PERFORMANCE ANALYSIS OF A RESIDENTIAL, WIND-ENERGY THERMAL STORAGE SYSTEM

by

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The undersigned hereby certify that they have read and recommend to the Faculty of Graduate Studies for acceptance a thesis entitled “Performance Analysis of a Residential, Wind-Energy Thermal Storage System” by James Parsons in partial fulfilment of the requirements for the degree of Master of Applied Science.

Dated: September 1, 2011

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Dedication

First of all, I would like to thank my supervisor Dr. Larry Hughes for his commitment to learning along with his considerable knowledge, passion and enthusiasm for energy research engineering. I owe him a debt gratitude for his role in my significant learning. Thank you as well to Dalhousie University and the former TUNS; I continue to be a proud alumnus. I would like to thank my committee members to Dr. Peter Gregson and Dr. Robert Bauer for their support with this thesis. Thank you to the Department of Electrical and Computer Engineering and the Faculty of Graduate Studies.

I am honoured to have had the opportunity to work with the current and former members of the Dalhousie Energy Research Group: Alain Joseph, Mandeep Dhaliwal, Nikita Sheth, Tylor Woods, Andrew Barnes, Dave Ron, Anirudh Muralidhar, Jacinda Rudolph, Harisubramanian Lakshminarayanan, Shanmuga Sundaram, Vinay Kumar, Ashish Ranjan and Nikhil Chowdry. I thank them for their contributions.

I would like to thank my colleagues at the Nova Scotia Community College for their encouragement and support.

To my family... I dedicate this work.

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Abstract

Wind-generated electricity is presented as a means to reduce anthropogenic greenhouse gas emissions and improve a region's energy security. The variable nature of wind-electricity means that electricity providers face challenges when trying to incorporate it to meet the service requirements of on-demand electricity. In the residential sector in a northern country like Canada, the largest and most important energy demand is in the heating service.

In regions where there is a good wind regime, much of their energy needs could be met with wind. Newspaper headlines read that a given new wind farm installation will produce enough electricity to power thousands of homes. The important temporal factor is excluded from these calculations. The moment electricity from wind is available does not always correspond to when energy is required—an energy storage mechanism is needed to address this problem. This thesis addresses the question of the degree to which electricity produced from wind and employing thermal storage using commercially available electric hot water tanks can meet the demand for both space heating and domestic hot water in the residential sector. Maximizing usage of a renewable wind resource will result in both reduced greenhouse gas emissions and improved energy security for that region.

List of Abbreviations Used

ETS	Electric Thermal Storage
GHG	Greenhouse Gas
WEC	World Energy Council
CO_2	Carbon Dioxide
MW	Megawatt
MWh	Megawatt-Hour
kW	Kilowatt
kWh	Kilowatt-Hour
GW	Gigawatt
km	Kilometer
GWh	Gigawatt-Hour
kV	Kilovolt
kJ	Kilojoule
MJ	Megajoule
GJ	Gigajoule
PJ	Petajoule

A	Ampere
1° energy	Primary Energy
2° energy	Secondary Energy
3° energy	Tertiary Energy
IEA	International Energy Agency
UK	United Kingdom
CSA	Canadian Standards Association
DHW	Domestic Hot Water
NRCan	Department Of Natural Resources Canada
CO_2e	Carbon Dioxide Equivalent
DES	Distributed Energy Storage
TES	Thermal Energy Storage
ASHRAE	American Society Of Heating, Refrigerating, And Air-Conditioning Engineers,
PCM	Phase Change Materials
EPRI	Electric Power Systems Research Institute
DSM	Demand-Side Management

APERC	Asia-Pacific Energy Research Council
PHPS	Pumped Hydropower Storage
CAES	Compressed Air Energy Storage
LOS	Level of Service
LOU	Level of Utilization
°C	Degrees Celsius
HDH	Heating Degree Hours
SHS	Sensible Heat Storage
HDY	Heating Degree Year
HVAC	Heating Ventilation and Air Conditioning
NS	Nova Scotia
PE	Prince Edward Island
PEIEC	Prince Edward Island Energy Corporation

Chapter 1 Introduction

Two of the most significant energy challenges facing humanity in the twenty-first century will be climate change and energy security. Anthropogenic greenhouse gas emissions (GHG) from the extensive use of fossil fuels [**1**] are believed to be contributing to climate change [**2**] and ocean acidification [**3**]. According to a World Energy Council report in 2007, the energy sector is largely responsible for the world's GHG emissions. With the connection between GHG emissions and climate change established, energy is increasingly becoming the centre of the climate change debate [**4**]. These challenges are forcing some politicians and policymakers to reconsider how energy is used in their jurisdictions.

Energy security is defined as "the uninterrupted physical availability [of energy] at a price which is affordable, while respecting environment concerns" [**5**]. In 2007, Canada produced a little over 1 billion barrels of crude oil; most of this was exported to the United States, requiring Canada to import crude oil. Almost all of Canada's oil imports are destined for Ontario, Quebec, and Atlantic Canada. These provinces obtain about 72 percent of their oil from a variety of exporting nations. As supplies from major exporters (notably the U.K. and Norway) decline, they are being replaced by supplies from other, less secure exporters (such as Algeria and Angola). With offshore Newfoundland and Labrador's production in decline and no significant pipelines from western Canada to Quebec and Atlantic Canada, reliance on potentially insecure oil suppliers (and a subsequent decrease in energy security) is all but certain to increase[**6**]. One of the ways an improvement to a jurisdiction's energy security can occur is if imported supplies of carbon-intensive fuel sources are replaced by local and renewable sources such as wind, biomass and solar[**4**].

Renewable energy resources such as wind, hydro, biomass, solar and tidal are expected to play a large part in mitigating the problems of greenhouse gas emissions and in improving a region's energy security [**7**]. For example, the province of Nova Scotia appears ready to take these challenges seriously; the most recent announcement by government concerning implementation of renewable resources has Nova Scotia aiming for 40 percent of the province's electricity from renewable sources by 2020. The largest share of that is set to come from wind generation; more than 60 percent of the new electricity to come online will be from wind[**7**].

1.1 Energy Use and Greenhouse Gas Emissions in Canada

In the residential sector in a northern country like Canada, the biggest energy demand is in the heating service; both space heating and domestic hot water heating. Figure 1.1 shows that more than 80 percent of energy use in the residential sector in Canada is for heating.

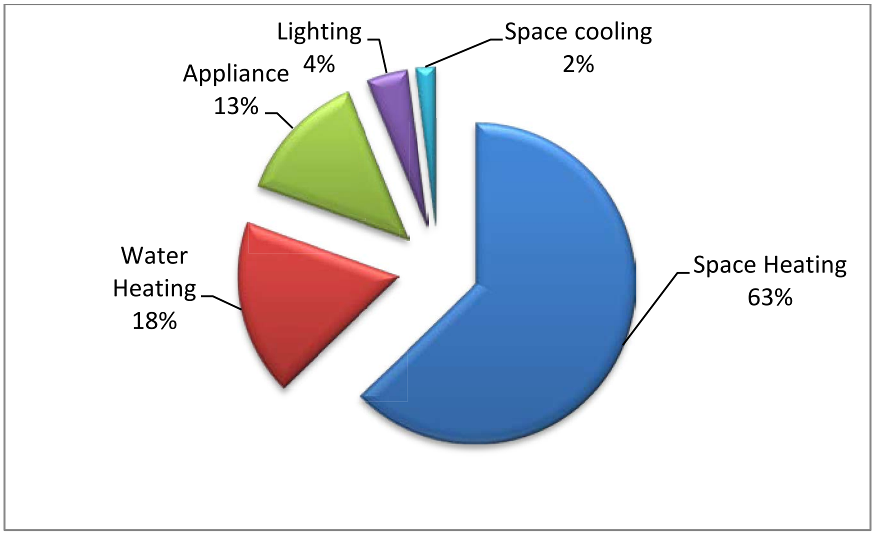

Figure 1.1: Secondary Energy End-Use in the Residential Sector in Canada [8]

The 2008 statistics shown in Figure 1.2 reveal that 12 percent of the total energy used is in the residential sector [**9**]. In 2008, 920 PJ were used for space heating and 256 PJ for water heating [**9**].

In 2008, Canada's greenhouse gas emissions were estimated to be 45.5 Mt of CO_2e for space heating and 13.1 Mt of CO_2e for water heating making up about 8 percent of the total GHG emissions [**8**].

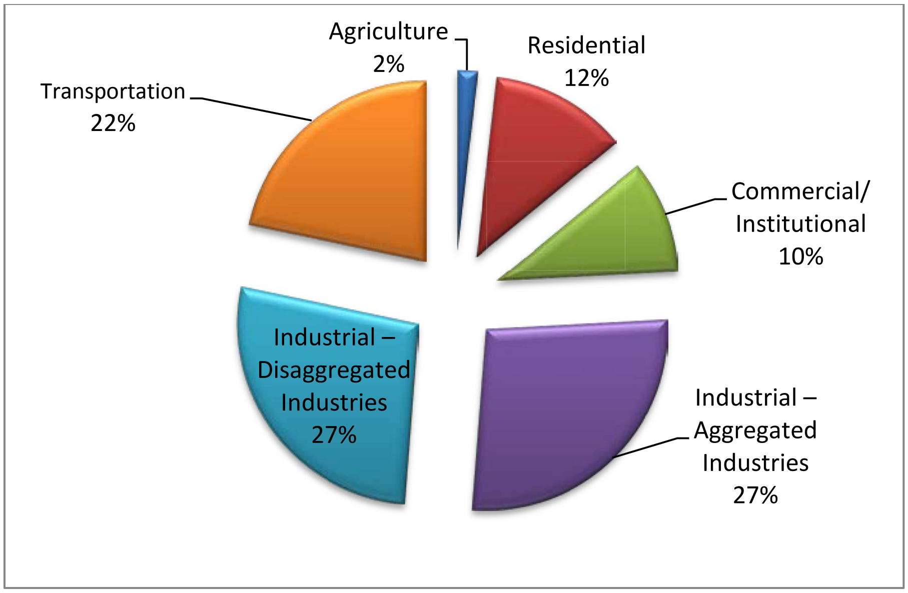

Figure 1.2: Energy Use by Sector in Canada in 2008 [8]

In terms of where those emissions are coming from in the residential sector, Figure 1.3 and Figure 1.4 show that the majority of it comes from fossil fuels such as natural gas and heating oil. Electricity for space heating and water heating may come from coal-fired or other fossil fuel based generation as well.

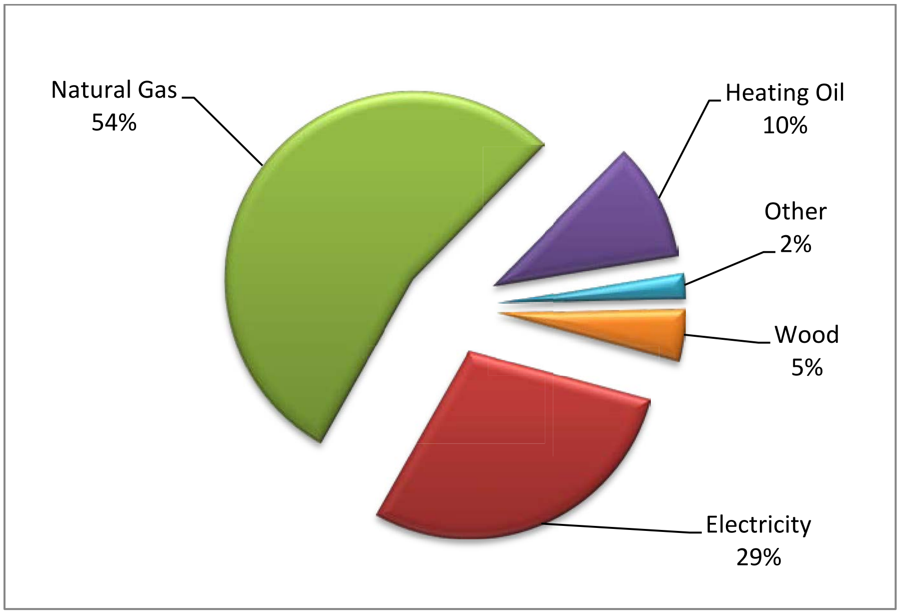

Figure 1.3: GHG Emissions by Energy Source (Mt of CO_2e) for Space Heating in the Residential Sector in Canada [8]

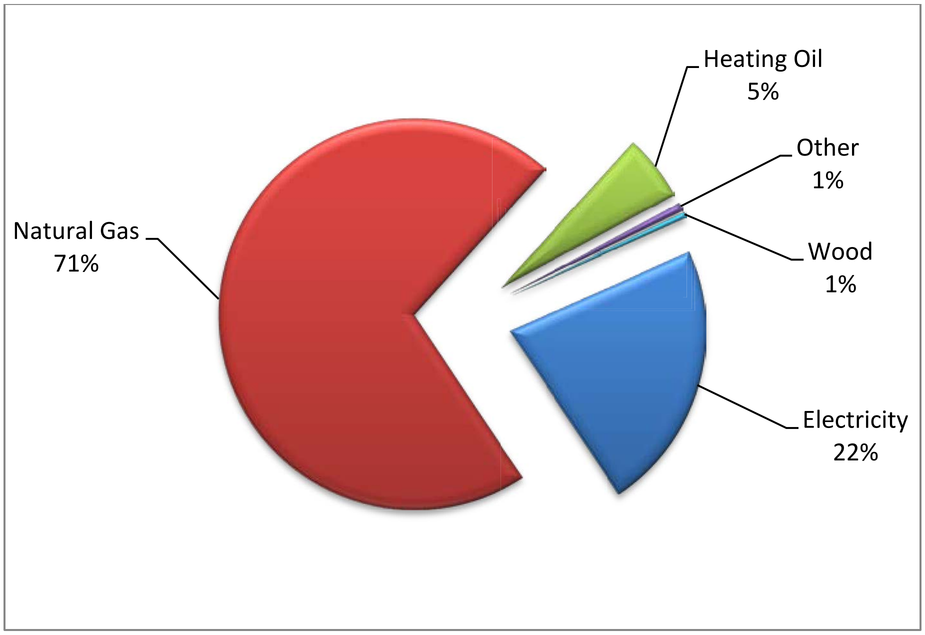

Figure 1.4: GHG Emissions by Energy Source (Mt of Co_2e) for Water Heating in the Residential Sector in Canada[8]

1.2 Renewable Energy Resources in Canada

Renewable energy sources currently meet approximately 14 percent of energy demands world-wide [**10**]. Renewable energy sources currently provide about 16 percent of Canada's total primary energy supply, making Canada one of the leaders in the production and use of energy from renewable sources. According to Natural Resources Canada, "Canada, with its large landmass and diversified geography, has substantial renewable resources that can be used to produce energy; these resources include moving water, biomass, wind, solar, geothermal and ocean energy. Moving water is the most important renewable energy source in Canada, providing about 59 percent of Canada's electricity. Some provinces generate more than 90 percent of their electricity demands from hydroelectricity. In fact, Canada is the second largest producer of hydroelectricity in the world. Biomass is the second most important renewable energy source in Canada. The primary types of bio-energy include electricity and industrial heat from wood waste, space heating from firewood, and bio-fuels from agricultural crops. While they are emerging sources, wind and solar energy are experiencing high growth rates" [**11**].

Worldwide, wind-electricity has experienced a rapid growth; by the end of 2007 Canada had a total installed capacity of 1,846 MW from 1,400 wind turbines. The graph of Figure 1.5 shows the increase in installed wind power capacity in Canada since 1997.

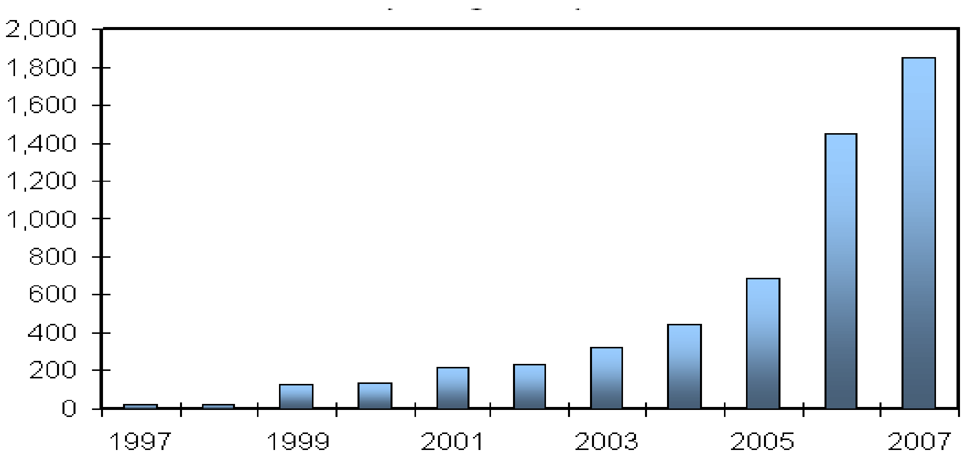

Figure 1.5: Installed Wind Power Capacity in Canada[11]

Where some hydro-endowed provinces are getting much of their energy needs from hydro, it makes sense that in regions where there is a good wind regime, such as Prince Edward Island and Nova Scotia in the eastern region of Canada, much of their energy needs could be met also with wind. The map of Figure 1.6 shows that the eastern region of Canada exhibits a particularly good wind regime (shown in red and violet).

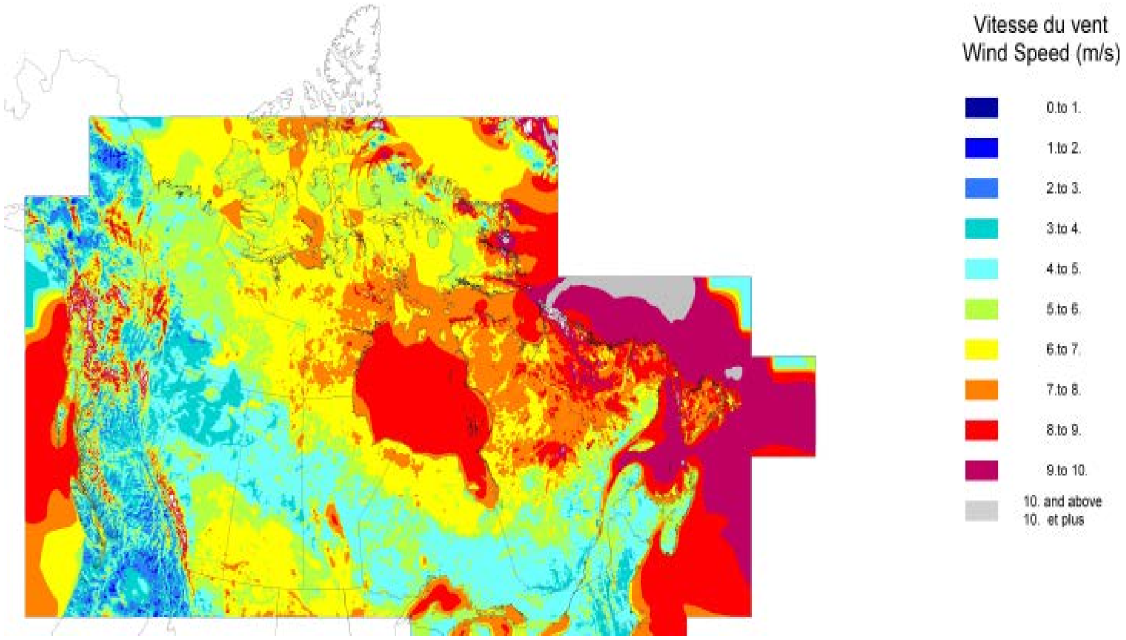

Figure 1.6: Mean Wind Speed at 50m above Ground[12]

Many see the large-scale adoption of wind-generated electricity as a way to reduce greenhouse gas emissions and improve energy security. Aside from the manufacturing and installation, wind turbines do not burn CO_2-emitting fossil fuels whilst in operation. Wind farms are typically located in the same jurisdiction where the wind-electricity is consumed. However, wind-electricity is variable, meaning that electricity providers face challenges when using it to meet the service requirements of an on-demand electricity supply.

1.3 Problem Description

Electricity systems require steady, reliable supply, with the ability to respond to fairly predictable changes in demand over the period of a day including, to a much lesser degree, random fluctuations minute-by-minute. Renewables are a disruptive factor in this and stress the balance of the electricity system, including both generation and distribution elements [**13**]. On the demand side, the need for energy cannot always coincide with the energy's availability. If the supply of wind-electricity suddenly becomes available through the overnight hours when demand is low, the maximum use of a supply of renewable energy is not achieved if there is no demand for it.

In northern countries like Canada, the need for heating in the residential sector is obviously important. In regions where there is limited connectedness with the North American energy supply chain, the reliance on energy insecure sources presents a problem. In jurisdictions with significant heating seasons, the loss of access to secure sources of energy to meet the heating needs of, for example, the residential and commercial sectors can have considerable impact on both the populace and the economy. The benefits of such an approach to meet the heating needs of a jurisdiction include the improved energy security of local generation; reduced greenhouse gas emissions from fuel oil; and a reduction in surplus intermittent electricity from the wind[**14**].

In general, if the problems of climate change and energy security are going to be mitigated by addressing energy concerns in the residential sector with energy produced from a renewable resource such as wind, it makes sense to go after the biggest and arguably the most important energy service in the residential sector first, namely heating. The problem this research attempted to address is how to make energy produced from wind available for use in the residential sector for the heating service. This thesis will present a straight forward solution along with the relevant analysis to determine how well a system which is powered by electricity from wind and employing thermal storage for heating in the residential sector might perform.

Newspaper headlines read that a given new wind farm installation will produce enough electricity to power thousands of homes. How are these figures arrived at? It appears to be a straight-forward calculation using the amount of energy produced (power rating times hours in service times capacity factor) divided by the average household energy consumption. The important temporal factor is excluded from these calculations. The moment electricity from wind is available does not always correspond to when energy is required. A mechanism is needed to address this problem.

1.4 Addressing the Problem

One way the problem can be addressed is to have demand follow supply; in other words to have an energy sink (in the form of an energy store) available to consume the energy when the source is producing. Figure 1.7 (left) shows how typically an energy source such as a power generating facility supplies (electrical) energy directly to the end user. The Figure 1.7 also shows (right) that when storage is integrated, the energy source supplies energy indirectly to the end user. The energy source supplies the energy store. In turn, the energy end-user then consumes energy from the energy store and not directly from the energy source or energy supplier. It is possible that the energy source is supplying energy at the same time or at a different time that the end user wants to consume it. The store creates the illusion of a temporal shift of when the production actually occurred thus allowing the supply to satisfy the demand without requiring that the two be coincident.

When a variable energy source such as wind is the source of energy, the effect of the temporal element of energy availability is taken out of the problem. The energy store means that the energy supply (in the energy source) and the energy demand (in the energy end-users) can occur at different times. With the energy source feeding the energy store, and provided the energy store is of sufficient size to absorb the energy being produced, demand can follow supply.

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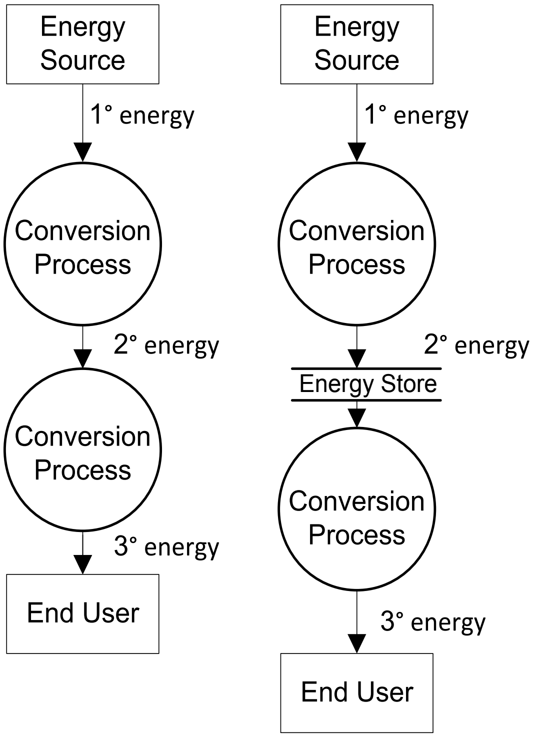


Figure 1.7: Energy Chains Without (Left) and With (Right) Storage

In large part, the size of the energy store determines the degree to which energy produced can be absorbed by the store and to what degree the store can be relied upon for energy when demanded.

1.5 Decentralized Energy Storage

Decentralized or distributed energy storage (DES) is defined as energy stored at (or closer to) the point where it will be consumed rather than at the source. This is expected to play an important synergistic role in buildings using renewable generation technologies [**15**]. Figure 1.8 shows the difference between local storage (right) and distributed storage (left). In both cases the end-user can call upon the store for energy needs. The large local store (right) tends to be comparatively inefficient and expensive. With distributed storage, shown in Figure 1.8 (left), smaller, comparatively more efficient and less costly distributed storage shows how each end user (or small group of end-users) utilize the energy. Energy stored as heat using residential electric-thermal storage units is an example of the latter technique.

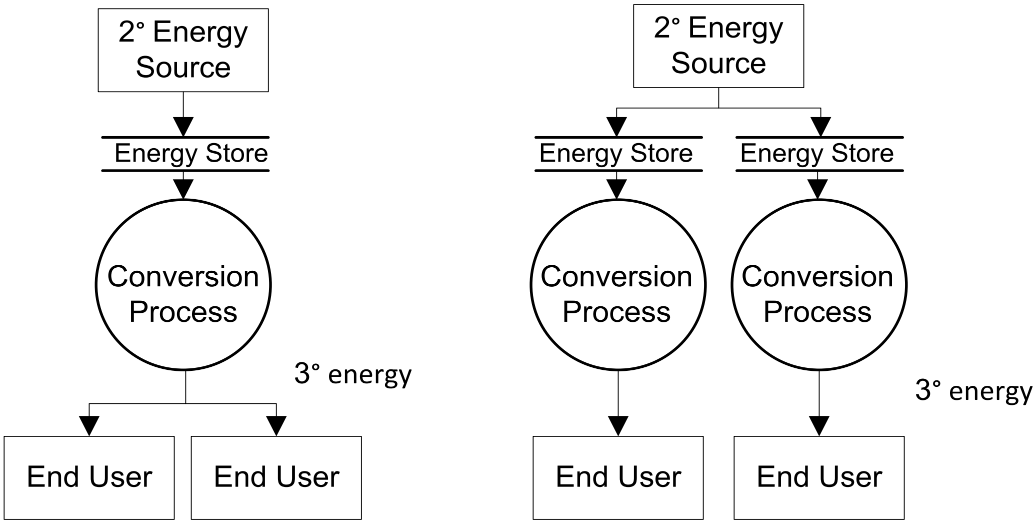


Figure 1.8: Local (Right) vs. Distributed (Left) Storage

1.6 Thesis Objectives

This research examines the degree to which a system employing distributed thermal storage in commercially available electric hot water tanks and powered by electricity from wind could provide for the largest energy service (heating) in the residential sector. The answer to the questions of how many homes can be serviced under this system, how well this system can provide heating in the residential sector without calling on external energy sources (such as on-demand electricity from the grid for backup) and how well the wind resource is utilized under this system will be addressed.

Employing decentralized storage of thermal energy in water, the solution presented is expected to be an efficient, completely scalable and low-cost solution to the problem posed. This solution addresses some of the shortcomings of the other systems in that it is of lower cost, potentially straight-forward to implement by a do-it-yourselfer and can integrate into existing residential building heating infrastructure. The system may prove to be able to be relied upon for long term space heating and domestic hot water needs. The system will act in place of an existing hydronic heating furnace and does not intrude into or displace the living area of the dwelling the way that thermal storage space heaters do. The energy delivered is converted to heat and extracted as required to fulfill the space heating and domestic hot water needs of the residents.

1.6.1 Supporting Thesis Objectives

In support of the main objective, the following will also be considered:

- The maximum number of houses that could be supported under this system
- The percentage of the total household demand for these two energy services this system could support at a prescribed level of service.
- The number of houses (if any) that could be supported at 100%
- The maximum level of utilization of the available wind electricity
- The optimal storage (tank) size
- The optimal energy throughput
- To determine the cost of this solution
- To determine if this approach will lead to an improvement in the energy security of a jurisdiction

1.7 Thesis Organization

The thesis is organized into five chapters. Following the introduction, Chapter 2 reviews existing energy storage systems along with terminologies common to the subject area.

Chapter 3 presents the design of the proposed system along with an implementation of the analysis model developed for a generic energy storage system employing commercially available domestic hot water heaters powered by wind generated electricity. The means to assess the potential of this approach through the use a computer simulation tool are discussed. In addition, this chapter provides insight, through the introduction of a parametric analysis model, into the real potential of the renewable wind resource to provide heating service in the residential sector.

In Chapter 4, a case study is conducted using locale or region specific data in an area which has a good wind regime that could employ the distributed thermal energy storage system in a residential setting. The results point to the potential of this approach through quantitative assessment of the approach using real-world data.

And finally, Chapter 5 concludes with some discussion of the practical limitations of the system and the computer simulation tools presented in this thesis. This chapter wraps up with some discussion of the future work to be considered and some commentary on whether or not this system could be practically implemented based on the results gathered.

Chapter 2 Background

This chapter examines the how the fundamental components of a thermal storage system employing commercially available electric hot water tanks to provide heating service from electricity produced from wind in the residential sector have been studied and analyzed according to the existing body of scientific and engineering knowledge. For the purpose of understanding the problem and the proposed solution, this chapter has three objectives:

1. To determine the key areas to be evaluated.
2. To examine how components of various solutions have been captured in the past.
3. To discuss the body of knowledge around energy storage.

Although the proposed approach appears to be novel in that literature does not show that this exact system has been implemented before, a review of existing systems or parts of existing systems are discussed for the sake of completeness. It will be shown that the components of the proposed system are well-known and have been dealt with in existing work.

2.1. The Problem

At the root, one might argue that the problem is the social and political need for improvements in energy security. Fortunately, methods exist whereby this can be quantitatively measured and compared with other jurisdictions. It can be said that an improvement in energy security will come when use of a sustainable and renewable resource such as wind is undertaken where a non-renewable resource, such as crude oil was used previously. Any attempt to maximize the usefulness of a renewable resource, thereby improving the energy security of that region, can only be construed as being beneficial to that region's energy security.

It has been pointed out by Hughes that[**6**] "*although Canada is one of a limited number of countries blessed with vast quantities of both renewable and non-renewable energy sources and the processes to convert and distribute them has recognized the need to begin the transition to a sustainable energy future. The topic of energy security will be an essential component in this transition. Despite its vast energy resources—both renewable and non-renewable—there is still a need to improve Canada's energy security; this will be especially true over the next decade given the expected challenges associated with energy supply and demand* [**16**]. *For instance, most of* *eastern Canada's demand for crude oil is met from imported sources* [**6**]*, meaning that any disruption to supply or increases in price will have economic and social implications to low and some middle-income Canadians* [**17**]*. Similarly, those provinces heavily dependent on coal for electrical generation may be subject to carbon pricing or required to restrict electrical generation to other sources, or both* [**18**]*, actions which may well result in increased electricity rates, again with economic and social implications*."

Under the IEA's definition of energy security, "the uninterrupted physical availability at a price which is affordable, while respecting environment[al] concerns" [**19**], in order for an energy source to be considered (energy) secure, it must have energy flows and processes that adhere to the 4As. The four 'A's developed by the Asia-Pacific Energy Research Council (APERC) are:

Accessibility to modern, affordable energy for all
Availability in terms of continuity of supply and quality and reliability of service
Acceptability in terms of social and environmental goals
Affordability

Should an energy process, energy store, or energy flow become unavailable, unacceptable, or unaffordable (or some combination thereof), the energy chain can no longer be considered secure and as a results the energy security is diminished. These attributes will be employed as the criteria in the assessment of the present work's ability to improve the energy security of the region under scrutiny.

The actions that a jurisdiction can pursue to improve its energy security can be classified under the 4Rs into one of [**20**]:

Reduction. These are actions that result in a reduction of energy consumption from a particular energy chain through conservation or measures usually targeting a conversion process resulting energy efficiency gains in the energy chain
Replacement. Replacement refers to changes made to existing energy sources or processes to make an energy chain more secure. In general, replacement is achieved by either diversifying energy supplies or changing a process, or both.
Restriction. These are actions that limit or restrict an existing or new energy chain to a particular energy source or process, or both. For example, policies may require that electricity generation be limited to natural gas rather than coal, causing an electricity

supplier to shutter all coal-fired thermal generation in favour of high-efficiency gas turbines supplied by natural gas. Restriction can also apply to the creation of new energy chains. Examples of such restrictions include policies for the adoption of renewables for the generation of electricity [**21**], feed-in tariffs requiring electricity suppliers to purchase increasing levels of electricity from renewables [**22**], and the use of biofuels for transportation [**23**].

Review: A continuous review (i.e., the application of the fourth 'R') of the criteria associated with each chain will determine when conditions change and what actions should be taken.

2.2. Establishing the Performance Indicators for Improving a Jurisdiction's Energy Security

A recent review paper on the state of solar thermal energy storage (TES) suggests that thermal storage of energy is now a mature technology [**24**]. The paper discusses solar thermal specifically but because the storage element of such systems is quite closely aligned with the proposed system in this work, the associated and existing work is relevant here. The paper points out that much literature exists around the details, modeling assumptions and simulation results for solar thermal systems to supply domestic hot water, space heating, and space cooling loads. The work shows that there are several proposed approaches for the analysis of the performance of solar water heating systems.

Yohanis et al. established a key performance indictor for solar thermal solutions where it was determined the number of days in each month when solar heated water above a set temperature is available from the system [**25**]. This performance indictor aligns with one of the two key performance indicators established in this thesis to quantify the level of service to the end user by determining how often this supply of energy is available to the end user and how often the system can be relied upon for the heating service in the residential sector. Under the 4As, the availability of a supply of energy for a region is a performance indicator for the energy security of that region.

Hughes describes how wind-generated electricity can be used for space heating when combined with electric-thermal storage (ETS) systems [**26**]. This work shows that despite the availability of thermal storage, intermittency means that there is still a need for backup electricity. There are periods of time where electricity is available but no outlet to consume it. The matching of consumption to production (supply and demand) continues to be an area of concern with wind generated electricity.

In support of the objectives of this thesis, the means to evaluate how effectively the energy produced from wind gets consumed will be captured in the second of two key performance indicators introduced here. The level of utilization performance indicator establishes, from the perspective of the supplier, what amount of the available wind generated electricity actually gets consumed as a percentage of the total available.

The level of utilization performance indicator is rooted in the replacement and restriction strategies presented under the 4Rs. The replacement of a less secure energy supply such as fossil fuels (heating oil and electricity from coal) with a more energy secure supply such as electricity from wind for heating service in the residential sector has the overall effect of improving the energy security of that region. It has been pointed out that by restricting less secure supplies of energy for heating in the residential sector, energy security will improve[**27**].

2.3. The Need for Energy Storage

If wind is to make a significant contribution to meet the world's rising demand for services such as heating then it will be necessary to change the way it is consumed. Demand must rise up at the time supply is available to ensure that the renewable resource is as completely consumed as is possible. Storage appears to be the easiest path to this need because it seems unlikely that consumers have the wherewithal to limit all of their energy consumption to times when supply of an intermittent resource is available. Energy storage not only reduces the mismatch between supply and demand but also improves the performance and reliability of energy systems and plays an important role in energy conservation[**28**].

2.4. Energy Storage Techniques

The discussion of materials used for thermal storage over the years has been the topic of many academic endeavours and inventive engineering undertakings. According to a 2009 paper by Sharma et al., energy storage techniques can be broken down into three broad categories [**28**]:

1. Mechanical energy storage such as gravitational energy storage or pumped hydropower storage (PHPS), compressed air energy storage (CAES) and flywheels. The PHPS and CAES technologies can be used for large-scale utility energy storage while flywheels are more

suitable for intermediate storage. Storage is carried out when inexpensive off-peak power is available, e.g., at night or weekends. The storage is discharged when power is needed because of insufficient supply from the base-load plant.

2. Electrical storage through batteries is an option for storing the electrical energy. Existing applications for batteries include utilization of off-peak power, load leveling, and storage of electrical energy generated by wind turbine or photovoltaic plants employing large scale redox battery technologies. Today, most common type of storage batteries for renewable remains the lead acid technology, mainly due to cost.

3. Thermal energy storage permits energy storage by a change in internal energy of a material as sensible heat, latent heat and thermo-chemical or combination of these. In sensible heat storage (SHS), thermal energy is stored by raising the temperature of a solid or liquid. SHS systems utilize the heat capacity and the change in temperature of the material during the process of charging and discharging. Water appears to be the best SHS liquid available because it is inexpensive and has a high specific heat.

2.5. Thermal Energy Storage

The use of a latent heat storage system using phase change materials (PCMs) is an effective way of storing thermal energy and has the advantages of high-energy storage density and the isothermal nature of the storage process. PCMs have been widely used in latent heat thermal storage systems for heat pumps, solar engineering, and spacecraft thermal control applications. The uses of PCMs for heating and cooling applications for buildings have been investigated within the past decade. There are large numbers of PCMs that melt and solidify at a wide range of temperatures, making them attractive in a number of applications. [**28**]. A paper by Paul Steffes of Steffes Corporation suggests that thermal storage of wind generated electricity represents a distributive electric storage technology that is a low cost, long life “renewable thermal battery”[**29**].

Kilkis suggests in a comparison of thermal space (heating) loads and wind in winter and summer that “wind energy is more sustainable and steady, where sunshine is strongly intermittent in winter months. In many cases there may be almost 6 to 8 hours of phase difference between the peaks of wind speed and the space heating load [**30**]. Yet in certain climatic conditions and geographic locations, peak wind speed may follow the space heating load more closely [**31**]. In any case wind energy seems to be more suitable when compared to solar energy for heating [**32**].

A report published by IEA found that the cost effectiveness of building new electricity storage is low for wind penetration levels of 10-20 percent. In other words, if the amount of wind available could only provide 10 to 20 percent of a wind generator’s nameplate capacity, investing in storage is recommended. Given the intermittency and variability issues of wind energy, wind could be better used to service loads that have the ability to store energy or those loads that would work as well without requiring a continuous supply of electricity. The report points out that intermittent renewable energy sources such as wind can be used to target specific loads or services such as storage heaters and batteries that don’t require a base-load supply of energy[**33**].

2.6. Thermal Storage with Commercially Available Electric Hot Water Tanks

In an experiment whose results support the system presented in this work, Cruickshank et al. evaluated the thermal response of a series- and parallel-connected solar energy storage tanks[**34**]. The thermal response of three standard 270 litre hot-water storage tanks were studied under variable charge conditions. Tests were conducted on an experimental apparatus that simulated the thermal charging of the storage system by a solar collector over predetermined periods. Both energy storage rates and tank temperature profiles were experimentally measured during charge periods representative of two consecutive clear days or combinations of a clear and overcast day. They studied the effect of rising and falling charge-loop temperatures and collector-loop flow rate on storage tank stratification levels.

Results of this study show that the series connected thermal storage reached high levels of temperature stratification in the storage tanks during periods of rising charge temperatures and also limited de-stratification during periods of falling charge temperature. This feature is a consequence of the series-connected configuration that allowed sequential stratification to occur in the component tanks and energy to be distributed according to temperature level. This effect was not observed in the parallel charge configuration. A further aspect of the study investigated the effect of increasing charge-loop flow rate on the temperature distribution within the series-connected storage and showed that, at high flow rates, the temperature distributions were found to be similar to those obtained during parallel charging. A disadvantage of both the high-flow series-connected and parallel-connected multi-tank storage is that falling charge-loop temperatures, which normally occur in the afternoon, tend to mix and de-stratify the storage tanks.

A 2010 paper published by the Electric Power Systems Research on a novel domestic electric water heater model for a multi-objective demand side management program[**35**] stated that one important way to reduce losses and increase power system stability is through advanced control algorithms on the load side. This idea is broadly referred to as demand-side management (DSM). Different objectives have been considered by past DSM programs found in the literature, such as peak shaving and valley filling. Their paper presented a novel domestic hot water heater model to be used in a multi-objective demand side management program. The model incorporates both the thermal losses and the water usage to determine the temperature of the water in the tank. Water heater loads are extracted from household load data and then used to determine the household water usage patterns. The benefits of the model are: (1) the on/off state of the water heater and temperature of the water in the tank can be accurately predicted, and (2) it enables the development of water usage profiles so that users can be classified based on usage behaviour. As a result, the amounts of ancillary service and peak shaving that can be achieved are accurately predictable and can be maximized without adversely affecting users.

2.7. Summary

This chapter has examined the fundamental components of a thermal storage system employing electric hot water tanks to provide heating service from electricity produced from wind in the residential sector. The presented solution relies in large part on the established and now considered mature areas of expertise around thermal storage of energy in hot water tanks. The commercially available electric hot water tanks themselves have been shown to be an area that is well documented and is also considered mature technology.

This chapter has shown that the proposed solution addresses the problem through the discussion of how parts or components of the solution have been captured in the past, discussion of the current body of knowledge of the elements in the proposed solution and identification of the key areas to be assessed.

Chapter 3 Design and Implementation

This chapter presents the methods required to simulate an energy chain consisting of a wind farm producing electricity and supplying it to residences employing thermal storage using commercially available electric hot water tanks for both space and domestic hot water heating. Diagrams of the proposed system are included and the methods for evaluating the system are discussed. A flowchart of a proposed implementation of a simulation model tool is shown and its constituent functions are discussed. The potential of this approach to storage of a renewable source of energy will be assessed in several ways through the software simulation tool provided with this thesis. Along with the design of the proposed system, the simulation software is discussed in this chapter.

3.1 Proposed Wind Energy Thermal Storage System

A diagram of the proposed wind-energy thermal storage system is shown in Figure 3.1. Electrical energy from the wind farm flows along either existing or newly dedicated high-voltage transmission wires to those households with the thermal storage in a given jurisdiction. The method assumes that the jurisdiction will be located such that the households are in reasonably close proximity to each other and to the generation source so that the resulting transmission losses would be minimized. The power measured at the wind producer is available when the wind is blowing and distributed among residences connected to this system.

The system proposed is a closed water-heating system. The working fluid (water) is heated to a temperature of a least 55 °C (minimum for indirect potable hot water heating) and not more than 95° C (less than the boiling point) for implementation in the hydronic heating systems such as hot-water baseboard.

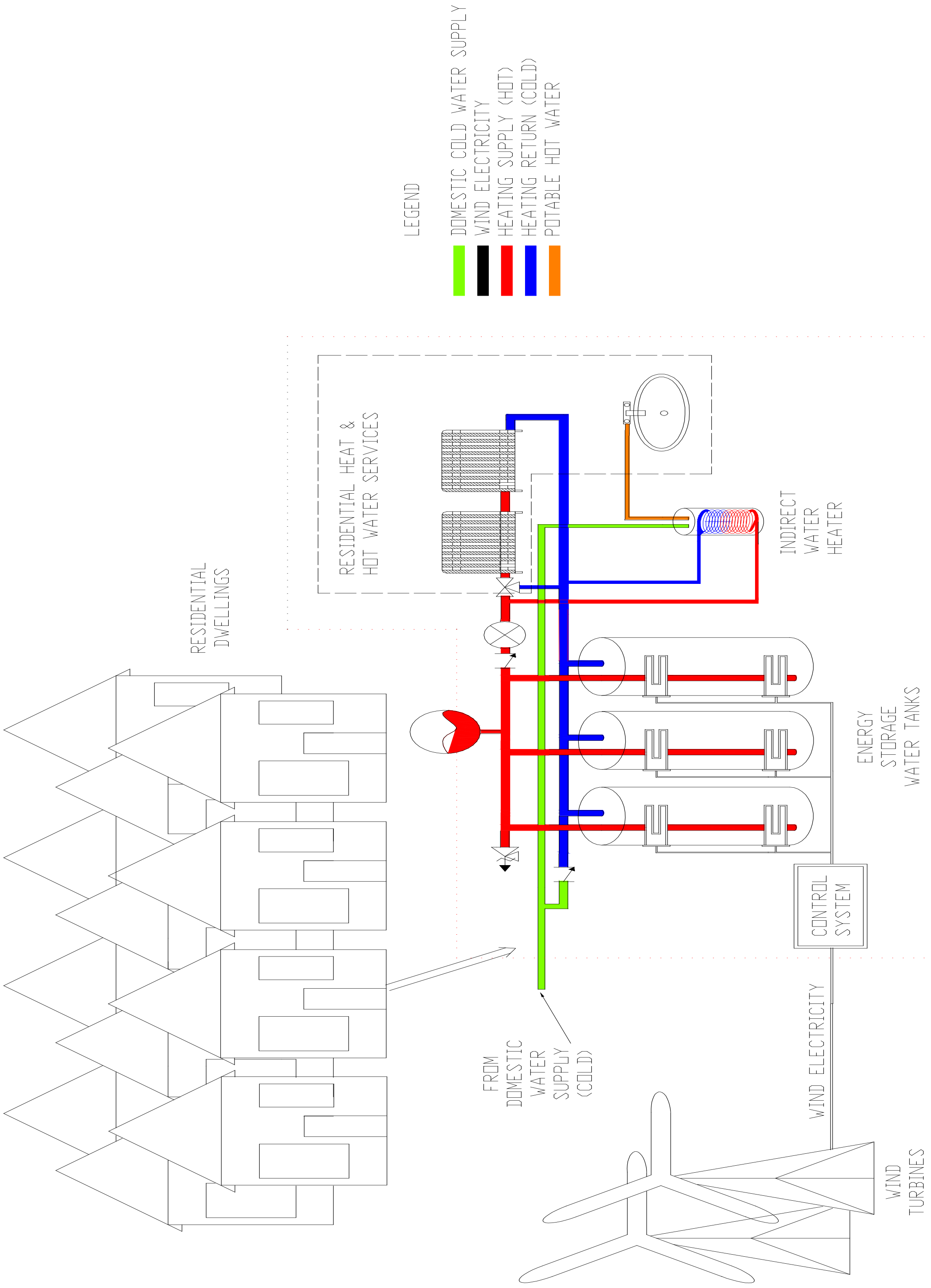


Figure 3.1: Proposed System Overview

As shown in Figure 3.1 the control (and electrical switching mechanism) is local to the installed system at each individual residence. The assumption that each individual residence is controlled remotely from the wind generation site is in accordance with the technique used currently with power generation facilities and their time-of-use customers. Although the complexity of the control system is beyond the scope of this research, the assumption is that a central control will oversee the entire system; something must supervise the distribution of power and match the load to the supply as best as possible. The action of the control system is such that when the wind is available and power is being produced, the control system acts to connect a number of residences to the line to consume as much of the power being produced as possible. It is possible that power is being generated but there will be no residence in need of it (i.e. the storage is full). In this case the control system would not allow the residence (the electrical load) to connect to the line. Subsequently the wind producer would have to handle that situation by presumably diverting it to another load. One of the goals of this work is to determine how often these situations occur and test several control algorithms (discussed in 0) to establish which if any provides the maximum level of utilization of the wind resource thereby minimizing the times that the renewable energy is not used.

The number of residences connected to the system can be considered a design parameter which will determine the loading (the number of households that can be connected to the system) of the system. Each residence will be considered identical and each residence represents an average dwelling in a given jurisdiction.

The use of non-specialized equipment and readily available hot-water storage tanks is expected to contribute to the cost savings of this system over other types of localized and distributed energy storage systems. The energy storage system implemented in individual residences employs a number of consumer-grade 40, 60, 80 or 120 gallon electric hot water heaters available from hardware stores and plumbing suppliers. The number of hot water heaters installed in each residential can be tailored to the household’s heating requirements. Topologically, this proposed system is similar to commercially available electric hydronic boilers with a modified control system. The two systems differ also in that the proposed system here employs more storage capacity and has been customized for thermal storage of wind electricity. The closed loop system requires a circulator pump to move water through the loop [**36**] but will aid in the de-stratification of the water in the tanks as well. The straight-forwardness and flexibility of this system are key features.

An adjustment or replacement of the thermostatic control element will be required to accommodate the non-standard high and low cut-out temperatures. In spite of the fact that an external control system could handle this control as well, in the interest of safety, redundant thermostatic and high-pressure control should be included [**36**]. It is assumed that the electric heating elements are one-hundred percent efficient.

Depending on the number of hot-water heaters installed in each residential system, the footprint of the proposed system is expected to occupy the about the physical space that a residential hot water (i.e., hydronic) space and hot water heating systems; although larger designs will require more floor area. The proposed system could most easily integrate into existing domestic hydronic space heating systems such as hot water baseboard, hot water radiator or in-floor radiant. A benefit of this system over thermal storage space heaters such as electric-thermal storage systems (ETS) is that it does not intrude on the residence's living space. This wind-powered heating system with storage is proposed as a replacement over existing oil-fired hydronic heating systems.

The domestic hot water component with its indirect water heater could be employed in residences where such heating systems are in place. In addition to the space heating zones, water is circulated through the indirect water heater to provide domestic hot water for the dwelling. The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) journal states that potable hot water temperatures typically range from 41°C to 60°C [**37**]. The controls of the indirect water heater's control system will not be modified for this work and the unit itself will handle the valves and temperature measurement and control for the potable hot water supply. It is assumed that the indirect water heater will connect to the proposed system in much the same way it would connect to any commercially available domestic hot water heating system.

Any boiler handling water is subject to the typical problems of any water circulating system. If the ambient temperature drops below freezing, the pipes and tanks may freeze and burst. Water treatment against corrosion and scale may be avoided by using de-ionized water or plumbing antifreeze in the closed system [**36**]. The working fluid is circulated around the heating system via an electric pump to provide space heating. The energy consumption of the circulator pump will be neglected because the times the pump run cannot necessarily correspond to when wind energy is available; the pump must run from on-demand electricity from the grid.

This design calls for a modification of the hot water heating appliance to suit the needs of thermal energy storage system. By increasing the upper temperature limit of the water inside the hot water tank, the temperature differential is widened thereby increasing the amount of stored energy inside the tank. In general, keeping the temperature differential as large as possible makes the size of the energy store as large as practically possible. Although an increase in temperature will result in an increase in pressure inside the tank. This problem can be alleviated by adding an expansion tank to the system [**36**]. The electric hot water heaters utilize a glass-lined inner wall which improves its resilience to internal corrosion (except around the welded fittings) and prevents premature failure. The addition of an expansion tank to the design will reduce the likelihood of the tank expanding beyond the point where the glass lining cracks, leading to premature failure.

The design employs a thermostatic mixing valve to ensure that the temperature of the water is correct for distribution to the hot water baseboards and indirect water heater (if required). The lower temperature limit could be reduced to about 30°C from 55°C if an in-floor radiant space heating system is employed. Once again, increasing the temperature differential (ΔT) has the effect of increasing the usable amount of energy stored in the tanks.

There are several options available to provide heating service during hours where heat or hot water, or both are required but energy from the storage tanks cannot furnish this energy. It is possible that an auxiliary, electric, oil-fired or gas-fired tank-less water heating system could be employed to provide both space heating and domestic hot water needs. Alternatively, off-peak electricity from the grid could be used to backup the heating service when required [**14**]. Electricity from the grid could be supplied to the system. Further discussion of backup is beyond the scope of this thesis and is merely presented for the sake of completeness. In general, when the working fluid temperature is below the lower cut-out limit, the energy is therefore not useable for either of the required services. At this point, the proposed system is unable to meet the needs of the residence and a backup system must be in place to meet the heating needs.

3.1.1 Electrical Subsystem

A one-line diagram showing the possible interconnection between the wind farm and the residences is shown in Figure 3.2. The method by which the available wind energy is distributed is as follows. At any given time and if wind is generating electricity, a quantity of energy is available from the wind producers. Based upon the amount of energy available, a certain number of houses will be selected as established by the strategy employed to receive share of the available wind energy. For example if there are 200 kW being produced that hour, 10 residences could be connected to the electricity supply by the control system to receive 20 kW of energy during that hour. Further to this if there are 210 kW being produced that hour, 11 residences could be connected to the electricity supply and 10 would receive a 20 kW share, with the remaining 10kW being supplied to the 11th residence. Allocating the left over energy ensures that waste is minimized and the utilization of the renewable resource is maximized. If a residence cannot accept energy (i.e. store is at capacity) then it will not be forced to accept any. Once again, if there is no power being produced, then there will be no residence selected to receive electricity.

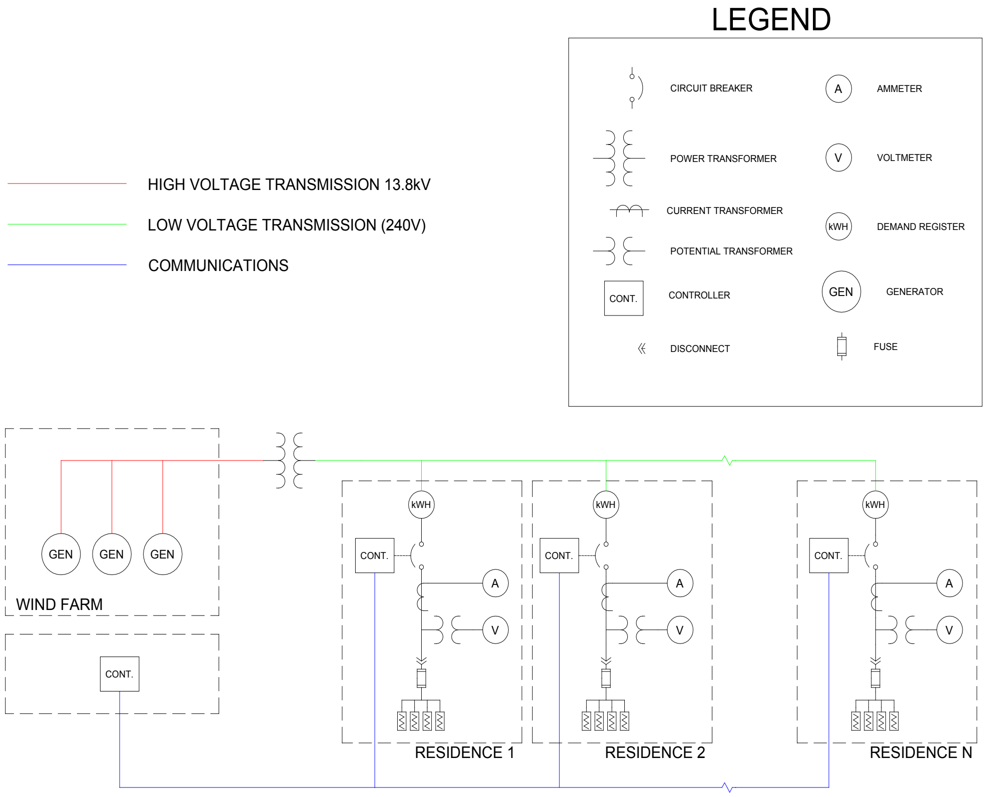


Figure 3.2: One-Line Diagram of Proposed Electrical Interconnections

The Table 3.1 summarizes the possibilities for the production and consumption of the wind electricity.

Table 3.1: Energy Supply and Demand Scenarios

		Residential demand	
		REQUIRED	**NOT REQUIRED**
Wind-electricity	**AVAILABLE**	Energy consumed	Energy not consumed
	NOT AVAILABLE	Energy not consumed	Energy not consumed

The validation of a 20 kW power throughput as a maximum under a typical 240 Volt, 200 Amp residential service entrance are shown in Equation (3.1).

$$\frac{20\ kW}{240V} = 83A \tag{3.1}$$

The calculated value of 83 A is in the range of acceptability for a 200 A residential service entrance. If less than 20 kW (i.e. the remaining power) is transferred, then the current draw would be correspondingly less. The electrical load the water heaters present to the line is assumed to be purely resistive.

3.2 System Analysis Design Model

The design presented in the previous section must be validated in terms of performance before implementation. Typically a computer simulation of any system is performed whenever possible before a prototype is built; this section will:

1. establish the model to be used to simulate the proposed system,
2. comment on what data would be required to model the system and
3. outline the steps in English pseudo-code needed to effectively and accurately simulate the system

3.2.1 System Model

The model for analysis of the potential of this approach is based on the energy flow method. It is a straight-forward energy balancing scheme with energy inputs, energy stores and energy outputs.

Figure 3.3 shows that energy is provided to the store in the form of electrical energy, which is converted into heat and stored as thermal energy in the store.

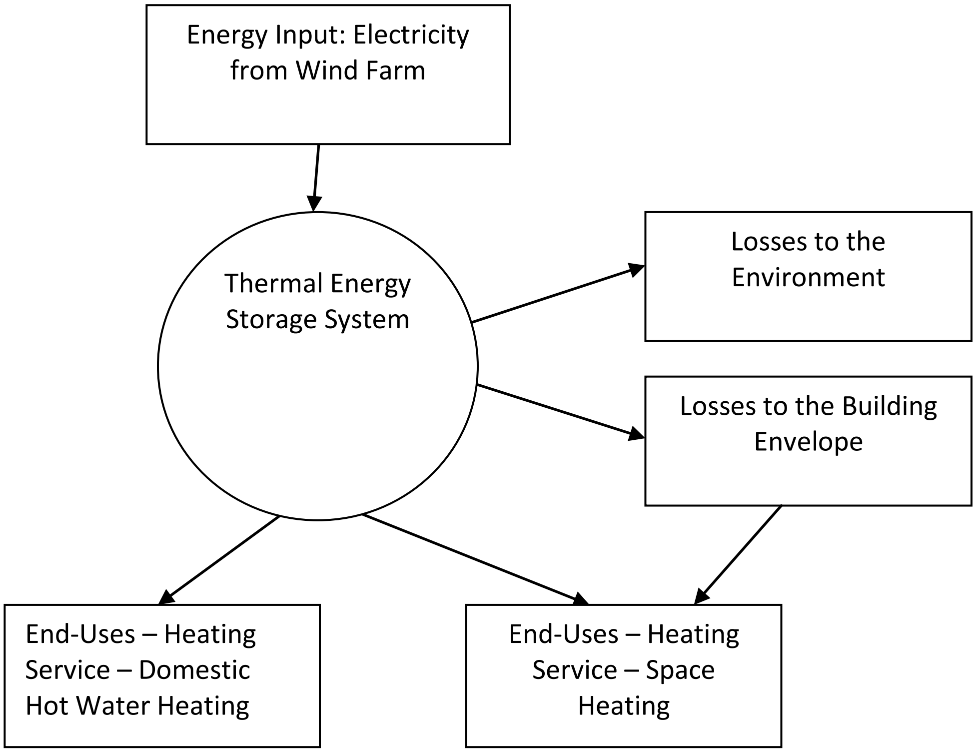


Figure 3.3: Energy Balance Model

The heating service draws energy from the store. The thermal energy is available only via the store and not directly from the source. The energy at the source is electrical and therefore not suitable for use in the proposed system until it has gone through a conversion to thermal energy.

The thermal energy is extracted from the store via three avenues. The largest quantity of energy is consumed for space heating. In the residential sector, space heating consumes about 63 percent of the total energy needs for a residence. The second avenue is the energy requirements for hot water heating account for 18 percent for the average family. Together, the heating service in the residential sector accounts for more than 80 percent of a typical Canadian residential energy demand [**38**]. Thirdly, there are energy losses from the thermal store. These are dealt with in two ways. During hours where there is a net positive heating degree hour and therefore a demand for space heating, the constant thermal losses from the storage tanks can contribute to the space heating demand. The result is that because energy losses escape to the building envelope, and therefore can be taken as a contribution to the overall space heating energy requirement. During hours where there is no net heating degree hour, the energy is not required for space heating and therefore must be considered as a loss to the environment. In this latter case, this effect may actually increase the demand for space cooling, but in northern regions space cooling can be done passively and without additional energy which accounts for the small amount of energy attributed to this demand. Overall, the demand for space cooling is low in Canada.

3.2.2 Input Data Required for System Model

In order to model the behavior of the proposed system with a goal of meeting the thesis objectives, input data for the model are required. The following list highlights what input data are expected to be needed.

1. Real-time (interval), time-stamped energy production data from a wind farm.
2. Energy characteristics of a typical residence
    a. Space heating needs
    b. Hot water heating needs
    c. Ambient temperature inside dwelling (to be used to determine energy losses from the store)
3. Real-time (interval) , time-stamped outside temperature (to be used in calculation of real time energy demands of the residence)
4. The current state of the energy storage system (temperature inside storage tanks)

3.2.3 Output Data Required from Model

In order to meet the thesis objectives, the following information is required from the model:

1. Real-time indication (interval) of whether or not the system was able to meet the energy demands placed on it by the residence. The indication should be a Boolean “yes or no” indication of whether or not the system could supply the energy required for heating. This model will treat hot water and space heating (the heating service) collectively. If there is enough energy for one and not the other then the result will be negative overall.
2. Real-time indication of the amount of available wind-electricity that was actually used. It will be known from the input how much electrical power is available at any given time. It

will be required for analysis that the quantity that is actually used (and quantity not used) at any given time is known.

3.2.4 Processing

To meet the thesis objectives, the following processing will be performed to model the system. As discussed, the supply and demand are occurring asynchronous to one another; the energy supply that is feeding the store does not necessarily occur at the same instant that energy is being drawn from the store. Although the sub-steps can occur sequentially (which will lend itself well to a structured programming language), it is important that the supply and demand processes be carried out concurrently at time-step intervals. Modeling concurrent processes typically requires special treatment in a structured (sequential) programming language. The flow diagram of Figure 3.4 shows the core processing steps required. This core process will be performed iteratively for each residence connected to the system and for each time-step interval the simulation is run.

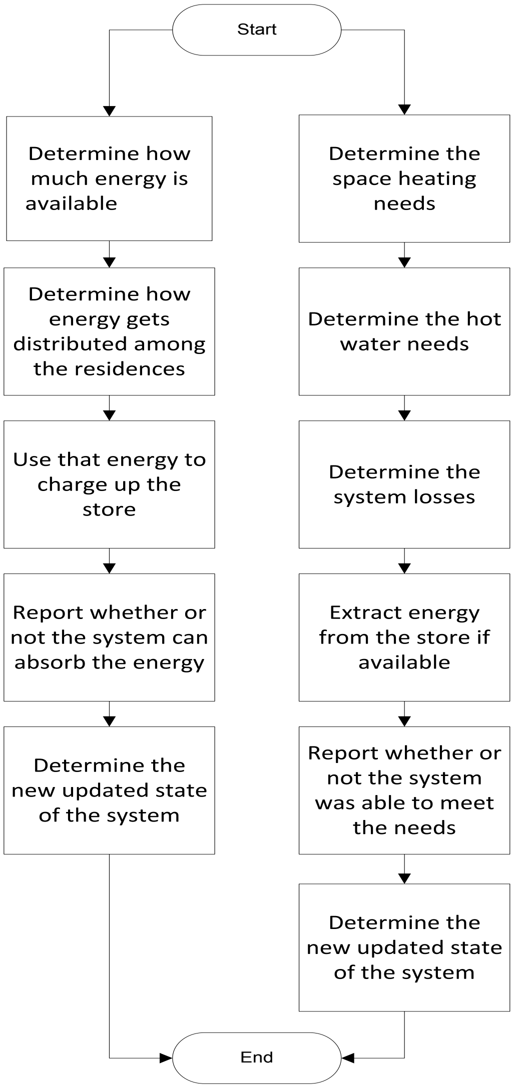


Figure 3.4: Algorithm for Core Processing Steps for the Simulation Model

3.3 Implementation of the Simulation Tool

In order to meet the thesis objectives, the software implementation has two modes of functionality. The first mode of functionality, the case study mode where a speeded up, hour-by-hour visualization of the current state of the system is presented. This case study analysis is performed for a particular region or jurisdiction where wind-electricity is available and the proposed system is to be implemented in each of several hundred residences. The user must define parameters which in turn define both the environment the system will exist in (such as ambient temperature, heating energy demand and how many residences are permitted on the wind-electricity system) and the makeup of the installed system (such as how many tanks, tank size, and energy throughput). These latter items govern how the system functions and will ultimately determine how well it performs in the given jurisdiction's environment.

The second mode of functionality of the simulation software is the parametric analysis. This mode allows the user to set up and test a range of system design parameters, such as the size of the residence's energy storage system. The user must specify parameters such as annual hot-water energy demand, that describe the environment of the region to be studied. The parametric analysis can also provide insight into how sensitive a system design is to certain parameters. The flexibility of this tool is such that it can be used for any jurisdiction where wind-electricity is available and the proposed thermal storage system is to be implemented. For the end-user of this tool, the benefit of being able to adjust the system parameters allows for the testing or verification of a scenario as well as performance of a 'what-if' analysis or parametric/sensitivity analysis. In this mode there is no visualization for the user because of the large quantity of processing involved.

In this section, a software tool using available data to model a system is implemented. This implementation is based on the model established in the previous section. This section will outline:

1. the data inputs to the computer simulation,
2. the control system algorithms used for how the energy is distributed,
3. thermodynamic calculations which are used as the basis of the computer simulation
4. the methods of the simulation tool for case study analysis
5. the method associated with the parametric and sensitivity analyses and
6. the outputs required to support the thesis objectives

The computer simulation is implemented using the high-level C programming language used in National Instruments' Lab-Windows. This visual, event-driven environment is well-suited to instrumentation-type analysis.

3.3.1 Inputs to the Computer Simulation

The proposed methods will assess the potential of this approach by applying the real, time-varying electrical power output from a wind farm which has a resolution of one hour. This feature has the added benefit of allowing the treatment of numerical quantities of electrical power and electrical energy to be used interchangeably thus facilitating both the energy balance model described and without the requiring further processing.

Hot water usage data is needed with one-hour temporal resolution to preserve the one hour resolution established with the wind-electricity power output. The model is an energy balance therefore, calculations are required to correlate 15 minute interval, volumetric hot water usage data to hourly energy demand for hot water. This is accomplished in Microsoft Excel where the required calculations and formatting in done for use in the simulation.

The energy requirements for hot water can be arrived at in two ways. The first technique sees the hourly energy consumption for hot water being synthesized by normalizing the water usage (with respect to the yearly water consumption) for the hour and then applying that normalized fraction to the yearly energy consumption for hot water. The second technique utilizes standard thermodynamic calculations for temperature rise of the hourly quantity of hot water as demanded in the residence. Both techniques reveal a very close result for both methods. These calculations are shown in section 3.3.3.2. Both techniques are implemented in Microsoft Excel for use in the simulation.

Environmental data showing outside temperatures at one-hour intervals is required to be input to the simulation and is available for many locales. This is used to calculate the heating-degree-hour which in turn is used to calculate the energy needs for space heating. Knowing the current outside temperature allows the energy demand for space heating to be synthesized from the data. The assumption that the energy usage of the building is strictly a function of the outside temperature is a simplification. Accuracy is maintained regardless because at the end, all of the energy gets accounted for under this implementation. The method presented here involves taking the normalized fraction of energy usage and then applying that normalized fraction to the yearly energy consumption for space heating.

All of the constituent pieces are assembled into an input data file. An excerpt of a sample input file showing all of the input data required is shown in Table 3.2.

Table 3.2: Wind Data Input File Excerpt

Date	Start	End	Power (kW)	Outside Temp	Energy Hot Water (kW)
Monday, July 01, 2002	0:00	1:00	2745.75	17.50	0.00
	1:00	2:00	3631.25	16.70	0.00
	2:00	3:00	1613.50	15.10	0.00
	3:00	4:00	1466.50	15.40	0.00
	4:00	5:00	780.50	13.90	0.00
	5:00	6:00	1449.00	13.80	0.00
	6:00	7:00	768.25	15.80	0.00
	7:00	8:00	381.50	17.60	0.00
	8:00	9:00	99.75	18.90	3.20
	9:00	10:00	689.50	20.70	0.00
	10:00	11:00	1349.25	22.70	0.00
	11:00	12:00	2390.50	23.80	2.07
	12:00	13:00	2063.25	23.20	0.00
	13:00	14:00	1575.00	23.50	0.00
	14:00	15:00	1116.50	22.80	0.00
	15:00	16:00	579.25	22.30	2.92

3.3.2 System Control Algorithms

At the location of the residence, the control system governs when the electrical load presented by the electrical hot water heating elements is connected to the supply. The simulation model tool implemented here has two straightforward energy delivery strategies for purpose of carrying out the analysis.

With the first strategy, the residences connected to the system are serviced in a priority sequence; the first houses in the sequence will always receive a share of the available wind electricity. As discussed earlier, each residence is a typical average residence but for the purpose of the analysis they will be numbered sequentially from 1 to n where n is the number of residences connected to the system. As the first houses in the sequence become fully charged and therefore cannot accept any more energy, successive houses down the line will receive more and more of the available wind energy. It is expected that this approach will keep the houses at the top of the priority sequence charged as much as possible while those near the end of the sequence will have a lower level of service. The order of the residences for the purpose of the computer simulation is arbitrary given that each residence is identical and each represents an average dwelling with an average number of occupants for the particular jurisdiction.

The second energy delivery strategy has the residences serviced in a round-robin fashion. In this, the residences each receive a share of the available wind energy as it becomes available; it is expected that the distribution of the energy will be much more rectangular and each house in turn will receive at least some energy. This approach attempts to keep all houses charged at about the same level all of the time. This energy delivery strategy aims to achieve that all houses will get energy but no one house will get significantly more than any of the others since they are all treated equally. These two strategies will be evaluated to determine the degree to which this system can provide the heating service and whether or not any residences could be serviced at a level of 100 percent.

The differences between these two approaches are discussed in the results chapter of this thesis in terms of overall residential level of service for individual residences. The other performance indicator, the overall level of utilization of the wind resource, is not applicable from the point of view of the residence.

3.3.3 Thermodynamic Calculations for the Simulation

Several thermodynamic quantities are required for simulation of the system. This section provides an overview.

3.3.3.1 Hourly Space Heating Energy Calculation

The hourly outside temperature data was provided alongside the electrical energy output from The Wind Test Site in North Cape, Prince Edward Island. Using the outside temperature, the hourly energy usage for space heating can be computed. The energy usage figure for hourly space heating needs of an average residence in any jurisdiction can be calculated by first determining the heating-degree-hour (HDH). The HDH threshold temperature is user configurable in the software but the default value used here is the generally accepted value in many thermodynamic texts.

$$\begin{aligned}&\mathit{If}\ \ \mathit{Current\ Outside\ Temperature} > 18°C\ \ \mathit{Then}\\ &\qquad \boldsymbol{Heating\ Degree\ Hour} = \mathbf{18°C} - \boldsymbol{Current\ Outside\ Temperature}\\ &\mathit{Else}\\ &\qquad \mathit{Heating\ Degree\ Hour} = 0\end{aligned}$$

(3.2) [39]

By comparing the hourly normalized fraction of the yearly space heating load to the total energy consumption for a year, the hourly energy demand can be calculated as shown in Equation 3.3.

$$E_{Hourly} = \frac{Heating\ Degree\ Hour}{\sum_{n=1}^{8760} \text{Heating Degree Hour}} E_{Yearly}$$

$$\begin{aligned}&where\ 24\ hours\ per\ day\ x\ 365\ days\ per\ year\\ &\qquad = 8760\ (i.e.\ the\ number\ of\ hours\ in\ a\ year)\end{aligned}$$

(3.3)

3.3.3.2 Hourly Hot Water Energy Calculation

Using the hourly domestic water usage data obtained from the IEA's Annex 42 report on European and Canadian non-HVAC Electric and DHW Load Profiles for Use in Simulating the Performance of Residential Cogeneration Systems, the hourly energy usage for hot water can be computed.

To correlate the water consumption with energy use, the following calculations were performed on each data point. The thermodynamic formula $Q = mc\Delta T$ where m is the mass of the water in kilograms, c is the constant of proportionality in joules per kilogram degree Celsius, ΔT is the change in temperature the water undergoes. In the example, the accepted inlet temperature of water is taken to be 15°C and the expected water temperature for domestic hot water is taken to be 60°C in accordance with Canadian building code. Where 1 litre of water has a mass of 1 kilogram, the energy (in joules) required to raise the temperature of 1 litre of water from 15°C to 60°C is shown in Equation 3.4.

$$(1\ kg)\left(4.186\frac{J}{kg\ °C}\right)(60°C - 15°C) = 188.4J = 0.052\ kWh$$

(3.4)

Because, the wind energy is given in kWh and because the system is modeled as an energy balance, the former is given in kWh where 1kWh = 3.6 MJ.

A second technique to calculate hourly energy consumption for domestic hot was analyzed. In this, the hourly energy consumption was synthesized from the normalized fraction of hourly DHW volume usage data. The calculation requires (from the user-specified parameters) the amount of energy that was consumed for a year for hot water heating needs. Like the former method, this calculation, shown in Equation (3.5) reveals how much energy (in kWh) is used for that hour's domestic hot water service based on volume usage.

$$E_{HOURLY} = \frac{V_{HOURLY}}{V_{YEARLY}} E_{YEARLY} \tag{3.5}$$

The results of these two techniques to calculate energy required for DHW on an hourly basis show a discrepancy of about 1.5%. In other words, one supports the other and the result is verifiable.

3.3.3.3 Hourly System Energy Losses Calculation

Numerically, the system losses are in accordance with standard thermodynamic evaluation of losses in domestic hot water heaters [**40**]. The calculations are based on a temperature differential between two surfaces, the inside and outside of the tank, with a predefined level of insulation. Furthermore, the system losses are compounded for the number of electric hot-water tanks employed. The actual losses are expected to be less than those calculated because of the interactions between the heaters which are physically in close proximity to one another thereby raising the ambient temperature. This error has been ignored for the sake of simplifying the calculations and because the overall systems losses are small compared to the main energy draws on the system.

The details of the how these losses are treated were discussed at the beginning of this section when the energy balance diagrams in Figure 3.3 were discussed. It pointed out how and why the system energy losses are dealt with from two perspectives.

Standard thermodynamic equations were used to calculate the storage tank losses are shown in Equation (3.6) [**40**].

$$H = A\,\frac{T_{hot} - T_{cold}}{R}$$

where:

H is the heat loss in Btu/hour
A is the surface area in square feet **(3.6) [**40**]**
T_{HOT} is the hot water temperature in °F
T_{COLD} is the ambient air temperature in °F taken as 18°C or 65°F
R is the R-value of the insulation in ft^2 hr F / Btu
Converting energy units Btu/hour to kWh involves the constant 3413 Btu/kWh.

3.3.4 Implementation of the Modeling Simulation Software

The software flow diagram shown in Figure 3.5 outlines the programming methods used to evaluate the proposed system; with a goal to get the results required to determine the true potential of this approach to thermal storage of wind energy. A graphical interface will allow users to visualize the process as it steps through the analysis at a rate which permits viewing of the state of the system at any given time. The simulation can be sped up to get to the final result more quickly or slowed down in order to view potential problem areas in greater detail. Being able to step through slowly also permits the user to confirm the fidelity of interim results and investigate problem areas which may permit system enhancement to better deal with potential problem areas. The simulation tool can be adapted to suit any jurisdiction. Values describing the particular region’s energy usage characteristics are inputted to the opening dialog displayed to the user when the program launches.

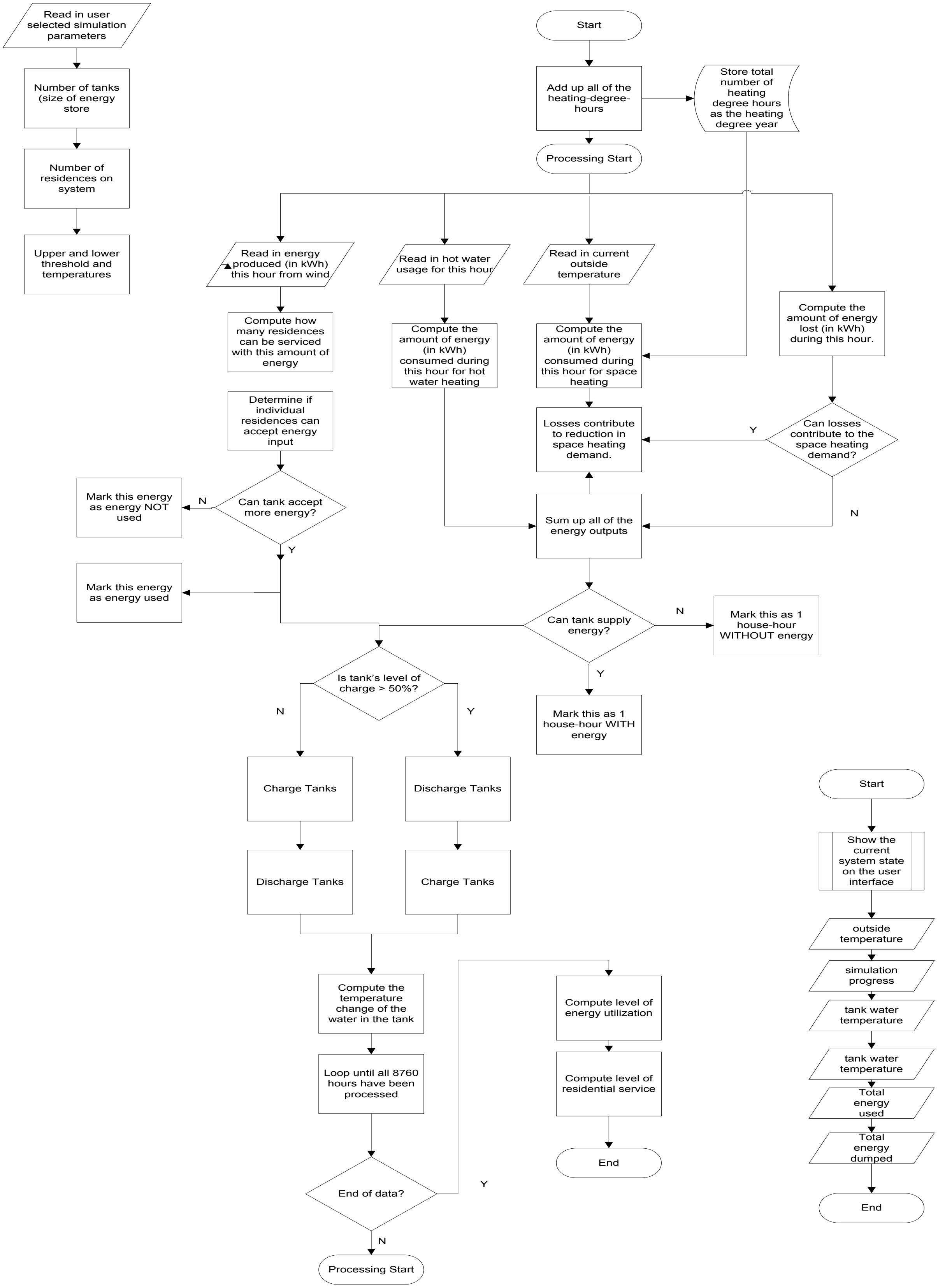


Figure 3.5: System Flow Diagram

3.3.5 Dealing with Concurrent Processes

Care must be taken to identify and handle concurrent events with structured programming languages. The energy balance model used must permit energy to be both inputted to and outputted from the storage system concurrently. The concurrency problem occurs when the system calls upon the store for energy and the store responds that energy is not available during the same hour that more that energy is being inputted to the store. The error is that the system erroneously reports that there isn't energy available during this hour when in fact, energy is being input to the system store that may meet the demand. This problem may also occur when the store is almost full and an energy input is denied while at the same time energy is being extracted making room for more energy to be stored.

The solution presented here is to have the simulation first determine the current level of charge of the system store before it decides on the order in which to process the energy transactions to and from the store. If the level of charge is less than 50 percent, the simulation will first input energy to the store from the supply before extracting energy from the store to service the demands. Conversely, the store is more than 50 percent charged; the energy transactions are in the opposite order. This technique will maintain the fidelity of concurrent processes.

3.3.6 Validating the Implementation

The implementation of the model in software must be verified for correctness. Several checksums and a validation test will be performed to ensure that the implementation is faithful to the algorithms and that the results will be trustworthy.

A summation of the wind energy data using spreadsheet software alongside a summation of the wind energy field from the data input file when it is read into the software demonstrates an agreement between the two and serves to validate the implementation. A redundant calculation performed to arrive at the total number of heating-degree-hours in both the spreadsheet and implementation software can be used to validate that the implementation is correct.

During the case-study, quantities such as energy input and energy output can be tallied and verified at the end of the run to ensure agreement between the two but it is expected that slight discrepancies will exist due to rounding errors and because of the methods used to calculate such quantities. Because the implementation will incorporate iterative looping, counting the number of loops and confirming in context of the current file position can done with some ease. In-process testing of the expected range of resultant calculations (such as tank temperature) can help confirm that the processing is accurate. An end-of-run verification that data constructs (such as the house-hour) agree with known and expected results will improve the trustworthiness of the overall results.

A validation of the software is performed by forcing winds to known values for periods of time and observing how the system reacts in comparison to what would be expected. The approach taken is to apply a fixed amount of wind energy to the system. The calculation to determine the amount of energy required to meet the space heating needs for 1000 residences when the outside temperature is held constant at -5C is shown in Equation (3.7).

$$E = \frac{\#\ Residences * (T_{HDH\ threshold} - T_{ambient})}{\sum_{n=1}^{8760} Heating\ Degree\ Hour} E_{yearly\ space\ heating}$$

$$\frac{1000\ * (18° - \ -5°C) * 12271kWh}{116733.7} = 2417\ kWh \qquad \textbf{(3.7)}$$

The validation test uses a month's worth of data. The amount of energy supplied to the tank matches the amount of energy drawn from the tanks to meet the space heating requirement. Other energy outputs (for hot water and losses) are set to zero to simplify processing. Given that the starting tank temperature is the default value (80°C), the expected result is that the tank temperature will remain constant over a period of time. If the energy balance is disturbed slightly by supplying a little less energy than required for the residences, then we expect the tank temperature to fall over time. Conversely, if excess energy is made available, then we expect the tank temperature to increase over time. The results of the data validation test in Figure 3.6 show that the actual results agree with the expected results.

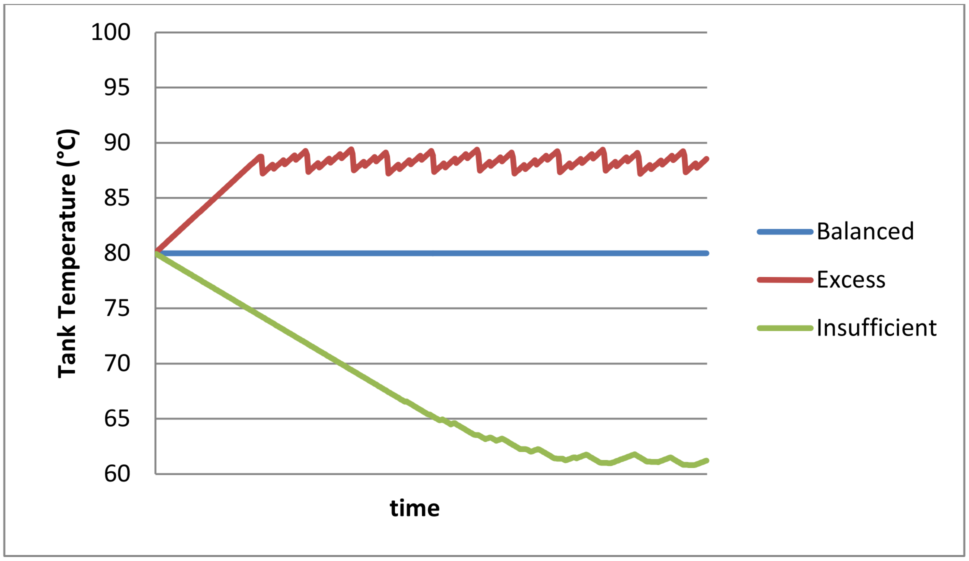


Figure 3.6: Data Validation Results

3.3.7 User Inputs – Defining the System through Software

In addition to the data input file, the case-study analysis will require the user to specify parameters which define the system:

1. The tank size, the size in gallons of the electric hot water heating tank used
2. The number of tanks, the number of tanks employed at each residence
3. The upper and lower threshold temperature, although limited for both practical and safety reasons, the user can adjust the upper and lower tank temperature.
4. The energy (power throughput for one-hour) that each residence will receive from the wind power facility.

The parametric analysis will require the user to specify information which not only defines the system but also, because some system values have been parameterized, define the upper and lower bounds of certain system design parameters. In addition to the general parameters required for the case study analysis, parametric analysis requires the user to enter starting and ending values for:

1. The number of residences connected to the wind generation facility – system loading.
2. The number of tanks each system employs – the energy store size.

These parameters have the most impact on the overall performance of the system. The goals of the parametric analysis are to answer the questions this thesis has proposed and include:

1. The maximum number of houses that could be supported under this system
2. The percentage of the total household demand for these two energy services that this system could support at a prescribed level of service.
3. The number of houses (if any) that could be supported at 100%
4. The maximum level of utilization of the available wind-electricity resource
5. The optimal storage (tank) size -- *the size of the energy store can be customized based upon the needs and/or desired level of service of the consumer.*
6. The optimal energy throughput.

3.3.8 Outputs

To assess the performance of the proposed system, two level of performance indicators are presented here. The first, the *level of service* quality indicator shows the degree to which electricity generated from wind and employing the proposed system is able to meet the needs of residential customers for the heating service. It is arrived at by comparing the how often the proposed system is able to meet the demand for heating services to the total. The second, the *level of utilization* of the wind resource, shows what percentage of the available energy actually gets used. It is arrived at by comparing how much energy gets consumed to how much could not be used.

3.4 Performance Analysis Methods

In addition to the performance analysis discussed thus far, in order to meet some of the thesis sub-objectives, the following methods for the analysis of other facets of the system's performance are presented.

3.4.1 Cost Comparison of this Solution

To determine whether or not the cost of the proposed system is an advantage, a cost comparison between the proposed system and existing electric thermal storage systems is shown. For the purpose of comparing the presented solution to available thermal energy storage solution, the comparison is based on:

1. the energy storage capacity, and
2. the cost to the consumer

3.4.2 Determination of Effects on a Jursidction's Energy Security

A World Energy Council conference paper by Hughes and Shupe [**27**] on the Asia-Pacific Energy Research Center's (APERC) four 'A's (Availability, Accessibility, Affordability, and Acceptability) will form the basis of evaluating the impact this work will have on energy security for the jurisdiction in which the proposed system will be evaluated. The paper describes a method that permits determination of the security of the various energy supplies used in a jurisdiction. The tool can create an energy security index result that is justifiable, understandable, and reproducible. This method employs a decision matrix to produce the energy security index. The flow of energy to the service or end-use can be affected by both the changes to the availability, affordability, or acceptability of an energy chain and the policies intended to reduce consumption or replace the processes or energy flows associated with a chain.

This thesis uses the method for determining the relative energy security of a jurisdiction's energy chain. The method applies a common set of conditions to the changes in equilibrium that can take place within any energy chain and examines the actions that the jurisdiction takes or plans to take to address them. The results will focus on how the replacement strategies (under the 4Rs [**20**]) affect the relative energy security index for that region.

3.5 Summary

This chapter has presented:

1. The design of a system employing thermal storage using commercially available electric hot water tanks that can provide heating service in the residential sector
2. The methods for a software simulation model used to determine the degree to which electricity produced from wind and employing the system proposed can provide both space heating and domestic hot water in the residential sector.
3. A suggested implementation of the model using a well-known instrumentation modeling development environment

The implemented simulation tool is used to both validate the system design and provide the user of the simulation tool quantifiable results on the expected level of performance of the proposed system under the defining system parameters established by the user. The flexibility of this tool is such that it can be used for any jurisdiction where wind-electricity is available and the proposed thermal storage system is to be implemented in several hundred residences.

Chapter 4 Results and Analyses

This chapter presents the simulation tool software which was used to evaluate the performance of the proposed system along with the analyses of the results obtained from using the simulation software. In this chapter,

1. the background for the case study locale, Charlottetown, PE is discussed,
2. the rationale for selection of the parameters is established,
3. the configuration of the simulation software to perform a case study is shown,
4. the corresponding case study results are discussed along with impacts on energy security for Charlottetown,
5. using start and end values, a parametric analysis is performed,
6. the results of the parametric analysis are discussed,
7. the cost comparison of the proposed system with other electric thermal storage systems is performed.

The graphical nature of the simulation tool allows the user to step through (at a user-selectable rate) the hour-by-hour analysis of the performance of the proposed system. The tool permits the user to view the system status on-the-fly. Using both modes of analysis of the simulation software, case study and parametric, the software was set up by having the input wind data available and specifying parameters that describe the system to be analyzed.

First, the case-study results will be examined. In this the determination is made on the degree to which electricity produced from wind and employing thermal storage using electric hot water tanks can provide heating service, both space heating and domestic hot water, in the residential sector. The case study is performed using typical data specific to the region and therefore, the results are discussed from the region’s perspective. The outside temperature data is locale specific for Charlottetown.

The second topic broached in addressing the questions central to this thesis are the parametric-sensitivity analyses. By varying the system parameters such as the size of the thermal energy store, users can determine what effect these will have on the overall performance of the proposed system. The performance will be discussed in terms of two key performance indicators; more detail on these in the next section. Determining the extent to which system parameters affect system performance will be important in terms of keeping the total cost of the system in check. These in turn will impact the likelihood of such a system being adopted. Where the case study allows the user to visualize the performance of the proposed system, the parametric analysis can be useful in identifying information that might help to optimize the system if this system was to be implemented.

4.1.Evaluating the Results – Performance Indicators

The level of service quality indicator is presented as a qualitative assessment of the degree to which electricity generated from wind and employing the proposed system is able to meet the needs for the heating service in the residential sector. It is arrived at by comparing how often the proposed system is able to meet the demand for heating services to the total.

The means to make this comparison is through the construct of the house-hour. Mathematically, it is the scalar product of the number of houses (residences) connected to the system and the number of hours in a calendar year. As an example with 1,081 residences on the system, the total number of house-hours for this system is shown in Equation (4.1).

$$(1081\ houses)\left(8760\ \frac{hours}{year}\right) = \text{ 9,469,560 house hours in 1 year} \qquad \textbf{(4.1)}$$

During any given hour, and for any given residence, the amount of energy stored is strictly able either to meet or not meet the heating demand placed on the system. This thesis does not consider the case where the amount of energy stored could partially meet the heating needs of the residence. The heating service in the residential sector addresses both space heating and water heating. Both of these are taken as a single entity under the heating service for this analysis. The thesis does not take the case into consideration where one part of the heating service could be met and the other could not.

By example, if the proposed system was able to meet the heating services for 7,150,000 house hours, we say that the level of service that system, under the current configuration is 76 percent.

$$\text{LOS (level of service)} = \frac{house\ hours\ where\ heating\ service\ needs\ met}{number\ of\ house\ hours\ in\ 1\ year} \qquad \textbf{(4.2)}$$

The second qualitative indicator of performance is the level of utilization of the wind resource. Where LOS speaks from the consumer side, this factor speaks from the producer’s end of the system. By comparing how often the available wind-electricity produced actually gets consumed, the level of utilization can be determined. The circumstances under which the wind is available but the system is unable to store that energy is due solely to the fact that every residence connected to this system would currently have a full charge and not be able to accept any more energy input. The level of utilization (LOU) is an important performance indicator in terms of maximizing the usage of the renewable resource which in turn contributes to improved energy security and reduced greenhouse gas emissions.

Mathematically, the level of utilization is arrived at by comparing the amount of energy used to the total amount of energy available.

$$LOU\ (level\ of\ utilization) = \frac{quantity\ of\ energy\ used\ in\ Wh}{quantity\ of\ energy\ available\ in\ Wh} \tag{4.3}$$

The data being used has shown that the total energy available for the period July 2002 through to June 2003 at the North Cape Wind Test Site was 17.4 GWh. If the total amount of energy that was used during that period was 16.1 GWh, then the level of utilization is:

$$\frac{16.1\ GWh}{17.4\ GWh} = 92\% \tag{4.4}$$

4.2.Case Study Background

Charlottetown, PE was chosen as the test case locale for evaluation of the proposed system because it is a major urban centre with a dense residential setting able to support deployment of the proposed system to several hundred homes. Average annual residential heating data are available for the city of Charlottetown as well as detailed temperature data from Environment Canada. The availability of data along with the heating needs of a northern city was a key factor for selecting this site. Charlottetown is a good choice because of its geographical proximity to the wind farm. The wind data for this research was obtained from the North Cape Wind Test Site in Tignish, PE, about 200 km west-north-west of the site of the case study locale. The map of Figure 4.1 shows the geographic location of both the wind farm site at North Cape and the case study locale, Charlottetown.

Figure 4.1: Map of Prince Edward Island[41]

The wind farm, developed by the Prince Edward Island Energy Corporation (PEIEC), consists of eight Vestas V47 turbines each rated at 660 kW giving a total installed capacity of 5.28 MW. The data covers the period from 1 July 2002 until 30 June 2003; the total annual output for this period was 17.45 GWh. The monthly output of the wind farm is shown in the graph of Figure 4.2. The data is plotted from July to June as this allows the heating season to be central to the graph. The graph shows that there is a good availability of wind during the heating season.

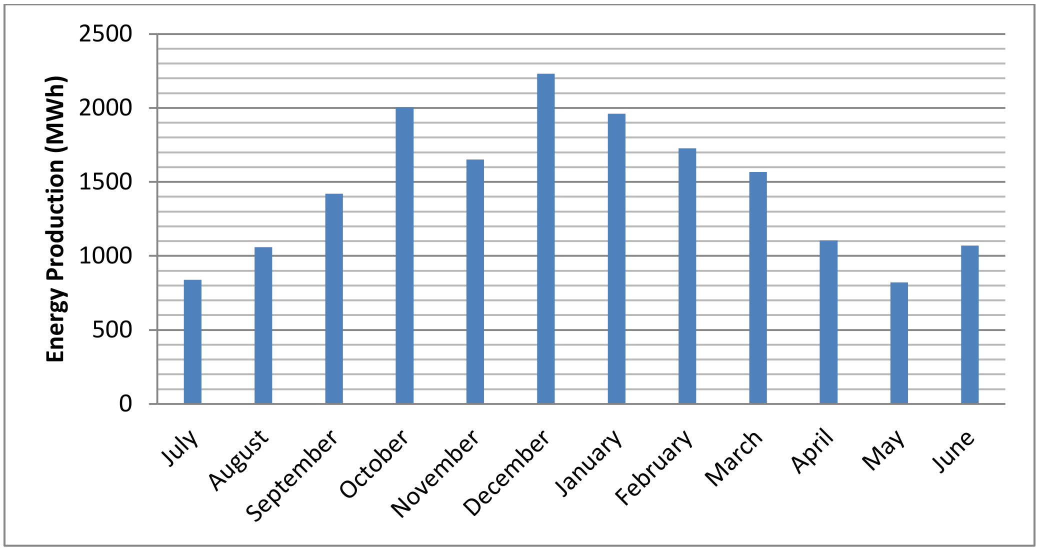


Figure 4.2: Monthly Wind Energy Production [42]

The wind data being used for this work shows that the North Cape Wind Test Site exhibits a very good capacity factor. The average capacity factor for wind farms is taken generally to be in the 20 to 40 percent range [**43**].

The nameplate capacity of the wind farm is calculated in Equation (4.5).

$$(5.28\,MW)\,(24\,\frac{hours}{day})\,(365\,\frac{days}{year}) = 46.25GWh \qquad \textbf{(4.5)}$$

The capacity factor is therefore:

$$\frac{17.45\;GWh}{46.25\;GWh} = 38\% \qquad \textbf{(4.6)}$$

The amount of energy used for heating in the residential sector in Charlottetown was obtained from energy usage statistics from Natural Resources Canada. The data shows that 12, 271 kWh is consumed annually for space heating and 3874 kWh consumed annually for domestic hot water (DHW) heating [**44**]. The graph in Figure 4.3 shows the monthly breakdown for heating demand (both space and hot water) for an average household in Charlottetown. The heating season is shown central to the graph to permit comparison with the wind-electricity production shown in Figure 4.2.

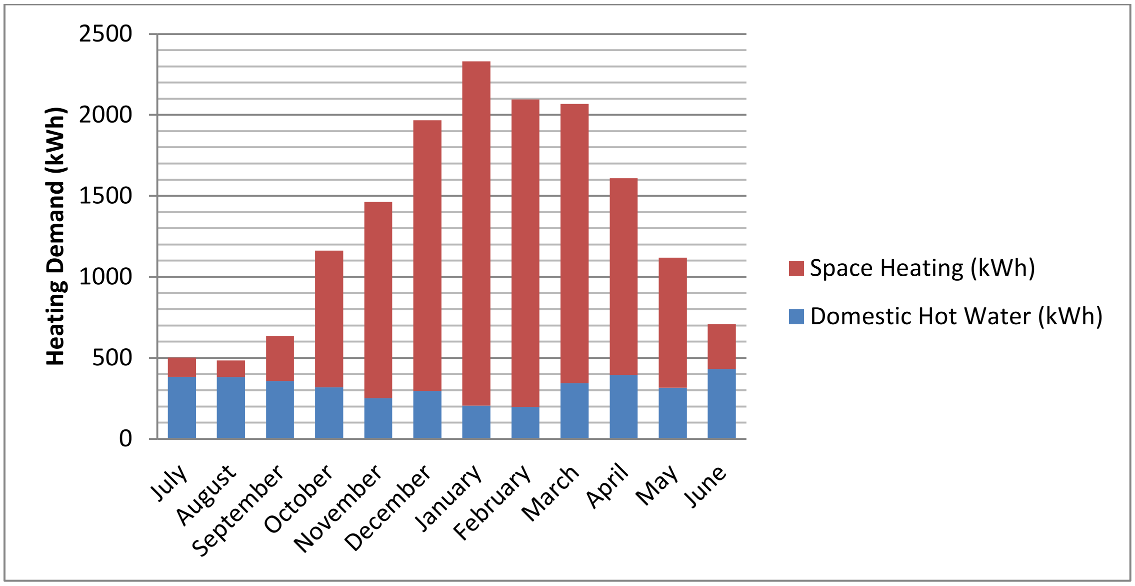


Figure 4.3: Monthly Space Heating Demand for Charlottetown [45]

The energy demand for DHW was extrapolated from hot water (volume) usage data that was obtained from the IEA's Annex 42 report on "European and Canadian non-HVAC Electric and DHW Load Profiles for Use in Simulating the Performance of Residential Cogeneration Systems". The energy consumption is based on consumption of 200 litres per day. To justify this rate of consumption for this case study: according to statistics, the average number of occupants in a residential dwelling in the province of Prince Edward Island is 2.5. The Canadian Building code allows 60 litres per day, per person when calculating the amount of hot water for new residences.

$$\left(60\,\frac{person\ \ litres}{day}\right)(2.5 \text{ persons}) = 150 \text{ litres} \qquad \textbf{(4.7)}$$

The space heating demand was calculated using outside temperature data for the city of Charlottetown.

A review of residential heating equipment for Prince Edward Island shown in Figure 4.4 reveals that 21 percent of the households utilize a boiler-based hydronic space heating system. With about 15,000 households in the City of Charlottetown [**46**], there would be 3200 that utilize a hydronic space heating system. It is assumed that the proposed system could most easily be implemented in place of an existing hydronic oil-fired or gas-fired furnace due to the similarities between them. It is possible that households employing other heating systems could also implement this system, but it is suggested that the aforementioned households could more easily implement it. For the analyses, the maximum number of residences connected to the system shall not exceed 3200. Because the proposed system would be most easily retrofitted to an existing hydronic space heating system, this work focuses on satisfying the heating needs households where this type of system is employed.

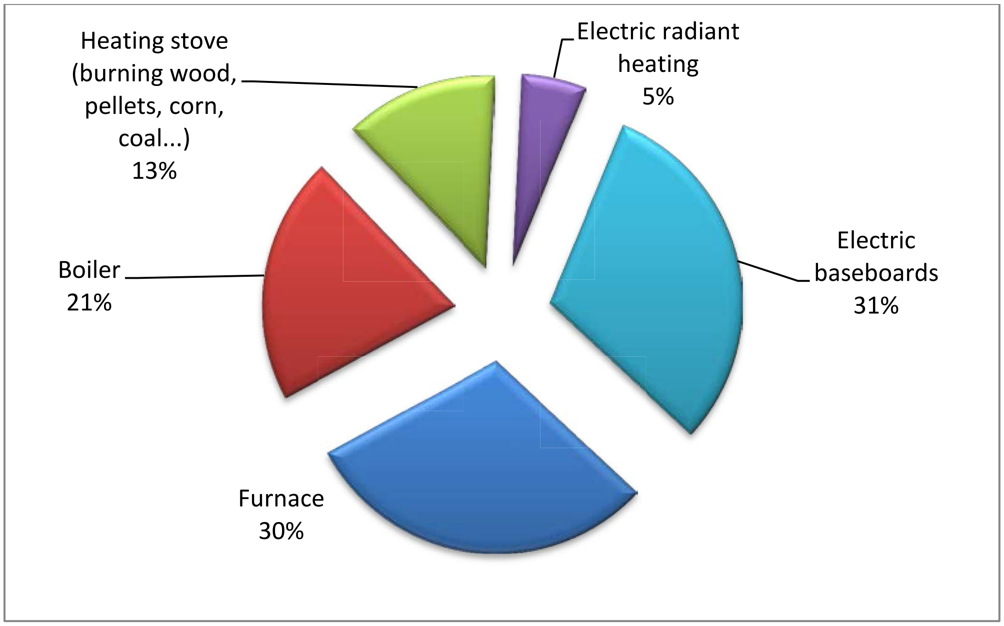


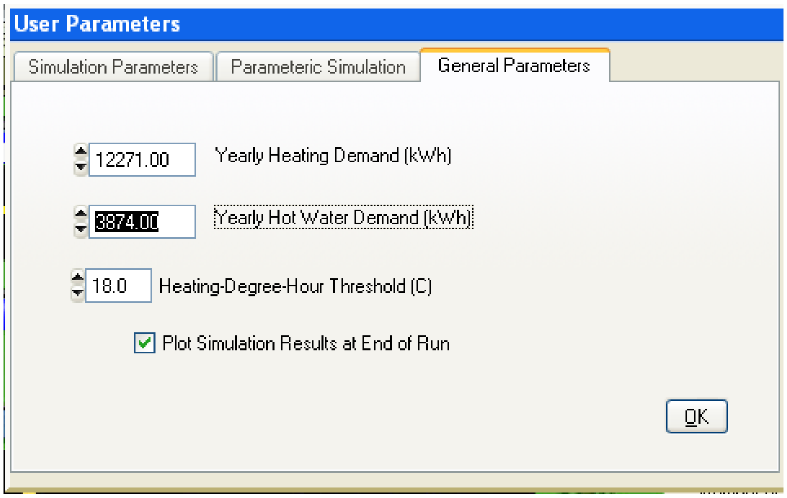
Figure 4.4: Prince Edward Island: Type of Space Heating Equipment [47]

The domestic hot water needs of households can be met with this system through the installation of an indirect water heater. Because DHW systems are inherently hydronic, the statistics around the number of households employing either electric or boiler hot water systems will not be considered. It is assumed that any residence employing a hydronic space heating system could have this system supplying its hot water heating needs as well. This proposed system will employ an indirect water heater to meet the residence's hot water requirements.

4.3.Case Study Simulation Software Setup

Once the simulation tool is running, the user is presented a dialog as shown in Figure 4.5. Under the tab for general simulation parameters, the NRCan data for the yearly space heating and domestic hot water heating energy demands are specified. The default and generally accepted value of 18°C for the heating degree day will be used for this case study.

The following discussion will serve to establish values for the system design parameters that will be used in the case study analysis. Also, the rationale for choosing the parameters will be discussed.



User Parameters

12271.00 Yearly Heating Demand (kWh)

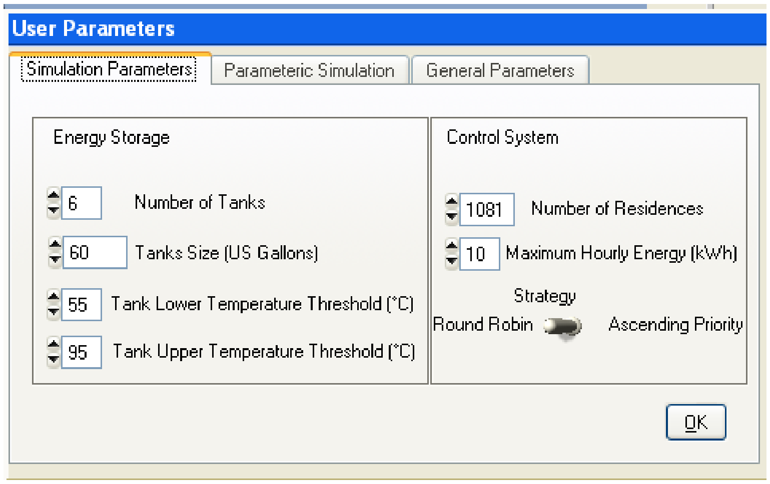
3874.00 Yearly Hot Water Demand (kWh)

18.0 Heating-Degree-Hour Threshold (C)

☑ Plot Simulation Results at End of Run

Figure 4.5: Specifying General Parameters Dialog

Under the simulation parameters tab, the software simulation tool end-user can specify parameters which define the system and allow customization based on needs of the dwelling, needs of the family or overall system cost. Figure 4.6 shows that under the simulation parameters tab of the user parameters dialog, the number of tanks and the size of the tank can be specified.



User Parameters

Energy Storage

6 Number of Tanks

60 Tanks Size (US Gallons)

55 Tank Lower Temperature Threshold (°C)

95 Tank Upper Temperature Threshold (°C)

Control System

1081 Number of Residences

10 Maximum Hourly Energy (kWh)

Strategy

Round Robin Ascending Priority

Figure 4.6: Specifying Simulation Parameters Dialog

The amount of energy stored as shown in Equation (4.8) is a function of the number of tanks connected to each residences thermal energy storage system, the mass of water (the working fluid) and the temperature differential (the upper and lower cutout temperatures). The mass (or volume) of water is determined by both the number of tanks on the system and the size of each individual tank; these ultimately define the amount of energy stored. These parameters define the size of the energy store.

$$q = nmc\Delta T \qquad \textbf{(4.8)}$$

The upper and lower tank temperature threshold temperatures are set according to other constraints besides desired energy capacity. The upper temperature threshold is selected to be less than the boiling point of water. Although the pressure inside the tank will raise the boiling point slightly, the software will not allow the user to set this temperature above 100°C. This ensures system safety and will avoid triggering the pressure relief valve. For the case study, this is set slightly lower to 95°C to allow for a safety margin.

The recommended temperature for a hydronic space heating system is 30°C [**48**]. In spite of the higher tank temperatures, that temperature can be obtained by utilizing a thermostatic mixing valve in the space heating water supply. The valve mixes the hot water supply with the cold return water supply on the closed loop system. If this system was to be used strictly for space heating, then this lower threshold temperature could be set to this lower temperature (30°C) thereby increasing the temperature differential and increasing the overall energy storage capacity.

The lower temperature threshold setting was chosen to accommodate the minimum temperature for potable hot water supply. As discussed, ASHRAE recommends a temperature between 41°C and 60°C for potable hot water. For the case study, 55°C is selected because it provides a margin of safety against legionella bacteria, while still maintaining a wide temperature differential.

Establishing the number of residences employing the thermal storage system that will be connected to the wind-electricity supply through the switching and control system is required. The total amount of energy available annually according to the wind-electricity data used is 17.45GWh. Each residence will require 12,271 kWh for space heating and 3,874 kWh for domestic hot water heating. Assuming that the available energy is to be divided equally among all residences, then the number of residences connected to the wind-electricity infrastructure is shown in Equation (4.9).

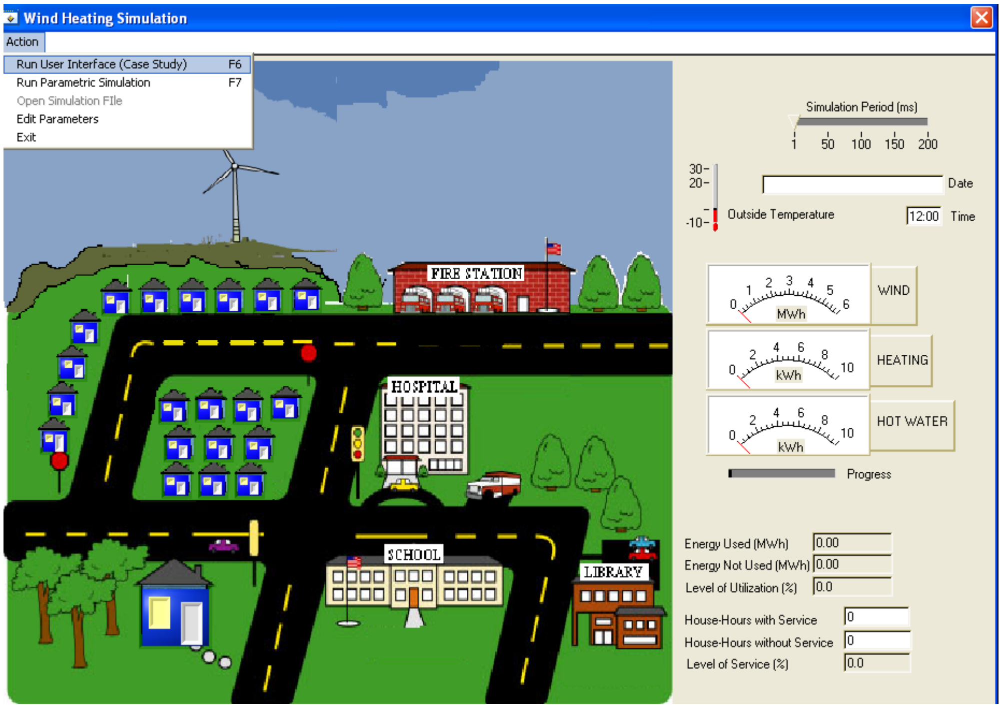
$$\frac{17.45\ GWh}{12271\ kWh + 3874\ kWh} = 1081\ residences \qquad \textbf{(4.9)}$$

This result will be taken as normal system loading. If fewer or more residences are connected, this will be referred to as light or heavy loading respectively

Further to defining the system, the user can specify the maximum amount of energy any single residence could receive in the one hour time slice. Although the hourly energy throughput is adjustable, the default setting of 10 kW is consistent with ratings seen on ETS units [**49**]. Ultimately, this figure is adjustable and will be a tradeoff between household wiring ampacitiy, the number of residences connected to the system and the share each household would like to receive in any given hour where wind generated electricity is available.

Two strategies are implemented to control when the residences connect to the wind-electricity infrastructure in order to get their allocation of energy. In the first, ascending priority strategy, the residences are arbitrarily numbered in sequence (all residences for the case-study have average energy needs) and when wind-electricity is available, those residences at the beginning of the sequence get asked if they need energy first. As the first residences beome fully chagred, the remaining residneces down the line will get charged . Under the second energy delivery strategy, the round robin strategy, each residence in turn will receive a quota of energy from the available energy. During any hour a block of 100 residences (number ed 0 through 99) may receive energy. During the next hour, the next block of 75 residences (numbered 100 through 174) may receive their allocation of energy and so on. All residences will receive energy in turn and once the last residence receives energy, the count starts over . The energy delivery strategy, as discussed determines the order in which the residences receive energy when it is available. The case study results will show the differences between these two in terms of the level of service to the homeowners.

Clicking *OK* on the user parameters dialog and then selecting the *Action* and *Run Case Study* from the main user interface screen will start the case study process. The user interface for the case study simulation is shown in Figure 4.7. The user interface is meant to be informative and displays energy usage statistics. The user can control the speed at which the simulation runs by sliding the simulation speed control to view the current state of the system and slow the simulation down to see details that may otherwise be lost. The user can view the current outside temperature, the time and date (whether within the heating season or not), and observe how that affects the heating load on the system. When the wind is blowing, the user can see how the energy is being distributed to the residences because the colour of the residence is indicative of its current state of charge; red for high and blue for low state of charge.



12:00 Time

Energy Used (MWh) 0.00
Energy Not Used (MWh) 0.00
Level of Utilization (%) 0.0

House-Hours with Service 0
House-Hours without Service 0
Level of Service (%) 0.0

Figure 4.7: Simulation Tool Graphical User Interface

Being able to vary these values contributes to the usefulness and flexibility of the tool. If the user wanted to determine how well this system could meet just the space heating needs, it is simply matter of zeroing the hot water demand. Likewise, if desired the system can be configured for use with in-floor radiant (hydronic) space heating systems by adjusting the upper and lower threshold temperatures.

4.4.Energy Storage Comparison

As an example of the capacity of the proposed system and to provide contrast with other energy storage systems such as ETS, the following calculations for the size of the energy store are presented. Equation (4.10) shows that the maximum amount of energy that can be stored for the system described in the case study.

$$q = nmc\Delta T = (6\ tanks)(227kg)(95 - 55°C)\left(4.186\frac{kgkJ}{°C}\right) = 228MJ$$
$$= 63kWh \qquad \textbf{(4.10)}$$

where: $60\ gallons = 227l = 227kg$ and $1kWh = 3600kJ$

The Table 4.1 and Table 4.2 provide a comparison between the energy storage capacities of existing thermal energy storage systems and various configurations of the proposed system.

Table 4.1: Storage Capacity of Steffes ETS Systems[50]

	Room Units					**Hydronic Heating System Furnace**		
Model	2102	2103	2104	2105	2106	5120	5130	5140
Storage capacity (kWh)	13.5	20.25	27	33.75	40	120	180	240

Number of Tanks	*6*	*12*	*8*	*16*	*24*	*8*	*12*	*24*
Tank Size (gallons)	*40*	*40*	*60*	*60*	*60*	*80*	*80*	*80*
Storage capacity (kWh)	*42.2*	*84.4*	*84.4*	*168.8*	*253.2*	*112.5*	*168.8*	*337.6*

shows a range of system size combinations and their associated heating capacity for the proposed system.

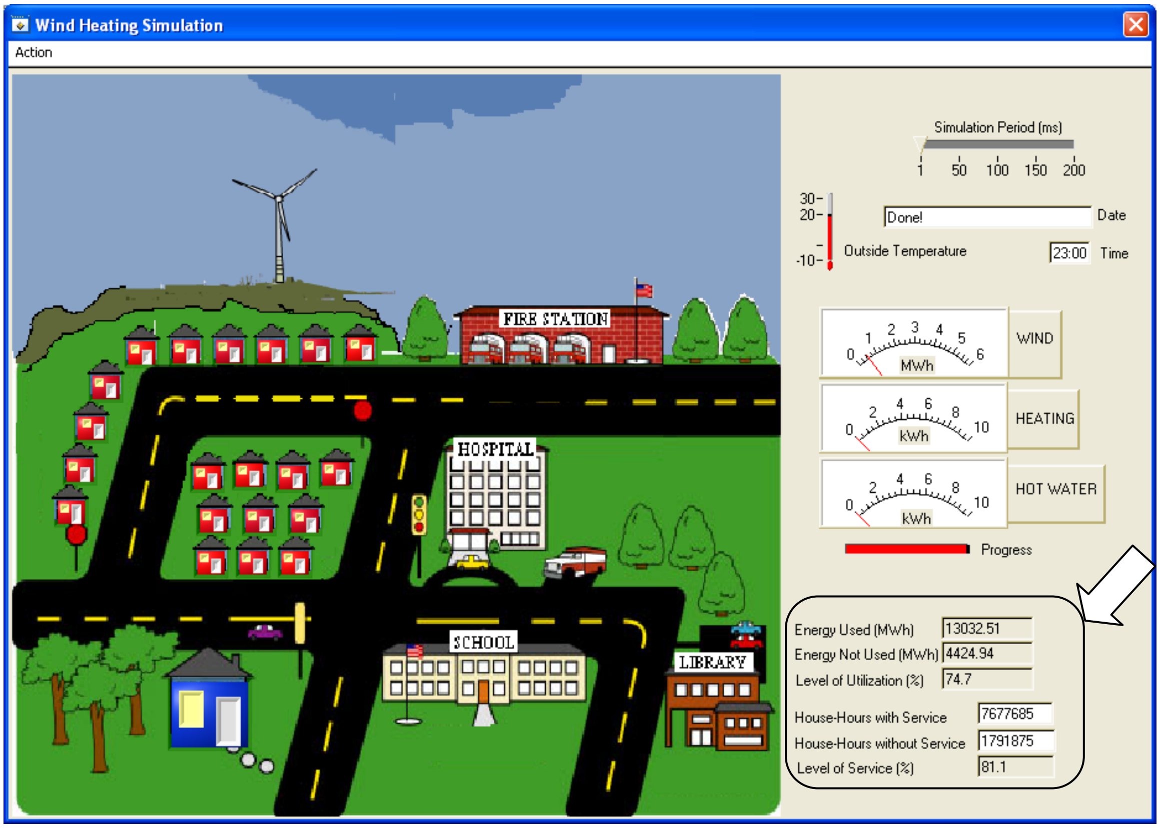
Table 4.2: Storage Capacity of Various Configurations of the Proposed System

Number of Tanks	*6*	*12*	*8*	*16*	*24*	*8*	*12*	*24*
Tank Size (gallons)	*40*	*40*	*60*	*60*	*60*	*80*	*80*	*80*
Storage capacity (kWh)	*42.2*	*84.4*	*84.4*	*168.8*	*253.2*	*112.5*	*168.8*	*337.6*

At 63 kWh, this system is about half the capacity (referring to Table 4.1 and Table 4.2) of the smallest Hydronic Heating System Furnace Model 5120 ETS available from Steffes Corporation but larger than the largest space heater.

4.5.Case Study Analysis Results

The results of the case study as shown in the Figure 4.8 reveal the overall performance of the system through the two key performance indicators introduced earlier. The level of utilization of the wind resource indicates the percentage comparison of how much energy of the total available gets consumed by the residences. The level of service to the residence indicates in percentage how often the system could be relied upon to provide the heating service needs.



Date: Done!
Time: 23:00
Energy Used (MWh) 13032.51
Energy Not Used (MWh) 4424.94
Level of Utilization (%) 74.7
House-Hours with Service 7677685
House-Hours without Service 1791875
Level of Service (%) 81.1

Figure 4.8: Case Study Results Display

The results indicate that almost 75 percent (13.0 GWh of the 17.5 GWh) of energy produced was consumed by residences employing the proposed thermal storage system. Under the system design parameters used and the environment described by the parameters used, the level of service performance indicator reveals that an average 81 percent of the residences heating needs were met by the system with design parameters as discussed.

The graph of Figure 4.9 shows the monthly breakdown of the level of service to provide insight into when this system is most dependable and when the homeowner will likely have to turn to backup to meet the heating needs. The results indicate that the system responded well to the needs of the homeowner up until the start of the heating season in November. Through the duration of the heating season the performance of the system was lower. Beginning in the month of January, wind does not come close to meeting the heating demand. It wasn't until the warmer weather arrived that the level of service rebounded. Through the heating season the level of utilization of the wind resource remained high. The results agree with what was expected in that during the heating season, the demand is higher and therefore performance from the perspective of the residence will be lower. This result was compared to calculated maximums for the level of service for each month the simulation was run for the sake of validating the results.

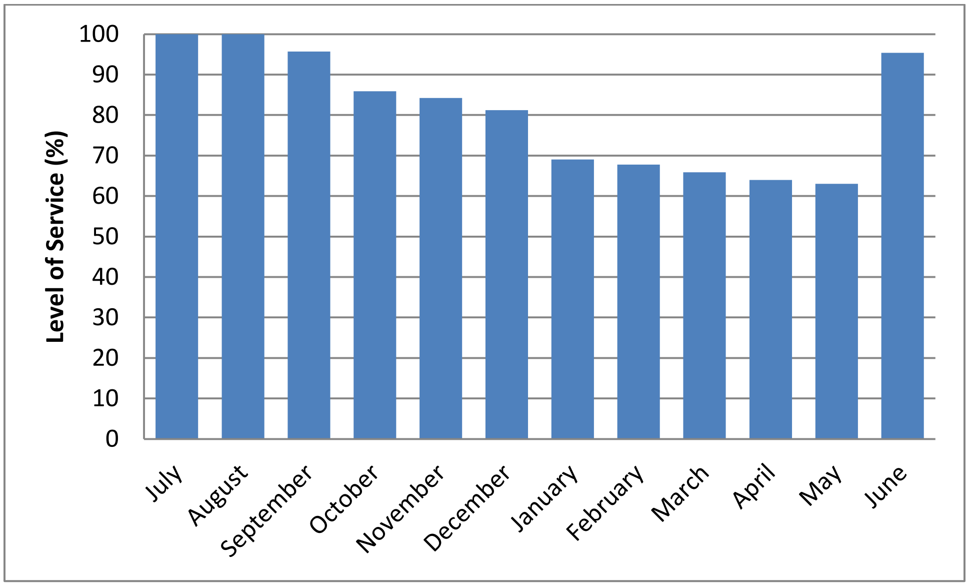


Figure 4.9: Monthly Level of Service Breakdown for Case Study

The graphs of Figure 4.10 and Figure 4.11 reveal the differences between two energy delivery strategies (round robin and ascending priority sequencing) the simulation tool offers. The overall average results are quite close; 81.1 percent for ascending priority and 81.8 percent for round robin but the graphs indicate that the two differ in the way the service is provided to residences. With 1081 residences run through the case study, the performance for the ascending priority customers shown in Figure 4.10 reveal that the customers with the priority service, those at the front of the queue receive very good performance (close to 100 percent) while those at the end of the sequence could expect lower than average performance.

Figure 4.10: Level of Service to Residences Using Ascending Priority Strategy

With the round robin scheme shown in Figure 4.11, the customers could expect to be treated almost equally with the level of service for any residences being quite close to the average.

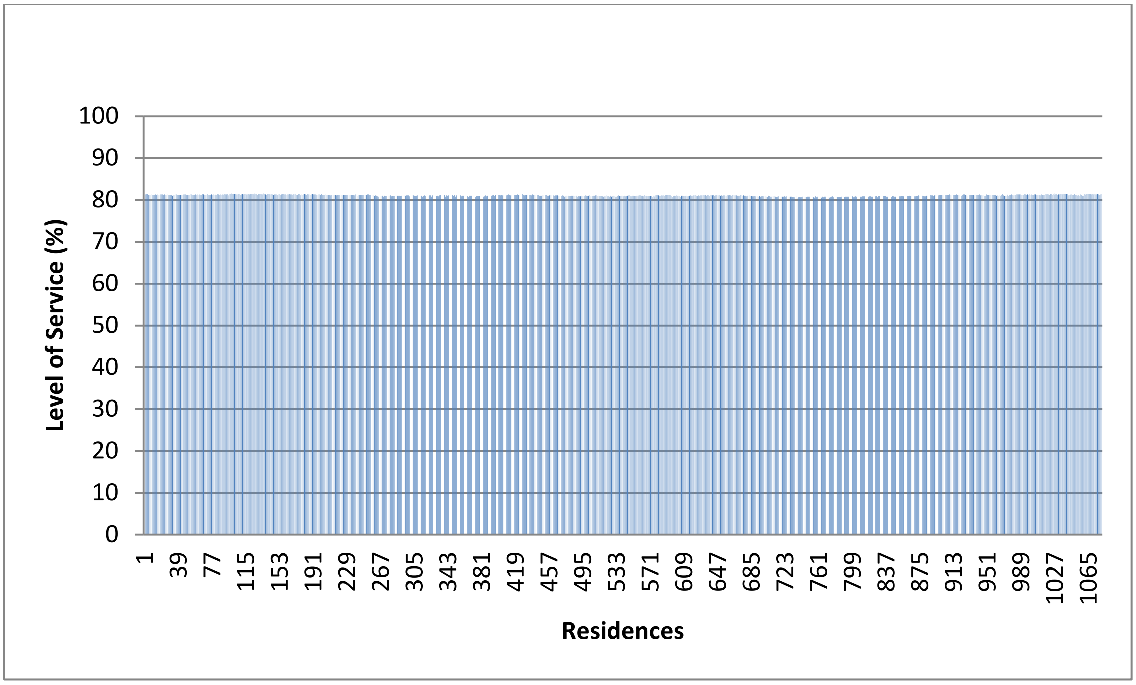


Figure 4.11: Level of Service to Residences Using Round Robin Strategy

Varying the energy throughput as had negligible effect on the overall performance of the system. It was observed that making the energy throughput delivery smaller tended to minimize any differences seen in level of service between the two energy delivery strategies discussed.

The results indicate that lowering the energy throughput made both strategies appear to offer the same performance from the point of view of the residence.

While varying the hourly energy throughput had little effect on the overall performance results, seeking out optimizations might include increasing the size of the energy store by adding more tanks or larger tanks to the residential system. The parametric analysis will reveal that better results will come by reducing the loading on the system as a whole by reducing the number or residential customers connected to the system. The parametric results will reveal where the optimizations can be made and what effect parameters such as system loading and energy storage size will have on the system performance.

4.6.Impacts on Energy Security

The work of the Energy Research Group at Dalhousie University is the basis of evaluating the impact this system could have on energy security on Charlottetown. These criteria are based upon the Asia-Pacific Energy Research Center's (APERC) four 'A's (Availability, Accessibility, Affordability, and Acceptability) (APERC, 2007). The flow of energy to the service or end-use can be affected by both the changes to the availability, affordability, or acceptability of an energy chain and the policies intended to reduce consumption or replace the processes or energy flows associated with a chain.

The results here focus on how the *replacement* strategy (under the 4Rs) impacts the energy security index with the proposed system compared to the existing energy security index for the same region. The proposed system will be regarded as a replacement and the corresponding amount of energy from the renewable wind resource replaces what would otherwise come from coal (through electricity generation) or oil. The overall impact results in a net improvement in the energy security for Charlottetown.

Equation (4.11) shows how much energy the heating service in the residential sector for Charlottetown would normally have consumed

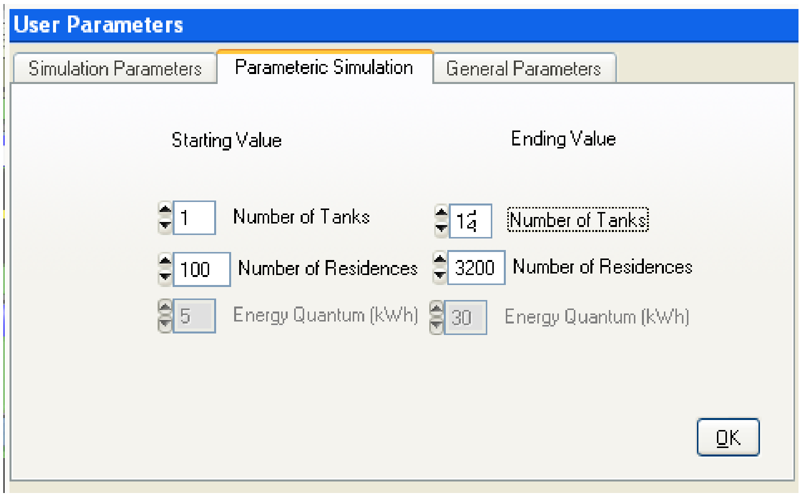
$$(15{,}000\, residences)(12271\ kWh + 3874\ kWh\ ) = \ 242.2\ GWh \qquad \textbf{(4.11)}$$

The case study results show that 13.03 GWh of that has been replaced at 1081 residences with energy from the renewable wind resource meaning that now only 229.2 GWh will come from energy insecure source resulting in an overall improvement to the energy security for this jurisdiction. The relative energy security improvement for Charlottetown, PE is improved.

The proposed system may also be regarded in terms of a restriction policy if new building requires adoption of storage systems connected to a renewable (wind in this case) source of energy. In this regard, energy security is improved through restriction of fossil fuel based heating in the residential sector. In general energy security can be improved through affordable and, with storage, available sources of energy for heating through replacement and restriction strategies.

4.7.Parametric Analysis Setup

Along with the tabs for general parameters shown in Figure 4.5 and the simulation parameters shown in Figure 4.6, one additional area requires discussion. The dialog in Figure 4.12 shows the tab on the user parameters dialog that is used to control the parametric sweep analysis. The user settings on the two other tabs are still valid, but the sweep starting values and ending values for the number of tanks contained in each residential system (the size of the energy store) and the number of residences connected to the system (the system loading) will override the corresponding settings used for the case study.



Starting Value
1 Number of Tanks
100 Number of Residences
5 Energy Quantum (kWh)

Ending Value
14 Number of Tanks
3200 Number of Residences
30 Energy Quantum (kWh)

Figure 4.12: Parametric Simulation User Parameters

As discussed earlier, varying the number of tanks that are part of each residential system ultimately vary the size of the energy store. The size of the energy store is therefore discretized to standard, fixed sized tanks and an integral number of tanks. The tank sizes are commonly available in 40, 60, 80 and 120 gallon sizes. It can be observed that in spite of the fact that there are constraints on the size of the energy store, it is not infinitely configurable but rather highly configurable in this regard. Equation (4.12) shows that there may be more than one way to construct a certain size of energy store.

$$6x80 \text{ gallon tanks} = 12x40 \text{ gallon tanks} = 8x60 \text{ gallon tanks} = 480 \text{ gallons} \tag{4.12}$$

For the parametric sweep, the tank size is set once in the simulation parameters tab and is fixed for the analysis. For this analysis, the 40 gallon tanks were used. Varying the size of the energy store is therefore accomplished through varying of the number of tanks that constitute each residential system. The range of values chosen for this analysis provided a range of energy storage sizes from small and a low cost single 40 gallon tank system to multiple-tank systems comparable to the larger ETS storage systems.

The parameters for the parametric sweep analysis were chosen around several factors. The normal loading of the system under the energy requirements of the locale used in the case study were calculated at 1081. The number of residences chosen for the starting value is one order of magnitude lower than normal loading. The ending value for the number of residences connected to this system is set to be the calculated number of residences that currently employ hydronic hot water heating systems and is assumed that they could most easily implement this system.

4.8.Parametric Analysis Results

The graphs of Figure 4.13 and Figure 4.14 highlight the principle results obtained from the parametric analysis. The discussion of these results follows presentation. Both plots are arranged and shown together to permit presentation of the tradeoffs in the system design parameters in terms of system loading (number of residences connected to the system) and energy storage size (size of individual tanks and number of tanks that comprise each residential system).

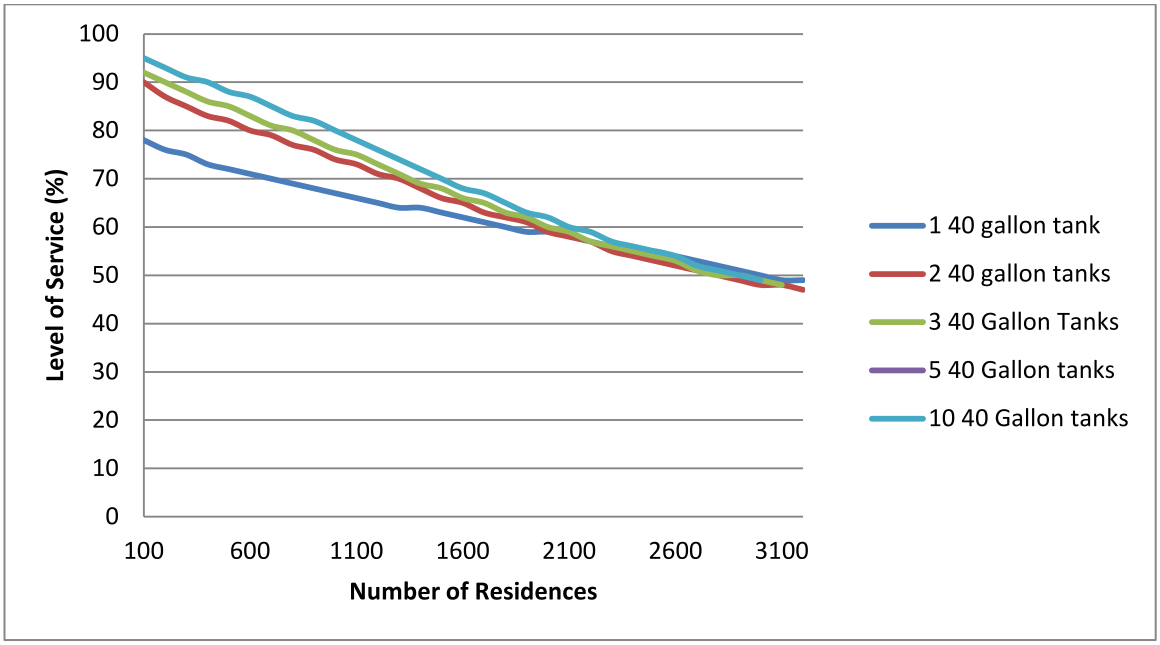


Figure 4.13: Level of Service to the Residence

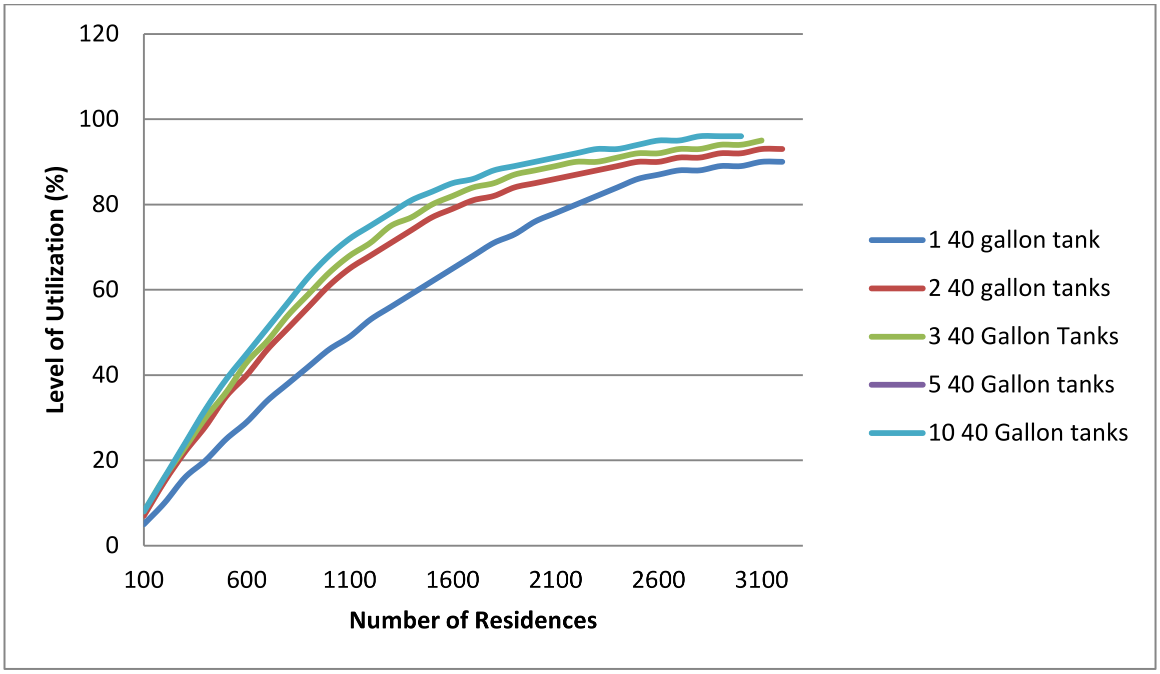


Figure 4.14: Level of Utilization of the Wind Resource

4.9.Discussion of Parametric Results

This section will discuss the results obtained for the parameter sweep analysis performed. The goal of this discussion is to answer the thesis question around the degree to which the proposed energy storage system could meet the heating demands in the residential sector.

4.9.1. Level of Service Performance Indicator

The graph in Figure 4.13 displays the level of service performance result when the parameters (1) size of the energy store and (2) the number of residences on the system are varied. The starting and ending values for the size of the energy store are chosen to provide insight into the performance of a range of sizes and prices for the thermal energy storage system. A single, 40-gallon electric hot water tank, as seen from the results, provides a reasonably high level of service. A larger system employing 10 40-gallon tanks does offer better performance but it is interesting that the improvement in the level of service from 2 tanks to 10 is within 10 percent.

The results show an almost linear effect that varying the number of residences connected (system loading) has on the level of service. Connecting more houses to the system will have the effect of loading down the system – making less of the available energy to others. Fewer houses connected results in a light loading of the system. It appears that even with light loading; the level of service approaches but ultimately cannot reach 100 percent.

As the number of residences connected to the system increased, this difference between the sizes of the energy store narrowed. The results seem to indicate that as the loading of the system increases, the size of the energy store appears to be a less important factor. One could conclude that the size of the energy store has less impact on the overall level of service to the residential customer than did the loading of the system. The performance of the system degrades almost linearly with increased loading.

4.9.2. Level of Utilization Performance Indicator

The graph in Figure 4.14 displays the level of utilization of the wind resource performance indicator result when the parameters (1) size of the energy store and (2) the number of residences on the system are varied.

As with the level of service to the residence, a larger system employing 10 tanks does not appear offer significantly better performance; that the improvement in the level of utilization of the wind resource when the size of the energy store is varied (from 2 tanks to 10) is negligible. The variance over the entire range of system loading is low.

The effect on level of utilization of the wind resource of loading on the system is non-linear. As the system loading is increased, the level of utilization increases. This result is consistent with what was expected and it makes sense that as more demand is placed on a fixed resource, the more likely that resource will get utilized. In the range of 100 to 700 residences, the level of utilization increase rapidly as the loading is increased. As the loading moves past the knee of the curve (past the point of about 1100 residences for normal loading), the increase in the level of utilization flattens out. The improvement in performance decreases as the loading moves past the knee.

4.10. Cost Analysis

The cost of the infrastructure to support these installations is not included in this analysis. The electrical infrastructure is assumed to be similar for both, given similar electrical requirement and power ratings. The differences between these system and the possibilities for configuration of the proposed system make comparison difficult. These systems differ in a number of ways but in order to make a reasonable comparison, they will be weighed on their thermal energy storage alone.

Table 4.3 shows the cost of various electric hot water heaters.

Table 4.3: Cost of Individual Electric Hot Water Heaters [51]

Capacity (Volume in Gallons / Litres)	Price (Canadian $)	Details
40 gallon / 184 litres	$305	Giant 152ETE
60 gallon / 284 litres	$395	Giant 172 ETE
80 gallon / 368 litres	$2000	A.L. Smith DRE80
120 gallon / 552 litres	$2700	A.L. Smith DRE120

In addition to the commercially available electric hot water tanks, the bill of materials shown in Table 4.4 shows other components are required to make a functioning system.

Table 4.4: Additional Components: Bill of Materials[51]

Item	Description	Cost Canadian ($)
Thermostatic Mixing Valves	Honeywell AM101 US	$100
Expansion tank	Flexcon TX30	$40
Circulator pump	UPS 1158	$85
Piping	Copper or PVC	$50

Items such as installation, the control system, electrical infrastructure and indirect water heaters which are common to both systems are not discussed. Table 4.5 show the overall cost of selected configurations of the proposed system. The cost of the system used in the case study comes in at $2645. The 80 and 120 gallon tanks are considered commercial (rather than residential) and are prohibitively expensive to be considered.

Table 4.5: Cost of Various Configurations of the Proposed System

Number of Tanks / Tank Size (Gallons)	Storage capacity (kWh)	Price (Canadian $)
1 / 40	7.1	$580
10 / 40	66.7	$3325
2/ 60	21.1	$1065
12 / 60	126.6	$5015
6 / 60	63	$2645

The cost of selected ETS technology is shown in Table 4.6 .

Table 4.6: Cost of Various Steffes ETS Space Heaters and Hydronic Furnaces [52]

Model	Storage capacity (kWh)	Description	Price (US$)
2102	13.5	Space Heater	$1012
2105	33.75	Space Heater	$1588
3120	86	House System	$3511
5120	120	Hydronic System	$3996

The costs of several thermal storage systems shown in Table 4.5 and Table 4.6 indicate that there are only marginal cost savings to be had under selected variations of the proposed system. The cost of the proposed system came in under the smallest ETS furnace (model 5120) but their capacities differ by a factor of 2. If the installation of the proposed system was taken into account, it is likely that there would be a cost disadvantage with the current design of the proposed system.

4.11. Advantages of the System Proposed

In the course of preparing this thesis, there are some observable advantages of this system over existing systems such as Electric-Thermal Storage.

- Marginally lower cost
- Non-specialized, commercially available CSA approved domestic hot water tanks
- Safe (water is the working fluid)
- Decentralized storage of renewable energy source in thermal energy
- Efficient, losses escape to the building envelop and contribute to space heating
- Energy storage is scalable
- Potentially for home constructor to implement this system
- Can integrate into existing residential building infrastructure
- Can (depending on size) potentially be relied upon for long term space heating and domestic hot water needs
- Does not intrude or displace into the living area of the dwelling.
- This energy is converted perfectly to heat and extracted as required to fulfill the space heating and domestic hot water needs of the residents.
- Could facilitate thermostatic setbacks during the overnight hours such as features available on programmable thermostats.
- High capacity: heat pumps [and room ETS units for example] have longer operation times than conventional furnaces because their heating capacity is considerably lower. (http://oee.nrcan.gc.ca/publications/infosource/pub/home/heating-heat-pump/asheatpumps.cfm)

4.12. Summary

This chapter presented the simulation tool software setup which was customized for the case study region chosen, Charlottetown, PE. The energy vital statistics on Charlottetown were discussed. The rationale around selection of the parameters was established and the configuration of the simulation software to perform a case study was shown. The tool was used to evaluate the performance of the proposed system with parameters as established and the corresponding case study results were discussed along with impacts on energy security for Charlottetown.

Using a range of values for the parameters swept, a parametric analysis was performed and the results of the parametric analysis were discussed. The cost comparison of the proposed system with other energy storage systems was completed.

The results of a case study and the results of parametric analyses were performed around the implementation of a system where residential dwellings had installed a thermal storage system energy produced from a modestly sized wind farm. The question central to this thesis has been answered, which was to determine the degree to which electricity produced from wind and employing thermal storage using electric hot water tanks can provide heating service in the residential sector.

Chapter 5 Conclusion

Recent statistics show that more than 80 percent of Canada's residential energy usage is for space and water heating (the heating service). If renewable sources of energy such as wind, solar, and tidal are expected to make an impact in northern hemisphere countries such as Canada, it makes sense to focus on energy reduction and fuel replacements targets that are both technically achievable and important to citizens. In regions with lengthy heating seasons, energy secure and low emission supplies of energy for heating in the residential sector is a challenge because of the price and supply volatility of overseas energy markets.

Electrical power suppliers treat the challenges of integrating wind-electricity and electrical demand separately. If heating demand could be met from a renewable yet variable supply of electricity, then both challenges could be addressed. One such approach is presented in the proposed system which employs off-the-shelf electric hot-water heaters in a thermal energy storage system.

In spite of advances in wind forecasting, wind is not without its drawbacks: the supply of wind and therefore the supply of energy from wind does not always correspond with the demand for energy. With higher initial capital costs, a low capacity factor compared with typical thermal (coal-fired) base-load generation and new investments in renewable technologies increasing year over year, if renewables are to meet even a portion of our energy requirements, this issue of storage must be addressed.

The issue of energy security can be improved through affordable and, with storage, available sources of energy for heating through replacement and restriction strategies. The work presented in this thesis has shown that through straight-forward thermal storage systems, the most can be made of a renewable resource such as wind. If wind is going to have maximum impact and be able to meet some or most of our energy demands, there must be a change in the way energy is presently being used – demand must follow supply and this is most easily accomplished through storage. The thermal storage of energy is the bridge between those times when the wind isn't blowing and when energy is needed for heating.

5.1.Discussion of Results

This thesis has addressed the central questions posed which was to determine the degree to which electricity produced from wind and employing thermal storage using commercially available electric hot water tanks can meet the demand for both space heating and domestic hot water in the residential sector. Using the data provided from the one-year period July 2002 through to July 2003, the thesis results showed that with a lightly loaded system of around 300 homes, homeowners could expect to get a significant percentage of their heating needs met while at the same time not utilizing the wind resource to its full potential. For the period analyzed and under normal system loading, homeowners employing the energy storage system could expect to have most of their heating needs met with wind. With heavier loading of 2500 residences, households could expect to have only some of their heating service needs met. Once again, the heating service accounts for more than 80 percent of the energy end-use in the residential sector so these findings still represent a significant portion of the residential sector's energy requirements.

The thesis results showed that the size of the energy store had less impact on the overall level of service to the residential customer than did the loading of the system. The results showed that there is only about a 10 percent difference between the smaller (and therefore less expensive) system studied (two 40-gallon tanks) and the largest (ten 40-gallon tanks) which means that a the homeowner could rely on a low-cost system to meet their needs while at the same time knowing that a significant portion of their energy needs are being met with a renewable source of energy that does not generate greenhouse gasses. The attractiveness of a low-cost, straight-forward and potentially do-it-yourself solution which offers a good end-result in terms of performance will be the impetus to implement the proposed system.

The results have also shown that such a system would have a positive impact on a jurisdiction's energy security. This conclusion is evidenced by how well the wind resource was utilized based on the most important system parameters,: the size of energy store (determined by the number of hot water heaters and the size of each) and the overall loading of the system (i.e. the number of residences connected to the system). Maximizing usage (i.e. maximum level of utilization) of the renewable wind resource through fuel replacement along with a corresponding reduction in the use of non-secure resources (such as imported coal) will result in an overall improvement to a jurisdiction's energy security. The results have shown that where otherwise carbon-intensive energy supplies were used, the more energy that is replaced with renewable and low carbon sources, the greater the relative energy security improvement to that region.

The thesis has also answered the question of how many residences could obtain 100 percent of their heating needs from the wind resource and the proposed system. They show that with a lightly-loaded system, the level of service approaches 100 percent of the residence's needs for heating but it seems unlikely that a backup source of energy would not be required. Without storage, energy demand must be coincident with wind supply; if not then heating requirements cannot be met. The undependable nature of the wind resource means that it cannot be completely relied upon for essential services such as heating in the residential sector and it points to the need for backup. While there was no definitive answer to the question of the maximum number of houses that could be supported under this system, the results showed the typical trade-offs with utilization and performance.

With a normally loaded system, much of the energy produced from the sample wind farm could have a consumer both ready and waiting in this thermal energy storage system. The results indicate that the more heavily loaded the system is, the higher the level of utilization of the renewable wind resource. The trade-off being that when the most is made of the renewable resource, there will be a corresponding reduction in the level of service to the homeowner. Also, like the level of service, the size of the thermal energy store had less impact on the overall performance which leads us to conclude that even small and low-cost systems present significant overall benefits.

With a heavily loaded system, the level of utilization of the wind resource approaches 100 percent but the level of service to the residential customer correspondingly declines. Again, there exists a tradeoff between meeting the needs of the individual residences and making the most use of the renewable resource. When the most is made of the renewable resource, the homeowners must rely on a backup energy source. Conversely, if wind generated electricity is to be expected to meet the vast majority of energy needs in the residential sector, the storage system is likely to be large and expensive and not result in an overall high level of utilization of the renewable resource.

It was shown that there was no optimal storage size but rather that a tradeoff between performance and the size exists. Increasing the size of the tanks and the number of tanks showed only marginal improvement in the performance of the system. The direct relationship between size and cost was also recognized. The analysis was performed for an array of average dwellings, so it remains a system feature that the size of the energy store can be discretely customized based upon the needs desired level of service of the consumer for their particular (non-average) dwelling.

The energy throughput to the storage system did not appear to be a key parameter in the determination of overall performance but remains a feature for systems when the energy requirements exceed or fall short of the average energy requirements for a jurisdiction. The impact the energy throughput parameter had was in how the available wind-energy was distributed among residences. Smaller quantities of energy delivery meant that more residences received a share (albeit a smaller share) when wind-energy was available.

5.2.Benefits

Through the preparation of this thesis, a number of benefits of the system proposed have come to light. Because the system is based around commercially available and CSA approved domestic hot water tanks, the implemented system with discrete components has a lower cost than other thermal energy storage systems such as ETS space heaters and ETS furnaces which are available to residential homeowners. The proposed system incorporating storage was designed specifically to take advantage of variable supplies of wind energy. Like its counterpart, the electric hydronic furnace, the proposed system does not intrude or displace any living area of the dwelling the way that ETS space heaters do.

The system itself represents the decentralized storage of [heat] energy (DES) which is known to have a number of advantages over large-scale energy-storage not least of which is the overall system efficiency. The standby losses of electric hot water heaters are low to begin with (compared to the amount of energy stored inside) but efficiency is improved even further in that losses escape to the building envelop and contribute to building space heating when demanded. Electrical transmission losses are minimized due to the close proximity of local generation under the DES model. Conversion losses are minimized because the conversion of electricity to heat is reasonably assumed to be 100 percent with electric resistance heaters. Energy once converted is extracted only as required to fulfill the space heating and domestic hot water needs of the residents.

Aside from the straight-forwardness of the system itself, the system may potentially be simple to implement. It is expected that the proposed system could integrate most easily into existing residential hydronic heating system infrastructure but is not strictly limited to this application. The system can respond to residential demands for space heating, domestic hot water or both. Depending on the size of the energy storage system, the proposed design could potentially be relied upon for long term space heating and domestic hot water needs. Because of the flexibility in the design in terms of the number of hot water heaters employed and the size of the individual heaters, the system's energy storage is discretely scalable and therefore customizable based on the individual needs of residences.

The system has the heating capacity to permit time-of-day temperature setbacks which can be problematic with some other renewable space heating systems like geothermal or ETS space heaters whose operational instructions recommend a single temperature setting. The flexibility of the proposed system is enhanced furthermore in that it could potentially be backed-up with off-peak electricity from the grid or thermal energy from a solar thermal installation.

5.3.Limitations

Through the preparation of this thesis, a number of limitations of the system proposed have come to light. The limitations should not be taken to discourage the implementation of the overall design. In general, the analysis has shown that the results are favourable and the recommendation shall be to proceed with a test implementation.

There are several components that cost analysis did not take into consideration and that was because items such as the indirect water heater and the control and switching system were considered as external to both the proposed system in this thesis and existing ETS furnaces. The cost advantages of the proposed system over existing electric-thermal storage systems is marginal and could be considered a disadvantage depending on the selected configuration of hot water tanks.

Because the system is based around commercially available and CSA approved electric hot water tanks, it is important to point out that these were not designed for this purpose and therefore may not perform as expected. The CSA approval will undoubtedly be voided in this case because they are being used in an application for which they were not designed. The operational parameters such as flow rate and pressure which dictate appropriate usage of the hot water heating appliance shall not be violated with the proposed design. The higher tank temperatures are not expected to be a cause of concern, although the higher pressures associated with the higher temperatures have been addressed in the design.

Another limitation that has been discussed is that although it is possible to integrate this system into any residential setting where a hydronic heating system could be installed, it is expected that it would be most easily integrated into residences which employ existing hydronic heating systems such as hot water baseboard or hot water in-floor radiant heating systems. Although similar in makeup to existing electric hydronic furnaces, this design was based on the need to store wind generated electricity for heating but overall may prove too simplistic or simply inadequate to be of practical long-term use.

It would appear that in most jurisdictions, the system could not be relied upon for 100 percent of the residences heating needs to handle those times of little or no wind, meaning that a backup supply of energy for heating will be required. In the examples considered, even with light system loading, 100 percent of the demand could not be met although it was close to 100 percent.

The wind data used is an excerpt from one year in history. Changing weather patterns attributed to climate change through anthropogenic sources may have an impact on the future nature of wind availability. Further to this and in spite of advanced forecasting techniques, wind has an intermittent nature. The data used to analyze the potential of this proposed system showed the power at the gate of the wind farm. In the analysis, this number was taken as the energy available for distribution and ignored any transmission losses. Although the case study assumed that the region analyzed was in reasonable proximity to allow neglecting these losses, that assumption may not always be valid. The data used does not indicate whether there was any compensation made for equipment servicing or equipment failure. The capacity factor of the electrical generation was calculated to be almost 40 percent; the normally accepted figure is closer to 30 percent. In a jurisdiction which does not exhibit an above average wind regime, the decision to proceed with a design such as the one presented should be based on an analysis (using the tool provided) rather than relying on results obtained for the locale which was chosen for the case study.

5.4.Future Work

The next logical step for this work is to implement the system to determine if it will work practically and what the real results might be. The analysis performed in this thesis showed that this system holds some promise but there is much to learn and many problems can be expected through the normal course of design implementation. As mentioned, the control system element must be addressed but the design could proceed without considering the control system if other constraints were put in place. For example, a downscaled version of the overall system employing a single 20kW wind generator connected to an array of hot water tanks is one possibility.

The issue of the control system, both the electrical and logic elements must be addressed because without these, the system is incomplete. The analysis attempted to model the behavior of a straight-forward control system but the details of the control and implementation were beyond the scope of this thesis. The dead-band, on-off controller employing upper and lower threshold temperature set points is typical of off-the-shelf electric water heaters. A higher order control algorithm which takes the rate at which energy is being supplied or extracted as well as the temperature thresholds may reveal an improvement in the level of service to the residential home owner or improvements in the level of utilization of the wind resource or both.

The limitations discussed reveal that more simulations with data from other years should be done to determine if the results obtained here are sound. Also, because the large-scale implementation of wind-electricity is still growing, long-term data for analysis is limited. Because of the apparent need for a backup source of energy, it would be interesting to see if this system could be integrated easily into existing solar thermal installations. An analysis could reveal if there were any improvements to be had with a thermal solar-electric hybrid system. Likewise, an extension of this work could take the demand for an off-peak backup electricity supply required to meet 100 percent of the energy needs into account.

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