0
SH met (kWh)	0.5	0.5	0.0
ETS Grid (kWh)	0.0	0.0	0.0
ETS Wind (kWh)	4.7	6.0	6.0
Oil Backup (kWh)	0.0	0.0	0.5
DHW Met (kWh)	0.2	0.2	0.2
DHW Grid (kWh)	0.0	0.0	0.0
DHW Wind (kWh)	0.2	0.2	0.2

As it can be seen from Table 4 both the MIX and the MAX methods maximized its wind utilization. The MIN method did not effectively use the wind and created the maximum excess of the three methods. Although, the MAX method utilized maximum wind it did not meet the space heating load and had to depend upon back-up sources to meet the heating demands. The MIX method has the edge over the other two methods as it used wind electricity very efficiently by recharging the ETS with wind electricity and at the same time used wind electricity to meet the heating demands, thus totally eliminating the use of back up sources. Although the MIN method also did not use back-up sources to meet the heating demand, it did not use wind very effectively. All three methods utilized wind to meet the DHW demand. Overall the MIX method appears to be better as it not only contributed towards zero emission levels but also utilized wind to its maximum capabilities.

The initial assumptions were slightly changed to anlayse the effectiveness of the off-peak methods (MIN, MIX and MAX) during weekend period when compared to the weekend discharge recharge method (DIS). The SOC of the ETS was assumed to be 20kWh and SHL was 2.5kWh all other initial assumption remained unchanged. The change in SHL was to show some variation in the allocation technique. Simulation was conducted for eight hour time period and allocation results for a given hour are as shown in Table 5.

Table 5: Allocation results for maximum wind condition for one weekend off-peak hour

	Methods			
	MIN	**MIX**	**MAX**	**DIS**
System demand (kWh)	2.9	6.2	6.2	6.2
Excess wind (kWh)	7.1	3.8	3.8	3.8
ETS SOC (kWh)	20.3	23.5	26.0	23.5
SH met (kWh)	2.5	2.5	0.0	2.5
ETS Grid (kWh)	0.0	0.0	0.0	0.0
ETS Wind (kWh)	2.8	6.0	6.0	6.0
Oil Backup (kWh)	0.0	0.0	2.5	0.0

DHW Met (kWh)	0.2	0.2	0.2	0.2
DHW Grid (kWh)	0.0	0.0	0.0	0.0
DHW Wind (kWh)	0.2	0.2	0.2	0.2

As it can be seen from Table 5 the least amount of wind utilization was by the MIN method and all other methods used wind electricity to its maximum effectiveness. Although the maximum ETS charge was from the MAX method, it had to use back up sources to meet the heating demand. This could potentially increase emission levels compared to the other methods lowering its acceptability. The MIX and the DIS methods showed same characteristics in terms of allocation technique. Except the MAX method all other methods used wind to meet their heating demands. None of the methods used grid electricity to meet the heating demands. Over all the MIX method could be used potentially for weekday off-peak hours and the DIS method can be used for weekend off-peak hours.

3.5.3 Average wind condition

As the name suggests, average wind electricity (available wind electricity is half of wind available during maximum wind condition) was made available during the time frame of the analysis. All initial assumptions made remained the same except wind availability and Space heating load. Wind availability was assumed 5kWh and SHL was assumed 0.5 kWh. Simulation was conducted for an eight-hour time period on all three off-peak methods (MIN, MIX and MAX) and allocation results for a given hour are as shown in Table 6.

Table 6: Allocation results for average wind condition for one weekday off-peak hour

	Methods		
	MIN	**MIX**	**MAX**
System demand (kWh)	4.9	5.2	5.2
Excess wind (kWh)	0.1	0.0	0.0
ETS SOC (kWh)	4.2	4.5	5.0
SH met (kWh)	0.5	0.5	0.0
ETS Grid (kWh)	0.0	0.0	0.0
ETS Wind (kWh)	4.7	5.0	5.0

Oil Backup (kWh)	0.0	0.0	0.5
DHW Met (kWh)	0.2	0.2	0.2
DHW Grid (kWh)	0.0	0.2	0.2
DHW Wind (kWh)	0.2	0.0	0.0

As it can be seen from Table 6 both the MIX and the MAX methods maximized its wind utilization. The MIN method did not effectively use the wind and created an excess of the three methods. Although, the MAX method utilized maximum wind it did not meet the space heating load and had to depend upon back up sources to meet the heating demands. The MIX method has the edge over the other two methods as it used wind electricity very efficiently by recharging the ETS with wind electricity and at the same time used wind electricity to meet the heating demands, thus totally eliminating the use of back up sources. Although the MIN method also did not use back up sources to meet the heating demand, it did not used wind very effectively. Except for the MIN method, all methods had to use grid electricity to meet the DHW demand. Although the MIX method has a slight advantage over the MIN method in terms of better utilization of wind electricity, the MIN method excels in terms of acceptability as it did not use any back up source or grid electricity to meet the heating demands, thereby omitting emission.

The initial assumptions were slightly changed to anlayse the effectiveness of the off-peak methods (MIN, MIX and MAX) during weekend period when compared to the weekend discharge recharge method (DIS). The SOC of the ETS was assumed to be 20kWh and SHL was 2.5kWh all other initial assumptions remained unchanged. The change in SHL was to show some variation in the allocation technique. Simulation was conducted for eight hour time period and allocation results for a given hour are as shown in Table 7

Table 7: Allocation results for average wind condition for one weekend off-peak hour

	Methods			
	MIN	**MIX**	**MAX**	**DIS**
System demand (kWh)	2.9	5.2	5.2	5.2
Excess wind (kWh)	2.1	0.0	0.0	0.0
ETS SOC (kWh)	20.3	22.5	25.0	22.5
SH met (kWh)	2.5	2.5	0.0	2.5
ETS Grid (kWh)	0.0	0.0	0.0	0.0
ETS Wind (kWh)	2.8	5.0	5.0	5.0
Oil Backup (kWh)	0.0	0.0	2.5	0.0
DHW Met (kWh)	0.2	0.2	0.2	0.2
DHW Grid (kWh)	0.0	0.2	0.2	0.2
DHW Wind (kWh)	0.2	0.0	0.0	0.0

As it can be seen from Table 7 that the least amount of wind utilization was by the MIN method and all other methods used wind electricity to its maximum effectiveness. Although the maximum ETS charge was from the MAX method, it had to use back-up sources to meet the heating demand. This could potentially increase emission levels compared to the other methods lowering its acceptability. The MIX and the DIS methods showed same characteristics in terms of allocation technique. Except the MAX method, all other methods used wind to meet their heating demands. All of the methods had to use grid electricity to meet the hot water heating demands. Although the MIX method and the DIS method exhibit the same allocation properties there may be variation to the allocation if the wind availability changes or system demand increase. One more set of simulations were done to analyse the method's functionality, by lowering the available wind electricity to 2kWh. No other assumptions were changed. Simulations were conducted for an eight-hour time period and allocation results for a given hour are as shown in Table 8.

Table 8: Allocation results for average wind condition weekend off-peak hour

	Methods	
	MIX	**DIS**
System demand (kWh)	2.2	2.2
Excess wind (kWh)	0.0	0.0
ETS SOC (kWh)	20.3	19.6
SH met (kWh)	1.7	2.5
ETS Grid (kWh)	0.0	0.1
ETS Wind (kWh)	2.0	2.0
Oil Backup (kWh)	0.8	0.0
DHW Met (kWh)	0.2	0.2
DHW Grid (kWh)	0.2	0.2
DHW Wind (kWh)	0.0	0.0

As it can be seen from Table 8 that as the available wind electricity was reduced, the MIX method had to use backup sources to meet the heating demand potentially leading to an increase in emission levels thereby lowering its acceptability. Rather than meeting the heating demand, it increased its stored energy by recharging the ETS. Overall the DIS method has the edge over the MIX method.

From the comparative analysis of the wind allocation methods it can be seen that based on the wind condition the methods vary and no single method can be classified as the best method. All methods are designed to offer the best functionality under different wind conditions, in terms of wind allocation techniques. Based on the wind availability for any given hour, from wind forecasting methods, the wind allocation methods can be changed by the hour to obtain optimal results every hour thus increasing the ability of the wind allocation methods to improve the energy security of the jurisdiction.

A software tool was developed incorporating the five different wind-allocation strategies for off-peak charging. A second charging scenario, anytime charging, was developed as an alternative to off-peak charging. In this scenario, the ETS units are charged whenever wind-electricity is available (Hughes, 2010b); it was introduced to demonstrate its advantage over off-peak charging and its ability to improve the energy security of the jurisdiction.

The simulation software comprises two distinct modules: simulation and analysis.

3.6 Implementation

3.6.1 Simulation module

The simulation module allocates the available wind-electricity to meet the demands of the ETS and DHW units and depends upon the hour of the day, the allocation method, and the scenario selected. The simulator inputs are:

- day,
- hour of the day,
- hour status (i.e. Peak or off-peak),
- hourly wind available for allocation,
- hourly space heating load, and
- percentage contribution of wind-electricity from the different suppliers,
- number of ETS and DHW units in the system,
- maximum storage capacities (MSC) of the individual ETS and DHW units,
- maximum input charge (MIC) of the individual units,
- percentage of space heating load (pSHL),
- initial state of charge (SOC) of the ETS and DHW units,
- daily hot water demand,
- charging scenario,
- wind-allocation method.

The flowchart in Figure 3 shows the steps used by the simulation software for each allocation technique being tested.

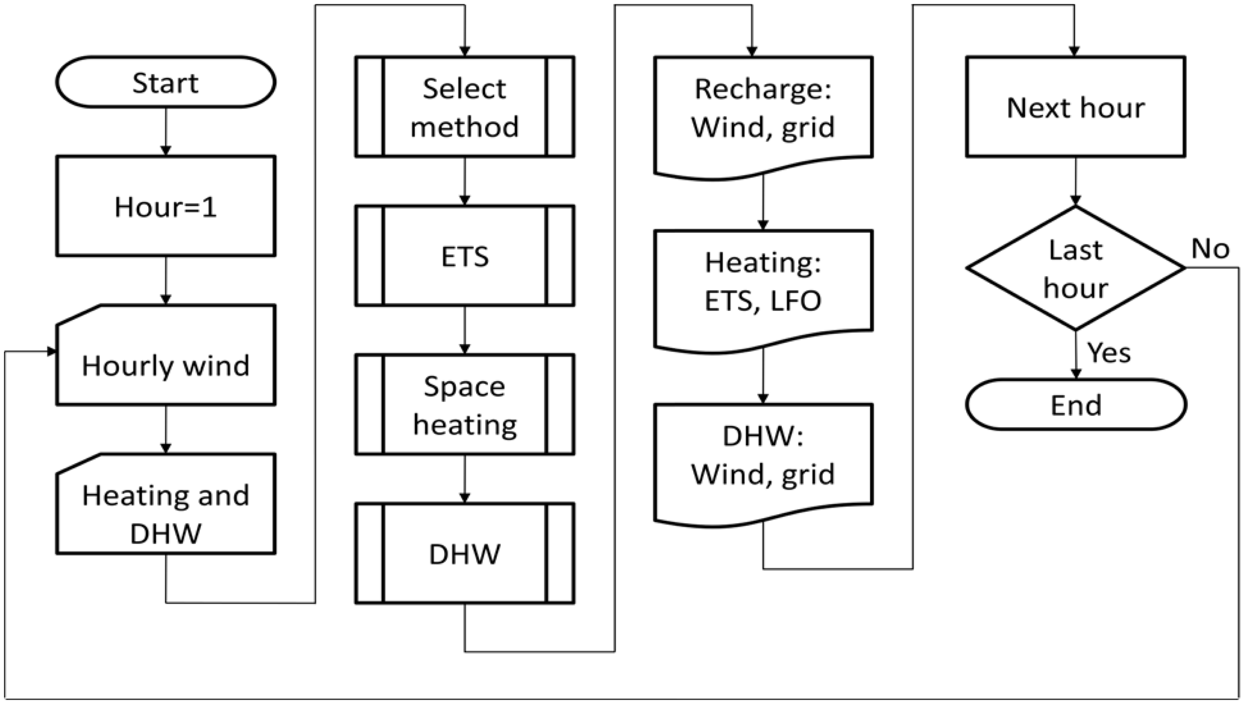

Figure 3: Simulation software flowchart

3.6.2 Analysis module

Once the method and scenario are selected, the simulation module attempts to meet each household's hourly space and water heating demands with the hourly wind-electricity production data. The simulation module operates for the period specified (for example, an hour, a week, or a month) and maximizes the use of the available wind each hour. The simulator produces hourly results for total grid electricity used by the participating households, system demand, excess wind available, state of charge of each household's ETS and DHW units, space heating load and domestic hot water load met, grid electricity used by the individual ETS and DHW units, wind electricity used by the individual ETS and DHW units and the volume of LFO used for back-up.

This module allows analysis of the wind-heating system, producing graphs for customer cost, emissions, supplier balance, ETS vs. non–ETS, and wind usage.

3.6.3 Software

Microsoft Office Excel 2007 is one of the most popular and commonly available spreadsheet tools. It allows the user to import data, create tables, and establish formulae written directly in cells to organize and filter data. This software is able to handle numerous large data sets using built-in functions, and perform detailed analyses. Using its built-in charting tools, charts can be developed from the data in order to display the results graphically.

Visual Basic for Applications (VBA) is a programming language that can be used within Excel 2007 to perform complex computations that involve repetitive operations. With this application, macros or complex programs can be developed to automate operations and perform analyses with more consistency than that which is manually in Excel spreadsheets. Also, long, iterative, and time-consuming tasks can be computed more quickly than in the default Excel spreadsheets. In light of this, it was decided that spreadsheet and its associated tools will be used for the development of the software and implementation of the methods.

3.7 Summary

This chapter presented a set of methods to handle variable load and allocate wind electricity effectively to improve energy security. It also included a comparison analysis of the different methods. It also discussed the software tools used to implement the proposed methods were also discussed.

CHAPTER 4 CASE STUDY AND RESULTS

This chapter presents a case study platform to examine the proposed methods. The test site selected to implement the methods was the City of Summerside, P.E.I. It also presents the rationale for selection of Summerside, along with the input data required to perform the simulation. The case study is implemented using the software tools, Microsoft Office Excel 2007 and VBA.

In June 2011, the city started to build its communication network by connecting the participating households to a control center through optical fiber cables for a bi-directional communications for effective monitoring with the smart meters and control of the individual ETS and DHW systems. As of January 2012, more than 100 households were connected to the control center with ETS, DHW and smart meters installed enabling a perfect platform to implement the methods.

Summerside Electric, through its in-house IT staff, had already created the Summerside Electric Energy Transmission Scheduling System (or SEETSS) in 2010 to track grid loads on the system and the current available generation supplies of the wind farm component and make decisions to schedule the electricity required by the city to meet the next hour's load. SEETSS has the following capabilities:

- Summerside load forecasting
- Summerside wind farm forecasting
- West Cape wind farm forecasting
- Electric grid load monitoring
- Diesel generator supply monitoring

For this study, the average hourly wind-electricity generation data from Summerside wind farm and West Cape wind farm and load data was obtained from the SEETSS ; the data is for a full heating system, in this case, July 2010 to June 2011.

The City's charging methods are as follows: both the ETS and DHW units worked on a simple timer-based charging scenario in which they automatically become available for recharging during the weekday off-peak hours (11:00 PM to 7:00 AM, Mondays to Fridays), the weekend off-peak hours (Friday 11:00 PM to Sunday 11:00 PM, after which it followed the normal 11:00 PM to 7:00 AM weekday off-peak charging scenario). During the peak hours, the ETS units were designed to discharge up to a set hourly maximum. Since no form of control or flexibility was offered within the system in the form of wind allocation methods, this was the ideal platform to implement the developed methods to study the effects of energy security of the wind heating system. For the case study 100 ETS and 100 DHW systems were taken as the base as this was the number of units Summerside had installed as part of the smart grid pilot program. By using the same number of units the simulation results could provide a more realistic view on the functionality of the wind allocation methods and energy security. The type and size of households in Summerside that installed ETS and DHW units were not similar and it was very difficult to calculate the heating load requirements. To have a more realistic approach, three types of households were selected for the case study which represents the 100 household in the Summerside smart grid pilot program which are classified as small (34% of the total 100 household), medium (33% of the total 100 household)and large (33% of the total 100 households). Since heating load data was obtained from NRCan/OEE, small households in the case study were assumed to have 75% of the annual heating loads, medium household were assumed to have 100% of the annual heating load and large households were assumed to have 125% of the annual heating load.

4.1 Data Sources

The simulation program was used for the analysis of the Summerside wind-heating program. For the analysis to be conducted as accurately as possible, the city of Summerside supplied the following data for the simulation:

- Hourly wind production data from Summerside’s wind farm and hourly wind supply data from the West Cape wind farm (Summerside Electric, 2011),

- Pricing structure for residential-class customers participating in the wind heating pilot project for the 2010-2011 study period (Summerside Electric, 2011A),
- Electrical purchase cost from NB Power (Summerside Electric, 2011B) and West Cape (Summerside Electric, 2011C) for 2010-2011,
- Summerside's wind production cost (Summerside Electric, 2011),
- ETS (Steffes Corporation, 2011) and DHW specifications (Marathon water heaters, 2011) which included the different maximum storage capacities used under the wind heating program of individual ETS and DHW units and maximum input charge (i.e. element size)
- Light fuel oil cost (IRAC, 2011), and
- Average oil furnace efficiency for households participating in the wind heating pilot project (Natural Resource Canada/ Office of Energy Efficiency-B).

Other data required for the simulation were:

- Hourly temperature data to calculate the total degree-hours (obtained from (Environment Canada, 2011)),
- Residential data for P.E.I., notably the number of households and the average household heating-loads to calculate hourly space heating demand and DHW usage (from the (Natural Resource Canada/Office of Energy Efficiency, 2011)),
- Daily domestic hot water usage profile (Biaoua & Bernie, 2008); (Perlman & Mills, 1985),

Carbon dioxide equivalent emission for grid electricity was taken from (NB Power, 2010) and light fuel oil emission data was taken from (Environment Canada, 2011)

4.2 Case study Simulation Results

Simulations were conducted for 100 ETS and 100 DHW units for the two charging scenarios—off-peak charging and anytime charging—for July 2010 to June 2011. In the off-peak scenario, the available wind-electricity was allocated to the wind-heating system only during the off-peak hours, whereas in the anytime scenario, wind-electricity was allocated when available throughout the day. Household heating-loads were taken from the NRCan/OEE residential data for P.E.I. (described below); three levels of household energy consumption were used with demands of 75%, 100%, and 125% of the NRCan/OEE heating-loads.

The simulator output analysed and discussed in this section includes customer cost, supplier balance, emissions, ETS vs. non-ETS, and wind usage.

4.2.1 Customer Cost

The price of both off-peak and on-peak electricity for the customers was \$0.082/kWh, while the cost of LFO was taken as \$1.034/litre (IRAC, 2011). Customer costs were obtained from the total amount of electricity used by the ETS and DHW units to meet the daily demand and the amount of LFO used for backup. The annual customer costs for all 100 ETS and DHW units for the anytime-charging scenario are shown in Figure 4.

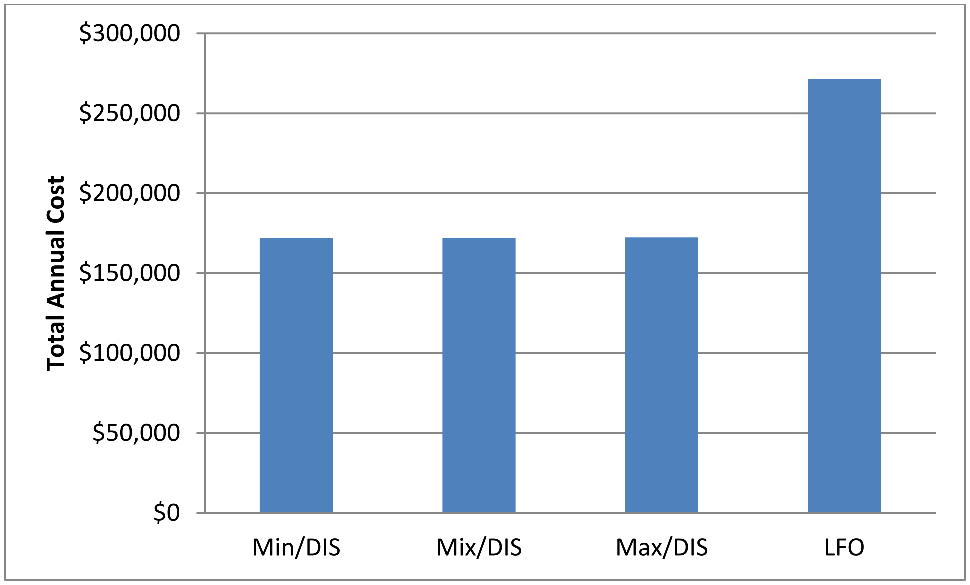

Figure 4: Total annual customer costs for Anytime-charging scenario for 100 households

From Figure 4, it can be seen that the annual cost of an household without the ETS and DHW system, i.e., only furnace heating system represented by LFO cost, is higher than the households with ETS and DHW system incorporated. This shows that by allocating wind electricity effectively the cost for wind heating is lower than the cost of using furnace oil alone.

From Table 9, it can be seen that the cost of using wind for ETS and DHW heating for the three different proposed methods is about 36% less than the cost of using LFO alone for anytime charging and about 30-32% less for off-peak charging. Although the savings are almost the same, the cost for oil backup increases to about 21% of the total cost in the off-peak charging case. Off-peak charging not only increases customer costs but also increases the dependency on fossil fuels. With oil prices continuing to rise, affordability becomes a main factor in deciding on the type of heating system required as it is one of the ways a customer can improve energy security. Replacing traditional oil-furnace-based heating with wind-electricity ETS-DHW heating has improved Summerside's energy security from its current state by reducing its dependency on fossil fuels. Any move from off-peak charging to anytime charging also improves Summerside's energy security. Although the overall affordability is improved, the impact on individual households must be considered in terms of potential annual savings and the payback period for any capital costs incurred.

Table 9 : Summary of Combined Annual Customer Cost

	Anytime Charging Scenario			Off-peak Charging Scenario			LFO
	Min/DIS	Mix/DIS	Max/DIS	Min/DIS	Mix/DIS	Max/DIS	
Total Cost	$172,037	$172,030	$172,382	$184,073	$184,053	$187,766	$271,397
Savings	36.6%	36.6%	36.5%	32.2%	32.2%	30.8%	
Oil Backup	3.9%	3.9%	3.9%	21.0%	21.0%	20.6%	

Figure 5 shows the annual individual household cost based on the fraction of NRCan/OEE residential heating loads for P.E.I. (Units 1, 2, and 3 correspond to 75%, 100%, and 125% of the annual heating loads, respectively). The division of the cost for the customer across the various sources of electricity is also shown in the figure. The annual savings in the anytime-charging scenario for all three units are about 36% of the total LFO cost and range from 30% to 32% for off-peak charging scenario.

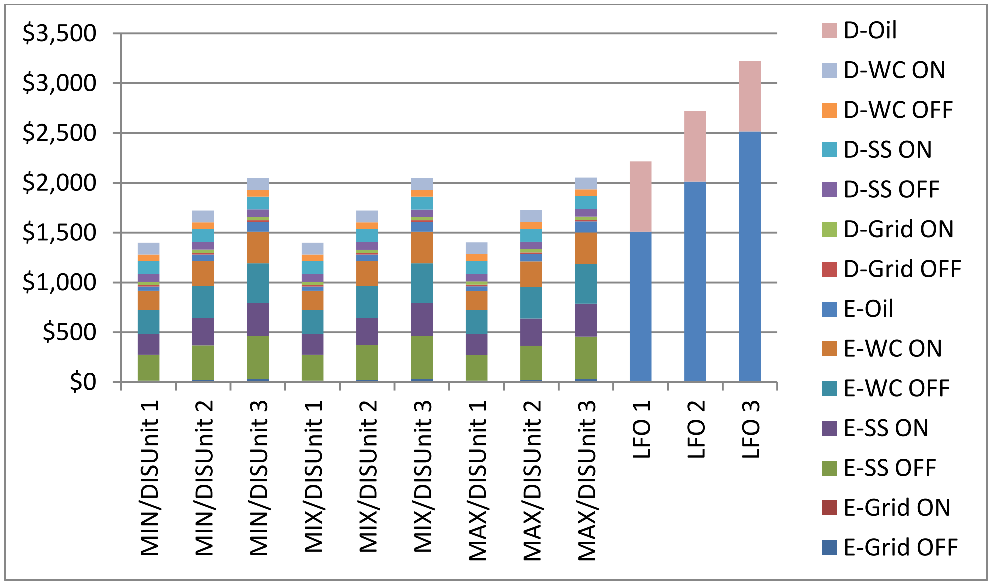

Figure 5: Individual customer annual cost with heating load factors of 0.75, 1, and 1.25 for the anytime charging scenario

Table 10 shows the individual annual savings for each unit under different simulation methods for both scenarios. The major contributor towards these savings is the fact that Summerside uses wind-electricity to meet its heating demands by storing electricity when wind is available thereby reducing the need for fossil-based grid-electricity. The savings may vary, depending on the cost of grid-electricity purchased from NB Power, the heating demand, and the availability of wind-electricity. Since affordability plays an important role in determining the energy security of any jurisdiction, it is in the best interest of Summerside to reduce its dependency on electricity imports and light-fuel oil.

Table 10: Summary of Annual Savings for individual units

	Anytime Charging Scenario			**Off-peak Charging Scenario**		
	Min/DIS	**Mix/DIS**	**Max/DIS**	**Min/DIS**	**Mix/DIS**	**Max/DIS**
Unit 1	$815.82	$815.88	$813.58	$774.27	$774.44	$736.62
Unit 2	$997.01	$997.07	$993.81	$880.25	$880.47	$842.35
Unit 3	$1,173.37	$1,173.47	$1,168.43	$968.19	$968.43	$933.00

From Table 11, it can be seen that grid-electricity's share of the total cost for ETS units, under both scenarios, is marginal. However, for DHW, the cost of grid-electricity ranges from 12% to 20% in the off-peak charging scenario and in the 2% to 3% range for anytime charging. The difference is due to the ability of the wind-heating system to effectively use wind-electricity to charge ETS and DHW systems during the anytime charging period (i.e., peak hours) when wind is available. Reducing its dependency on electricity imports through the use of anytime charging will improve energy security in terms of affordability.

Table 11: Percentage contribution of grid-electricity cost for ETS and DHW units

	Anytime charging scenario		Off-peak charging scenario	
	ETS	**DHW**	**ETS**	**DHW**
MIN/DIS Unit 1	1.1%	3.5%	2.6%	20.6%
MIN/DIS Unit 2	1.4%	2.8%	2.6%	16.1%
MIN/DIS Unit 3	1.6%	2.4%	2.7%	13.1%
MIX/DIS Unit 1	1.1%	3.5%	2.5%	20.6%
MIX/DIS Unit 2	1.4%	2.8%	2.6%	16.1%
MIX/DIS Unit 3	1.6%	2.4%	2.6%	13.1%
MAX/DIS Unit 1	1.0%	3.5%	2.2%	20.0%
MAX/DIS Unit 2	1.3%	2.8%	2.3%	15.8%
MAX/DIS Unit 3	1.6%	2.4%	2.4%	12.9%

Customer savings are meaningless if the payback period is too long for the capital costs incurred (such savings are termed as indirect savings). Indirect savings may affect affordability and have a detrimental effect on Summerside’s energy security. Table 12 shows the ETS and DHW specifications and the corresponding all-inclusive prices used in this report.

Table 12: Specification of ETS and DHW units (Summerside Electric, 2011)

Model	**Capacity**	**Watts**	**Price**
Steffes ETS Units- 2105	33.75 kWh	6000	$2,388
Marathon Water Heater-MR50245	50 U.S. Gal	4500	$1,892

Table 10 shows the potential annual savings by the different households under both scenarios. Assuming that all of the potential annual savings go towards repayment of the capital costs incurred, the payback period can be calculated as the time taken in years to attain breakeven, at which point indirect savings are treated as direct savings for each household.

As shown in Figure 6, the payback period is under six years for all three types of household and anytime charging exceeds off-peak charging in all cases. Because of the savings, households with larger demands tend to have faster payback times than smaller ones. Furthermore, households with larger demands in the anytime scenario have about 17% faster payback times than those using the off-peak charging scenario because of cost savings due to the reduced use of oil for backup (required during peak hours).

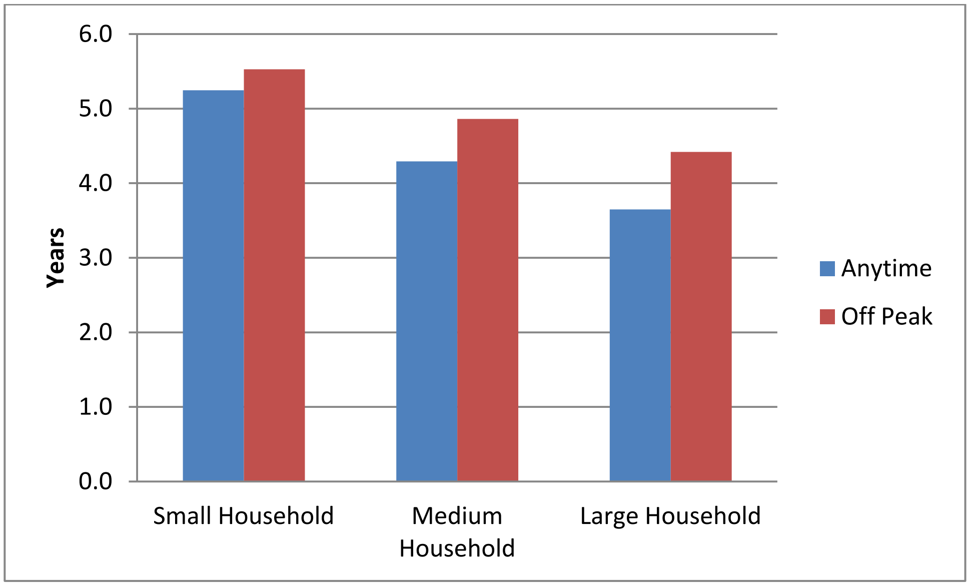

Figure 6: Payback period in years

4.2.2 Supplier Balance

Supplier balance is the net profit made by the electricity provider after deducting the cost of electrical purchases and in-house electrical production from the total revenue from the sale of electricity; revenues are directly related to the cost of electricity purchased or produced and the price of the electricity sold to the customer. Any fluctuations in electricity prices will have an impact on the provider's revenues.

Summerside Electric's average annual electricity purchase costs for 2010-2011 are summarized in Table 13; the costs vary by supplier and time-of-use. Prior to the introduction of the wind-heating program, all surplus wind-electricity (from both West Cape and Summerside) was exported and sold, at a loss, for between $0.03 and $0.05 per kWh.

Table 13: Summerside Electric's electricity purchase costs for 2010-2011 (Summerside Electric, 2010)

Source	Off-peak	On-peak
West Cape	$0.071	$0.067
Summerside	$0.082	$0.082
NB Power grid	$0.070	$0.083

Summerside's residential-class rate structure for wind-heating customers is divided into three block rates by season (winter and summer), as shown in Table 14.

Table 14: Residential electrical pricing (Summerside Electric, 2011A)

Rate code	Winter rate (October 1 to April 30)		Summer rate (May 1 to September 30)	
	Energy Charge/kWh	kWh Allowed	Energy Charge/kWh	kWh Allowed
Block A	$0.08	2700	$0.08	200
Block B	$0.1464	2000	$0.1464	2000
Block C	$0.1136	Balance	$0.1136	Balance

The rate codes are based on the assumption that each household will have at least one ETS unit and one DHW unit. Since the maximum space-heating load requirement in kWh for any of the months in 2010-2011 did not exceed the Block A rate code, for the purpose of this thesis, a flat rate of $0.080 per kWh was taken as the price per kWh for households participating in the wind-heating program.

The supplier balance from the sale of electricity to wind-heating customers from West Cape during the off- or on-peak hours is always positive, whereas the sale of electricity from NB Power generates a positive supplier balance during the off-peak hours and a negative balance during the on-peak. Because of the pricing structure, electricity from Summerside Electric's Wind Park is always sold at a loss, generating a negative supplier balance. In certain situations, Summerside Electric's revenues could turn negative and run at a loss, meaning that it would essentially be subsidizing the wind-heating customers.

Table 15 shows the combined annual cash-flow for Summerside Electric under the wind heating program. Although both the scenarios generate a positive balance, off-peak charging revenues are about 46% to 50% of those of anytime charging. With anytime charging, wind electricity is used more effectively during the peak hours when wind is available to not only meet the heating demands but to also recharge the ETS and DHW systems, thereby generating more revenues for the electricity supplier. The anytime charging scenario also benefits the environment by using wind-electricity throughout the day to meet the heating demand; in the off-peak scenario, customers use oil as the backup to meet the heating demand during the on-peak period, increasing the cost of heating for the customer and reducing revenues for Summerside Electric.

Table 15: Combined Annual Cash Flow

	Anytime Charging Scenario			**Off-peak Charging Scenario**		
	Min/DIS	**Mix/DIS**	**Max/DIS**	**Min/DIS**	**Mix/DIS**	**Max/DIS**
Cost	$155,937	$155,950	$155,389	$140,708	$140,767	$134,975
Revenue	$165,319	$165,331	$164,749	$145,407	$145,442	$139,300
Supplier Balance	$9,381	$9,380	$9,359	$4,699	$4,675	$4,325

Figure 7 shows the breakdown of the balance generated by individual households for the utility with the anytime charging scenario.

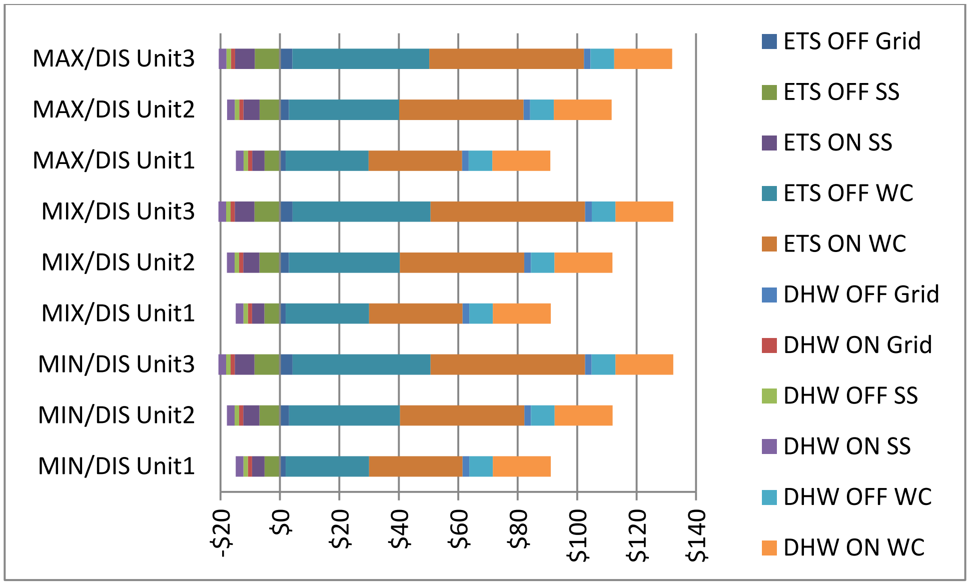

Figure 7: Breakdown of balance generated for individual households by anytime charging scenario (note: "unit" refers to household)

Although the net balance is positive, there are times when the price of electricity for the wind-heating program is subsidized, meaning the net balance is affected because the purchase cost is more than the sale price. These losses are between 14% and 15% and are shared between the ETS and DHW units, most often while charging from Summerside's wind-electricity but also when on-peak grid-electricity is drawn by the DHW units. Restricting the recharging of DHW units to the off-peak will affect their ability to deliver hot water to meet the household's hourly demand. Any variations in electricity pricing, the availability of wind, or heating demand could also affect the revenues generated. To assess the affordability criteria from the electricity supplier's standpoint, it is necessary to analyse individual monthly cash flows; for example, Table 16 shows the actual pricing structure for January 2011, while Table 17 shows the associated cash flows generated based on the same pricing structure.

Table 16: Electricity purchase cost and sale cost for January 2011 (Summerside Electric, 2011; Summerside Electric, 2010)

	Off-peak		**On-peak**	
	Cost	**Charge**	**Cost**	**Charge**
West Cape	$0.071	$0.080	$0.067	$0.080
Summerside	$0.082	$0.080	$0.082	$0.080
NB Power Grid	$0.085	$0.080	$0.098	$0.080

Table 17: January 2011 cash flow

	Anytime-charging scenario			**Off-peak charging scenario**		
	Min/DIS	**Mix/DIS**	**Max/DIS**	**Min/DIS**	**Mix/DIS**	**Max/DIS**
Cost	$22,623	$22,624	$22,494	$18,541	$18,541	$17,947
Revenue	$23,678	$23,679	$23,546	$18,505	$18,505	$17,891
Net Balance	$1,055	$1,055	$1,052	-$35.99	-$36.03	-$56.33

The off-peak charging scenario in January 2011 has a negative balance, indicating that the affordability criteria is compromised. Although the losses generated by one month can be compensated by the cumulative profit generated by other months, it is an indication that the off-peak charging scenario could jeopardize the overall energy security if similar conditions prevailed during other months. On the other hand, anytime charging has proven its effectiveness by using on-peak wind—which is available at a lower cost—to meet the demands and at the same time reduce grid-electricity demand and maximize the electricity supplier's net balance, placing Summerside in a more secure state.

Overall, in terms of affordability, a strategy could be adopted that would initially maximize revenues to pay back the capital cost incurred by the electricity supplier for the wind-heating program and then change based on individual months to maximize customer savings. To avoid potential losses in the revenue stream and to have a sustainable future, Summerside Electric should restructure its rate classes for residential users by matching wind production cost to sale cost and to consider anytime charging.

4.2.3 Emissions

Under the wind-heating program, Summerside's greenhouse gas emissions can be classified as indirect emissions, as there are no contributions to direct emissions (direct emissions include all pollution contributed directly and controlled by the producer or supplier, while indirect emissions include all emissions that result from the use or purchase of a product). The emission index for indirect emissions from purchased grid electricity and light fuel-oil are listed in Table 18.

Table 18: Indirect Emission Index (NB Power, 2009/10; Environment Canada, 2011)

Type	Value	Units
Light fuel oil	2.725	kg CO_2e/litre
Grid electricity	0.835	kg CO_2e/kWh

Figure 8 shows the combined annual greenhouse gas emission levels for anytime charging and off-peak charging. Emissions are calculated based on annual grid electricity usage required to recharge the ETS and DHW units and the oil backup needed to meet the heating demands; both are expressed in terms of the mass of CO_2e emitted. To assess the acceptability of the wind-heating system, the benchmark for greenhouse gas emission levels was taken as the emissions emitted by an oil-based system to meet the entire annual heating demand. The effectiveness of the wind-heating system is determined by the level of greenhouse gas reduction achieved. Using a furnace efficiency of 75% (Natural Resource Canada/Office of Energy Efficiency, 2008), the annual CO_2e emissions from all 100 households using oil-based heating systems was about 700,000 kg CO_2e. The shift from traditional oil-furnace heating system to the wind-electricity ETS-DHW heating system will improve Summerside's energy security in terms of acceptability from its current state by reducing total emission levels.

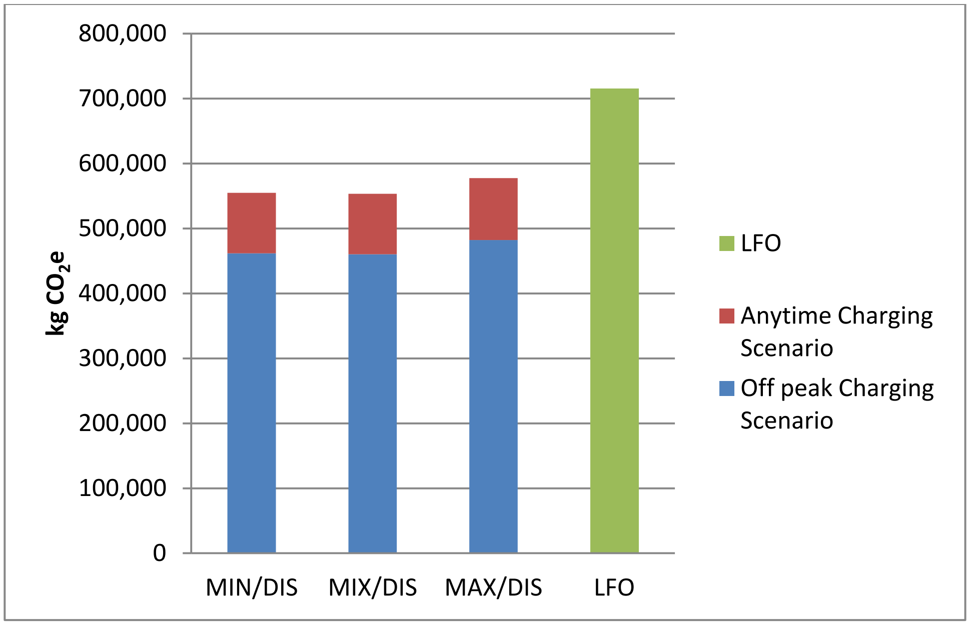

Figure 8: Combined Annual Emissions for all 100 participating households

From Figure 8, it can be seen that the annual emission of an household without the ETS and DHW system, i.e., only furnace heating system represented by LFO emissions, is higher than the households with ETS and DHW system incorporated. This shows that by allocating wind electricity effectively the emissions associated with wind heating is lower than the emissions associated using furnace oil alone.

From Table 19 it can be seen that emissions reduction in the off-peak charging scenarios is between 32% and 35% for the three different types of household, based on the annual heating loads and about 86% in the anytime charging scenario. A shift from off-peak charging to anytime charging puts Summerside in a more secure state. Although the overall acceptability is improved, the individual emission contributors, such as the emissions from using backup oil and emissions from using grid electricity, must be reduced to further improve energy security. The amount of CO_2e saved by the wind-heating system can be applied to carbon trading in order to generate additional revenue.

Table 19: Percentage of annual emission reduction

	MIN/DIS	MIX/DIS	MAX/DIS
Off-peak charging scenario	35.45%	35.64%	32.57%
Anytime charging scenario	86.96%	86.99%	86.68%

Figure 9, shows that the most significant contributor of emissions are the DHW units, ranging from 46% to 65%, depending upon the annual household heating load. The emission levels for the DHW systems are high, in part because no actual hot water usage profile was available and the DHW systems were programmed to meet the same, common demand profile each day of the year. Ideally, by managing individual hot water loads, the actual demands can be determined and the DHW units can be recharged based on wind availability and a known household profile, not on a single, commonly-applied hourly demand, thereby enhancing the wind-heating system's ability to work with the wind to reduce emission levels. Although the emission levels of ETS are much lower, they can be brought down further by increasing the storage capacity of the individual room heaters or restricting the space-heating source to a whole-house ETS furnace. Increased storage capacity improves the efficiency of the ETS system by storing more heat at times of high wind availability and avoiding the need to recharge during off-peak hours when no wind condition occurs, thereby reducing overall emission levels. In terms of environmental acceptability, Summerside's wind-heating is a marked improvement over traditional heating solutions; as a result, the city is positioning itself a step closer to achieving reduced carbon emissions and an improved energy security.

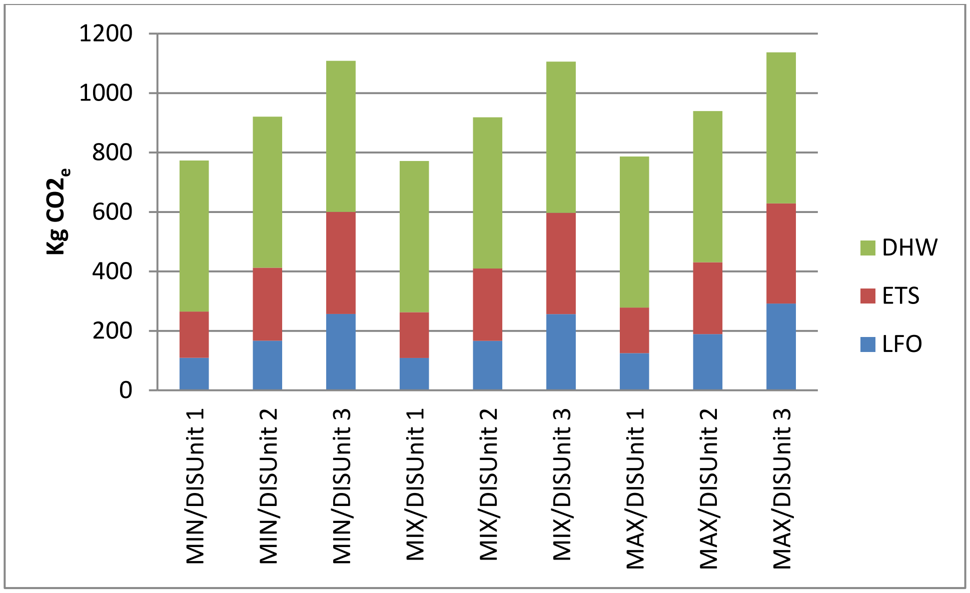

Figure 9: Individual emission contributors for anytime charging scenario

4.2.4 ETS vs. Non-ETS and Wind Usage

System reliability refers to the ability of an ETS unit to meet its household heating demand and the ability of the wind-heating program to match the unit's demand. From Table 20 it can be seen that under both scenarios, the ETS units were able to deliver and meet the heating demands demonstrating its reliability. Although the overall system reliability favors the wind-heating program, wind availability for the ETS system has to be considered as meeting heating demands with grid electricity reduces system reliability. Only about 3-4% of the available wind was used for wind-heating, suggesting a potential for expansion of the wind heating program and, by maximizing storage, making Summerside's energy security more favorable in terms of availability.

Table 20: Percentage for heating load met by ETS and Non-ETS

	Anytime-charging scenario			Off-Peak charging scenario		
	MIN/DIS	MIX/DIS	MAX/DIS	MIN/DIS	MIX/DIS	MAX/DIS
ETS	96.6%	96.7%	96.2%	80.7%	80.8%	75.9%
Non-ETS	3.3%	3.3%	3.8%	19.3%	19.2%	24.1%

4.3 Summary

This chapter presented the rationale for the selection of Summerside as a case study. It also discussed the current charging method currently used and the data required for the simulation. This chapter discusses the number of ETS and DHW units selected for the case study and also explains the different types of household and their heating load requirements. The results of the simulation were presented, based on customer cost, supplier balance, ETS vs. Non-ETS and Wind Usage. The rationale for improving a jurisdictions energy security in terms of availability, affordability and acceptability was discussed.

Chapter 5 DISCUSSION

The wind allocation methods proposed have helped in reducing a jurisdiction's dependency on imported energy sources (both refined petroleum products and electricity) by effective storage and efficient allocation of variable wind-electricity. From the results of the simulation it is clear that for the 100 ETS and 100 DHW systems only about 3-4% of the available wind electricity was used to meet the residential heating demands. The introduction of controllable electrical loads in the form of space and water heaters has allowed the wind allocation methods to exploit wind's variability effectively—adding flexibility to the system and allowing it to tap into the surplus wind-electricity generated that otherwise would be exported. With the assistance of smart-grid technology the wind allocation methods can be used to identify the heating demand requirements prior to the hour, and allocate only the required amount of wind electricity to meet this demand enabling effective control on the variable load.

For example, the simulation results show that under the existing off-peak scenario, revenues generated by the sale of the wind-electricity used for heating to NB Power (roughly 2.2% of the total wind-electricity generated) at $0.05/kWh would have been $69,000 per year, while the revenues generated by utilising this electricity to meet the heating demands of Summerside's pilot program would have been about $111,000. On the other hand, had the electricity used for heating in the anytime-charging scenario (about 3.2% of the total wind-electricity generated) not been used for heating, revenues generated by the sale of electricity to NB Power would have been about $98,000; however, by utilising wind-electricity to meet the heating demands, the annual revenues generated were about $158,000.

The benefits of the wind allocation methods are not limited to revenues: with the off-peak scenario, grid electricity consumption was 23.6%, while the anytime charging scenario used about 4.4%, meaning that, depending upon the source of grid-electricity, secondary greenhouse gas emissions associated with off-peak charging would be greater than those from anytime charging. With the proper wind allocation method, the wind electricity can be controlled and directed to meet the heating demands by storing when wind electricity is available thereby reducing emission levels.

Moreover, by utilising only 3.2% of the wind-electricity and with an annual surplus of 15% wind-electricity, the program can be extended to meet the heating demands of more households, without the need for an expansion of the wind farm or to incur any additional cost. Although it can be argued that the 3.2% of wind-electricity used for anytime wind-heating might not be purely from the surplus generated, with the help of the simulation and wind-forecasting tools, each hour's heating demand requirements and wind generation can be identified and with control strategies and allocation strategies put in place, a certain percentage of the wind-electricity generated can be directed to meet the heating demands, thereby effectively handling each hour's surplus wind-electricity.

The results from the simulation show that households using the wind-heating pilot program benefit from an annual savings of about 30% to 36% (compared to heating with light-fuel oil), with an estimated payback period ranging between 3.5 and 5.5 years and at the same time the utility generates a positive net revenue balance. The percentage of emissions reduction in the off-peak charging scenarios is between 32% and 35% for the three different types of household based on the annual heating loads and about 86% in the anytime-charging scenario. Heating demands satisfied by the wind-heating program ranges between 75% and 96% and total wind used for heating is between 3%-4% of Summerside's wind production for the 100 households. In short, the push from traditional oil-based heating systems to a more environmentally acceptable and affordable, wind-based heating system means that Summerside is positioning itself strategically for a more energy secure future. Overall the wind allocation methods has improved Summerside's energy security, by reducing customer cost, increasing utility revenues, reducing greenhouse gas emissions, and making ETS and DHW available to meet heating demands. The wind-heating program is proving instrumental in improving Summerside's residential energy security: by changing the energy required for space and water heating from a costly, fossil-based energy source (light-fuel oil) to a less expensive, more environmentally acceptable energy source (wind-electricity). The city has addressed the twin challenges of improving energy security and reducing greenhouse gas emissions by introducing ETS and DHW units, both controllable loads, to store wind-electricity to meet residential heating requirements when needed. By replacing part of the heating load with a more secure energy source and reducing back-up energy requirements, Summerside has not only improved its energy security in terms of availability, but also with respect to acceptability by lowering greenhouse gas emissions. The wind-heating program has proved its ability to bring down customer costs and at the same time increase electricity supplier revenues, thereby improving the affordability for both the customer and Summerside Electric.

Summerside's innovative approach to tapping into the surplus wind-electricity to meet its heating demands will reduce its reliance on fossil fuels and improve the revenues generated from the sale of electricity. As a co-benefit to the city, using wind-electricity will significantly reduce both primary and secondary greenhouse gas emissions from residential light-fuel oil consumption and NB Power's electrical generation, respectively. Summerside's wind-heating project will both improve the city's overall energy security and be an example for other jurisdictions to follow in the future.

Chapter 6 CONCLUDING REMARKS

Maintaining and improving energy security is essential in all jurisdictions, regardless of their size or location. However, energy depletion coupled with rising demand, environmental concerns related to energy, and unstable prices means that maintaining and improving energy security is becoming a greater challenge than in the past. In light of this, jurisdictions with limited domestic energy resources, such as those located on small islands, must develop novel policies to ensure economic and social wellbeing.

By examining a jurisdiction's different energy sources and services using the three indicators, availability, affordability, and acceptability, the current state and possible future states of energy security can be determined. With this information, policies can be developed to reduce energy consumption, replace an existing energy flow with one that is more secure, or find entirely new energy sources and processes to meet energy demand (restriction).

Worldwide, wind energy added to the energy mix of electricity suppliers is often seen as way of improving energy security and reducing greenhouse gas emissions. However, because of wind's variability, electricity suppliers face challenges incorporating it into their energy mix where on-demand services require a continuous supply of electricity. One solution to the variability problem is to adopt services that are capable of storing energy that can be used at a later time.

Given the need to address wind variability and energy security, the contribution of this thesis is the development of five new wind allocation methods (Minimum (MIN) recharge method, Maximum (MAX) recharge method, Mixture (MIX) recharge method, Discharge (DIS) recharge method and On-peak discharge method) that can be used to address the above two issues. Simulations were carried out for 100 ETS and 100 DHW systems under two scenarios namely; off-peak charging scenario and anytime charging scenario. Simulations conducted to study the methods show that each not only excels in maximizing the use of wind-electricity, lowering emissions, and reducing the need for backup energy, but also lowers customer heating costs and increases utility revenues.

To tie in with one of the secondary objectives which is to apply the developed methods to the Summerside Smart Grid program and analyse the effects of energy security in terms of availability of the wind heating program to meet the heating demands, affordability of the wind heating program and the acceptability of the wind heating program. The simulation results show that the wind allocation methods maximized the use of wind electricity by effectively allocating to the ETS and DHW systems to meet the heating demands, that households using the wind-heating pilot program benefit from an annual savings of about 30% to 36%, improving overall affordability. The wind allocation methods demonstrate that by effective allocation, the percentage of emissions reduction in the off-peak charging scenarios is between 32% and 35% and about 86% in the anytime-charging scenario, improving overall acceptability. Heating demands satisfied by the wind-heating program ranges between 75% and 96% and total wind used for heating is between 3%-4% of Summerside’s wind production for the 100 households. Overall the wind allocation methods have improved Summerside's energy security, by reducing customer cost, increasing utility revenues, reducing greenhouse gas emissions, and making ETS and DHW available to meet heating demands.

The availability of wind-electricity and the use of wind allocation methods as illustrated by the Summerside wind-heating project, have been instrumental in a number of ways. First, it demonstrates the practicality and functionality of wind-heating. Second, it demonstrates by effectively using wind electricity to meet residential heating demands, energy security can be improved in terms energy availability, energy affordability, and environmental acceptability. Third, over the longer-term, Summerside could expand the program to include space and water heating in other sectors, such as commercial and institutional, industrial, and public administration.

The work presented in this thesis showed that wind allocation methods not only have the potential to control variable load effectively but also improve a jurisdiction's energy security.

6.1 Recommendations

The following are a set of recommendations to improve the overall effectiveness of Summerside’s wind-heating program:

- Replace the existing off-peak charging scenario with the anytime charging scenario.
- Encourage the use of ETS furnace heaters rather than room heaters as furnaces offer more energy storage, reduce the need for grid-electricity, and are an effective load control and balancing technique for dumping excess wind-electricity.
- Increase the supply of wind-electricity to meet additional heating demand.

6.2 Limitations

The following limitations need to be considered when implementing the proposed methods:

- The results of the simulation are location specific.
- Transmission or distribution losses associated with the generation of wind or grid-electricity was not considered.
- The price of wind and grid electricity was subsidized; the outcome may vary with a different price structure.
- All ETS considered in the analysis were room heaters.

6.3 Future Work

This thesis shows the potential of storing wind electricity and using it to meet the heating demands can improve a jurisdiction's energy security. Further research work can be carried out to enhance the system:

- Develop and implement communication protocols between the wind heating system and the backup system in each household.
- Develop and implement control strategies to interconnect the wind farm, the smart grid, and the heating systems.

- Expand the wind heating program to create additional service loads that could be met with surplus wind-electricity; for example, space-cooling during the non-heating season.

6.4 Publications

The work presented in this thesis is based on a report "Improving energy security on a small island: Space heating and Prince Edward Island" developed in late 2011 for the City of Summerside by Dr. Larry Hughes (Dalhousie University) and the author as an analysis of Summerside's wind-heating program. The report was subsequently accepted by Federation of Canadian Municipalities (FCM) under the Green Municipality Fund (the funders of the wind-heating project).

This thesis was also submitted as a paper "Improving energy security on a small island: Space heating and Prince Edward Island " to the Small Island Journal in June 2012 and has been accepted.

This thesis was also submitted as a conference paper "Improving energy security and reducing greenhouse gas emissions using wind-electricity and storage heaters" to the International Renewable Energy Storage in November 2012, Berlin and has been accepted.

Bibliography

Anderson, D., & Leach, M. (2004). Harvesting and redistributing renewable energy: on the role of gas and electricity grids to overcome intermittency through the generation and storage of hydrogen. *Energy Policy*, pp. 1603–1614. doi:10.1016/S0301-4215(03)00131-9

Apergis, N., Payne, J. E., Menyah, K., & Wolde-Rufael, Y. (2010, June 12). On the causal dynamics between emissions, nuclear energy, renewable energy, and economic growth. *Ecological Economics*, pp. 2255-2260. doi:10.1016/j.ecolecon.2010.06.014

Asif, M., & Muneer, T. (2005, 12 19). Energy supply, its demand and security issues for developed and emerging economies. *Renewable and Sustainable energy Reviews*, pp. 1388-1413.

Baker, J. (2008). New technology and possible advances in energy storage. *Energy Policy*, pp. 4368–4373. doi:10.1016/j.enpol.2008.09.040

Biaoua, A., & Bernie, M. (2008, April). Achieving total domestic hot water production with renewable energy. *Building and Environment, 43*(4), pp. 651-660.

Blarke, M. B. (2008, July). The effectiveness of storage and relocation options in renewable. *Renewable Energy, 33*(7), pp. 1499-1507.

BP. (2012). *BP Statistical Review of World Energy.*

Carlin, P. W., Laxson, A. S., & Muljadi, E. B. (2003). The History and State of the Art of Variable-Speed Wind Turbine Technology. *Wind Energy, 6*, 129–159.

Chen, H., Cong, T. N., Yang, W., Tan, C., Li, Y., & Ding, Y. (2008, July 2). Progress in electrical energy storage system: A critical review. *Progress in electrical energy storage system: A critical review*, pp. 291–312. doi:10.1016/j.pnsc.2008.07.014

City of Summerside. (2010). *16th Annual Report.* Summerside.

City of Summerside. (2011). *2010 Annual Report.* Summerside: City of Summerside.

Clastres, C. (2011, June 23). Smart Grids: Another step towards competition, energy security and climate change objectives. *Energy Policy*, pp. 5399–5408. doi:10.1016/j.enpol.2011.05.024

Connolly, D., Lund, H., Mathiesen, & Leahy, M. (2009, Oct). A review of computer tools for analysing the integration of renewable energy into various energy systems. *Applied Energy, 87*(4).

EIA. (2011b). *International Energy Outlook.* Washington, DC: U.S. Energy Information Administration (EIA).

Environment Canada. (2011, 06 23). *Emission Factors from Canada's GHG Inventory-Fuel Combustion*. Retrieved 08 01, 2011, from Environment Canada: http://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=AC2B7641-1

Environment Canada. (2011). *Fuel Combustion*. Retrieved 07 01, 2011, from Environment Canada: http://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=AC2B7641-1

Environment Canada. (2011). *Hourly Data Report*. Retrieved 06 01, 2011, from National Climate Data and Information Archive: www.climate.weatheroffice.gc.ca

EPA. (2012, March 14). *Climate Change - Greenhouse Gas Emissions*. Retrieved April 20, 2012, from United Sates Environmental Protection Agency: http://www.epa.gov/climatechange/ghgemissions/index.html

Global challenges in energy. (2005, May 17). *Energy Policy*, pp. 1984–1991.

Goldemberg, J. (2004). The Case For Renewable Energies. *Secretariat of the International Conference for Renewable Energies.* Bonn. Retrieved from www.renewables2004.de

Hledik, R. (2009, March 28). How Green Is the Smart Grid? *The Electricity Journal*, pp. 29-41.

Hughes, L. (2009, Nov 26). Meeting residential space heating demand with wind generated electricity. *Renewable Energy*, 1765–1772. doi:10.1016/j.renene.2009.11.014

Hughes, L. (2009). The four 'R's of energy security. *Energy Policy*, pp. 2459-2461. doi:doi:10.1016/j.enpol.2009.02.038

Hughes, L. (2010b, April). The technical potential for off-peak electricity to serve as backup in wind-electric thermal storage systems. *International Journal of Green Energy*, pp. 181 — 193.

Hughes, L. (2011). A generic framework for the description and analysis of energy security in an energy system. *Energy Policy, 42*, pp. 221-231. doi:doi:10.1016/j.enpol.2011.11.079

Hughes, L., Dhaliwal, M., Long, A., & Sheth, N. (2006). A Study of Wind Energy Use for Space Heating in Prince Edward Island. *Second International Green Energy Conference (IGEC).* Ontario.

Ibrahim, H., Ilinca, A., & Perronb, J. (2008). Energy storage systems—Characteristics and comparisons. *Renewable and Sustainable Energy Reviews, 12*(5), 1221-1250.

IEA. (2009). *World Energy Outlook.* Paris, France.

IEA. (2010). *Energy Security*. Retrieved 12 27, 2010, from International Energy Agency: http://www.iea.org/subjectqueries/keyresult.asp?KEYWORD_ID=4103

IEA. (2011). *Measuring short Term Energy Security.* Retrieved from http://www.iea.org/papers/2011/Moses.pdf

IEA. (2011). *World Energy Outlook 2011.* Paris: International Energy Agency.

IEA. (2011a). *Key World Energy Statistics 2011.* Paris: International Energy Agency.

IEA. (2011a). *World Energy Outlook.* Paris: International Energy Agency.

IEA. (2011b). *World Energy Outlook 2011.* Paris: International Energy Agency.

IEA. (2012). *Energy Security*. Retrieved 02 14, 2012, from International Energy Agency: http://www.iea.org/subjectqueries/keyresult.asp?KEYWORD_ID=4103

IRAC. (2011, 03 15). Retrieved 07 01, 2011, from Regulatory and Appeals Commission: http://www.irac.pe.ca/

IRAC. (2011, March 15). *Petroleum Pricing Notice.* Retrieved 08 01, 2011, from Regulatory and Appeals Commission: http://www.irac.pe.ca/document.aspx?file=petrol/currentprices.asp

Jacobson, M. Z. (2008, Oct 31). Review of solutions to global warming, air pollution, and energy security. *The Royal Society of Chemistry*. doi:10.1039/b809990c

Jacobson, M. Z., & Delucchi, M. A. (2009). *A Path to Sustainable Energy by 2030.* Scientific American. Retrieved from Scientific American: http://www.sciamdigital.com/index.cfm?fa=Products.ViewIssuePreview&ARTICLEID_CHAR=7232617C-237D-9F22-E8D11BD75EC6B0D5

Kempton, W., & Dhanju, A. (2006). *Electric Vehicles with V2G*. Retrieved November 12, 2011, from University of Delaware: http://www.udel.edu/V2G/docs/KemptonDhanju06-V2G-Wind.pdf

Krewitt, W., Teske, S., Simon, S., Thomas, P., Graus, W., Blomen, E., . . . OliverSchafe. (2009, Aug 20). Energy [R]evolution2008—a sustainable world energy perspective. *Energy Policy*, pp. 5764–5775. doi:10.1016/j.enpol.2009.08.042

Lee, C., & Lam, H. (2007, Aug 22). Computer simulation of borehole ground heat exchangers for geothermal heat pump systems. *Renewable Energy*, pp. 1286–1296. doi:10.1016/j.renene.2007.07.006

Lund, H. (2007). Renewable energy strategies for sustainable development. *Energy*, pp. 912–919. doi:10.1016/j.energy.2006.10.017

Marathon water heaters. (2011). *Product Specification.* Retrieved 07 01, 2011, from Marathon water heaters: http://www.marathonheaters.com/cons_specs.html

Moslehi, K., & Kumar, R. (2010). A Reliability Perspective of the Smart Grid. *IEEE TRANSACTIONS ON SMART GRID, 1*(1).

Natural Resource Canada/ Office of Energy Efficiency-B. (n.d.). *Energy Efficiency - Product Model Listings*. Retrieved 07 01, 2011, from Natural Resource Canada: http://oee.nrcan.gc.ca/pml-lmp/index.cfm?action=app.welcome-bienvenue&attr=0

Natural Resource Canada/Office of Energy Efficiency. (2008, 12 12). *Typical seasonal efficiencies of heating systems*. Retrieved 8 01, 2011, from Natural Resource Canada: http://www.retscreen.net/ang/typical_seasonal_efficiencies_of_heating_systems_image.php

Natural Resource Canada/Office of Energy Efficiency. (2011). *Comprehensive Energy Use Database, 1990 to 2009*. Retrieved 06 01, 2011, from NRCan- Office of Energy Efficiency: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/comprehensive_tables/list.cfm?attr=0

NBPower.(2009/10). *Sustainability Report.* http://www.nbpower.com/html/en/about/publications/annual/2009-10AR-ENG.pdf

NB Power. (2010). *Sustainability Report 2009/10.* Retrieved from http://www.nbpower.com/html/en/about/publications/annual/2009-10AR-ENG.pdf

NRCan. (2012). *Heating Project Load and Energy Calculation*. Retrieved March 10, 2012, from Natural Resource Canada: http://www.retscreen.net/ang/heating_project_load_and_energy_calculation.php

Omer, A. M. (2006, may 24). Green energies and the environment. *Renewable and Sustainable Energy Reviews*, pp. 1789–1821. doi:10.1016/j.rser.2006.05.009

Perlman, M., & Mills, B. (1985). Development of residential hot water use patterns. *ASHRAE transactions, 91 (part2A)*, pp. 657-679.

PeterJ.Hall. (2008 15-Oct). Energy storage: The route to liberation from the fossil fuel economy *Energy Policy*, pp. 4363–4367. doi:10.1016/j.enpol.2008.09.041

Potter, C. W., Archambault, A., & Westrick, K. (2009). Building a smarter smart grid through better renewable energy information. *Power Systems Conference and Exposition.*

Rahimi, F., & Ipakchi, A. (2010, June). Demand response as a market resource under the smart grid paradigm. *IEEE Transactions on Smart Grid*, 82-88. doi:10.1109/TSG.2010.2045906

Saidur, R., Islam, M., Rahim, N., & Solangi, K. (2010, March 2). A review on global wind energy policy. *Renewable and Sustainable Energy Reviews*. doi:10.1016/j.rser.2010.03.007

Sioshansi, F. P. (2011, November 26). So What's So Smart about the Smart Grid? *The Electricity Journal*, pp. 91–99.

SKRECC. (2009). *Electric Thermal Storage*. Retrieved 10 10, 2011, from South Kentucky Rural Electric Cooperative Corporation: http://www.skrecc.com/ets.htm

Sovacool, B. K. (2008 16-July). The intermittency of wind, solar, and renewable electricity generators: Technical barrier or rhetorical excuse? *Utilities Policy*, pp. 288–296. doi:10.1016/j.jup.2008.07.001

Steffes Corporation. (2011). *Technical Data Sheet.* Retrieved 07 01, 2011, from Steffes Corporation: http://www.steffes.com/downloads/2100_tech_data_sheet.pdf

Summerside Electric. (2006). *Power purchase agreement (WEST CAPE WIND ENERGY INC and THE CITY OF SUMMERSIDE).*

Summerside Electric. (2010). *Energy purchase agreement (NB POWER and THE CITY OF SUMMERSIDE).*

Summerside Electric. (2011). *2011 power sales and purchase forecast.* Summerside.

Summerside Electric. (2011). *Electric Pricing Single Heater & Water Heater Comparison.* Summerside: Summerside Electric.

Summerside Electric. (2011). *Summerside numbers for research 2010-Aug2011.* Summerside.

Summerside Electric. (2011A). *RSP Manual.*

Summerside Electric. (2011A). *RSP Manual.* Summerside.

Summerside Electric. (2011B). *Power Purchase Agreement-NB power.* Summerside.

Summerside Electric. (2011C). *Power Purchase Agreement Summerside and West Cape.* Summerside.

Verrastro, F., & Ladislaw, S. (2010, January 05). Providing Energy Security in an Interdependent World. *The Washington Quarterly*, pp. 95-104.

Vriesa, B. J., Vuuren, D. P., & Hoogwijk, M. M. (2006, Nov 15). Renewable energy sources: Their global potential for the first-half of the 21st century at a global level: An integrated approach. *Energy Policy*, pp. 2590–2610. doi:10.1016/j.enpol.2006.09.002

World Bank. (2005). *Energy Security Issues.* Moscow-Washington: World Bank.

WWEA. (2011). *World Wind Energy Report 2010.* Bonn, Germany: World Wind Energy Association.