Long-Term Statistical Analysis and Operational Studies of Wind Generation Penetration in the Ontario Power System

by

Amr El-Mazariky

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AUTHOR'S DECLARATION

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

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

Abstract

Ontario, as the rest of the world, is moving towards a clean energy sector and green economy and to this effect, the Government of Ontario has set a goal of phasing out all coal-fired generation by the end of the year 2014. Wind energy is one of the most mature renewable energy technologies; it is clean and abundant. With Canada's wind profile and wind energy potential, Ontario has focused on increasing the wind generation penetration in its electrical grid to compensate for the phasing out of coal-fired generation.

In this thesis, long-term statistical trend analysis of wind generation patterns in Ontario is carried out, using wind generation data sets of Ontario wind farms during 2007 – 2010, on hourly, monthly, seasonal, and yearly time-scales. The analysis carried out, includes, long-term total wind generation capacity factor (CF) trends on yearly, seasonal, and monthly scales. To arrive at a better understanding of the wind generation intermittency and variability in Ontario, long term wind generation variability trends are presented. The correlation between the CFs of Ontario's wind farms is determined using the Pearson Product- Moment Correlation Coefficient and examined against their distances from one another to understand the effect of geographic diversity for wind farms on total wind generation. The electricity system demand for on- and off-peak periods is analyzed to examine the contribution of wind generation during these periods. These analyses provide critical inputs and guidelines to planners and policy makers on the role that wind can play in the supply mix of Ontario when coal-fired generating units are replaced with wind generation. Expansion of wind generation capacity requires a closer examination of the location and quality of wind resources and a detailed understanding of its operational impacts on the transmission grid.

A transmission network model is further developed in the thesis, for Ontario, based on the 500 kV and 230 kV transmission corridors with their planned enhancements for the three specific years under study- 2010, 2015 and 2025. The zonal supply mix of generation resources included are, nuclear, wind, hydro, gas-fired and coal-fired generation. An optimal power flow model is developed considering the future years' demand and generation scenarios, and used in a deterministic case study. Subsequently, Monte Carlo simulations are carried out considering the variability and uncertainty of wind generation. Both case studies examine the effect of different wind generation penetration levels on the Ontario electrical grid and analyze long-term wind generation impacts. Wind generation is characterized by its variability and uncertainty. Hence, wind penetration in the electricity grid

presents major challenges to power system operators. Some of these challenges are tackled by this thesis, such as the operating reserves required for different levels of wind penetration to maintain the system's adequacy, the operating costs as a result of wind generation's intermittent nature, and the impact on power losses as a result of wind generation's dependability on its location. Moreover, the associated Green-House-Gas emissions with different penetration level are determined. The results quantify the impact of the different wind generation penetration levels on the Ontario's power system.

Acknowledgements

First and foremost, I would like to thank my supervisors, Professor Kankar Bhattacharya and Professor Jatin Nathwani, for their continuous guidance, support, and encouragement throughout the whole period of my studies at the University of Waterloo. Their professionalism and dedication is a source of inspiration. It was a great honor to work with them.

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A heartfelt gratitude goes to my parents for their endless love, and for supporting my career even though it meant being away from them.

Last but not least, words could not express my gratitude to my sister Nada El-Mazariky and brother Ismael El-Samahy for their endless support during my studies; I truly owe them every success to come in the future.

This thesis is dedicated to my loving family, my father Mohamed El-Mazariky, my mother Maha Khalil, my brother Ismael El-Samahy, and my sister Nada El-Mazariky.

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Nomenclature

i, j	Zones indices.
k	Set of conventional generators.
K	Total number of conventional generators.
N	Total number of zones.
a_k	Cost coefficient of conventional generator *k*, \$/MWh.
b_i	Cost coefficient of wind generation in zone *i*,\$/MWh.
c_i	Cost coefficient of reactive power compensation in zone *i*, \$/MVARh
e_k	GHG emissions coefficient of conventional generator *k*, tons/MWh.
d_i	GHG emissions coefficient of wind generation at zone *i*, tons/MWh.
W_k	Binary variable of generator *k*.
ΔP_k	Generation output from unit *k* above its minimum capability, p.u.
P_i	Total active power generation in zone *i* , p.u.
Q_i	Total reactive power generation in zone *i*, p.u.
Pw_i	Total active wind power generation capacity in zone *i*, p.u.
Qw_i	Total reactive wind power generation capacity in zone *i*, p.u.
Wcf_i	Capacity factor of wind generation in zone *i*.
PG_k	Active power generation of generator *k*, p.u.
QG_k	Reactive power generation of generator *k*, p.u.
P_{LOLU}	Total active power loss of largest generating unit with a probability 0.001.
V_i	Voltage magnitude at zone *i* bus bar.
δ_i	Voltage angle at bus *i*, radians.
G_{ij}	Conductance of the transmission corridor connecting zones *i* and *j*, p.u.

B_{ij} Susceptance of the transmission corridor connecting zones *i* and *j*, p.u.

Y_{ij} Admittance matrix element, p.u.

θ_{ij} Angle corresponding to the admittance matrix, radians.

Pd_i Active power demand in zone *i*, p.u.

Qd_i Reactive power demand in zone *i*, p.u.

$PG_k^{\min}$ Minimum active power limit of generator *k*, p.u.

$PG_k^{\max}$ Maximum active power limit of generator *k*, p.u.

$QG_k^{\min}$ Minimum reactive power limit of generator *k*, p.u.

$QG_k^{\max}$ Maximum reactive power limit of generator *k*, p.u.

Qc_i Reactive power output from a capacitor in zone *i*, p.u.

$Qc_i^{\min}$ Minimum reactive power limit of a capacitor in zone *i*, p.u.

$Qc_i^{\max}$ Maximum reactive power limit of a capacitor in zone *i*, p.u.

$V_i^{\min}$ Minimum allowable voltage in zone *i* bus bar.

$V_i^{\max}$ Maximum allowable voltage in zone *i* bus bar.

P_{ij} Power flow from zone *i* to zone *j*, p.u.

$P_{ij}^{\max}$ Maximum allowable power flow from zone *i* to zone *j*, p.u.

Chapter 1
Introduction

1.1 Motivation

Electricity production has been dominated by fossil-fuel generation over the last century. Fossil-fuel generation is cheap, dispatchable, and has locational flexibility, and adds to the reliability of the electricity grid by its fast ramping capabilities, namely gas-fired generation. However, they have some significant drawbacks. First, all fossil fuels are a non-renewable resource, and second the emissions associated from their combustion, referred to as green-house-gases (GHG) cause global warming. Meanwhile there are different types of energy sources that are available naturally. Some are available in direct forms such as solar energy while others in indirect ways such as wind, biomass, wave, tidal and geothermal energy. Those natural resources of energy can be harnessed and turned into useful electrical energy, and are called renewable energy as they are infinite and not depleted by their usage. The renewable energy resources contribute minimal amounts to the GHG emissions at the production stage, through lifecycle emissions resulting from equipment manufacturing, installation, material requirements and construction.

Wind energy is the one of the most mature amongst the renewable energy technologies; it is clean, abundant, free and most importantly it can generate huge amounts of electrical power as a wind-farm (WF). A WF may consist of hundreds of individual wind turbines aggregated and spread over hundreds of square kilometers.

Ontario's goal is to develop a cleaner energy economy. The Government of Ontario has set a goal of eliminating all coal-fired generation by the end of the year 2014, which is envisaged to decrease the GHG emissions from electricity generation to below 5 mega tons/year by 2014 [1]. Ontario's energy infrastructure will require refurbishment in the near future, as existing nuclear facilities will reach the end of their life cycle and all coal-fired generation are retired by 2014. With Canada's wind profile and wind energy potential, Ontario has focused on increasing the wind generation penetration in its electrical grid. According to the Canadian Wind Energy Association (CanWEA), 20% of Canada's electricity demand could be supplied by wind energy by the year 2025 [2].

The Ontario Green Energy Act (GEA) was introduced in the Ontario legislature on Feb.23, 2009 to enact the Energy Conservation Leadership Act of 2006 and the Energy Efficiency Act. The GEA proposes to create substantial employment in a green economy and reduce Ontario's impact on the climate. The Ontario government is creating programs and initiatives to support the green energy economy. An important program created within the GEA is the Feed-in-Tariff (FIT) program. In fact, since the program has been initiated on October 1st, 2009 the Ontario Power Authority (OPA) has received 1200 applications for the micro-FIT program, out of which 700 have been approved with a cumulative capacity of 8.6 MW, and 1000 applications for the FIT program with a cumulative capacity of 2500 MW still being assessed [3].

An expansion of installed wind generation requires a closer examination of the location and quality of wind resources and a detailed understanding of its operational impacts on the transmission grid, which is the work carried and presented in this thesis.

1.2 Wind Energy Overview

1.2.1 Overview of Wind Energy Development

In many electric utility systems, wind energy has become a significant electrical supply resource in the past 10 years, from 2000 to 2010, with 194,390 MW of nameplate capacity installed worldwide at the end of 2010, as presented in Figure 1-1. Wind energy is now “utility scale” and can affect utility system planning and operations for both generation and transmission [4].

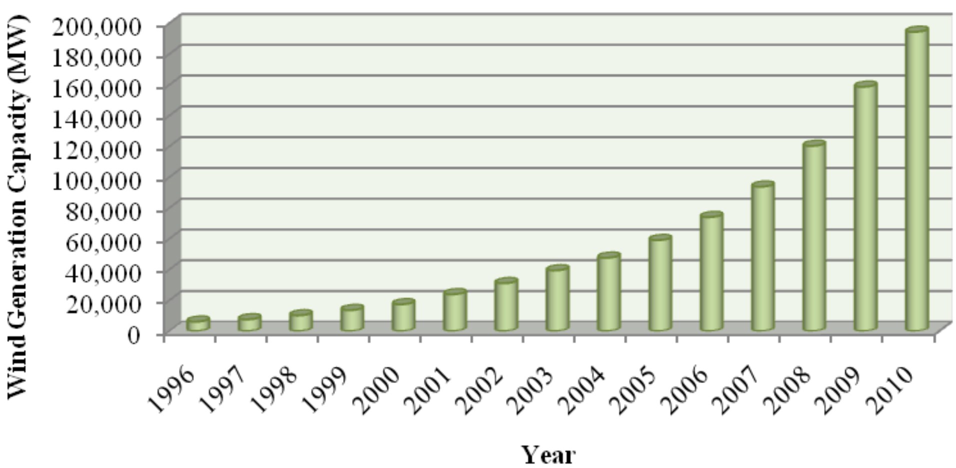


Figure 1-1: Global Cumulative Installed Wind Capacity 1996-2010 [4].

As observed in Figure 1-2, the global annual installed wind capacity is rapidly increasing, with a very high growth rate. The growth rate was 26.69%, 28.2%, and 32% for 2007, 2008, and 2009 respectively.

The global annual installed wind capacity in 2007 reached almost 20 GW, which was more than the global cumulative installed wind capacity in 2000.

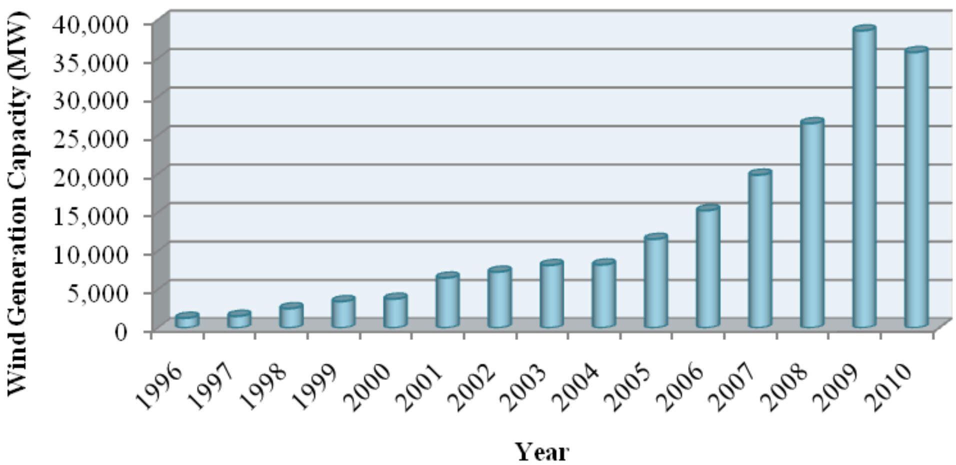


Figure 1-2: Global Annual Installed Wind Capacity 1996-2010 [4].

For the past several years the global wind energy market has developed on a large scale in Europe, North America (US), and Asia (China and India). As shown in Figure1-3, at the end of 2010, the wind energy markets in these countries accounted for 86% of total installed wind generation capacity. However, 80 countries including developed and developing, now have commercial WFs operating. According to the International Energy Agency (IEA), global wind energy capacity is expected to be 415 GW and 573 GW by the year 2020, and 2030 respectively [4]. A brief overview of the top countries with the highest percentage of wind generation penetration is presented next.

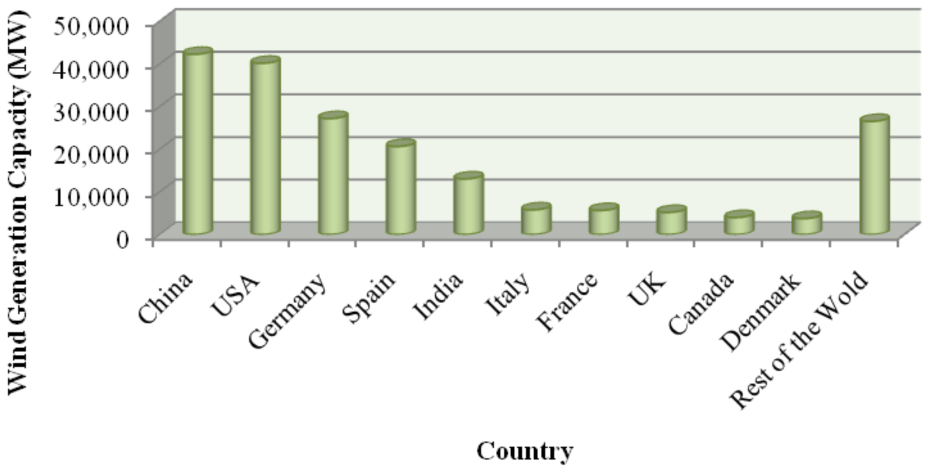


Figure1-3: Top 10 Countries Cumulative Capacity (Dec 2010) [4].

1.2.1.1 China

At the end of 2010, China installed 16.5 GW of wind capacity, which is 46.1% of the total global installed wind capacity that year, breaking their world record of 13.8 GW in the previous year, making it a world leader in terms of new installations in both 2009 and 2010 and the fastest growing wind industry. The total cumulative wind capacity in China is 42.3 GW accounting for 21.8% of the global cumulative wind capacity [4], making it also the world leader in terms of cumulative installed capacity. Despite this enormous growth in capacity, wind generation still provides less than 1% of China’s total electricity demand.

In 2005 the permanent committee of the National People’s Assembly passed the first renewable energy law and it was enforced in 2006. The law requires the energy distribution companies to purchase all the electricity produced from renewable resources [5].

1.2.1.2 US

In 2000, the US had a total wind capacity of only 2.5 GW, but since then its wind industry has been growing at a tremendous rate. By the end of 2010, the US was at the forefront of the global installed wind capacity with a total capacity of 40.2 GW, making it the second largest country in terms of cumulative installed capacity, after China. Wind generation now accounts for almost 2% of the US electricity demand, but with the right policies experts expect that percentage to significantly increase.

WFs are spread all over the country with 36 US states having utility-scale WFs. The leading state is Texas with 9 GW of wind energy. Texas has the world's largest WF (Roscoe WF) with a capacity of 781.5 MW; it consists of 627 wind-turbines and covers nearly 100,000 acres (400 km2). Iowa succeed Texas in terms of installed capacity with a capacity of 3.67 GW [6]. In 2009, 14% of Iowa's electricity demand was met by wind generation [7].

The US government has introduced various incentives for renewable energy production such as a National Production Tax Credit and the Renewable Energy Standard (RES) also know as renewable portfolio standard (RPS). The RES was introduced by the state of Texas, where it mandates that a certain percentage of the power generated in the state come from renewable sources. The RES is currently operational in 26 states.

1.2.1.3 Denmark

Denmark is the pioneer of wind energy in the world, with more than 12% of its electricity supply from wind energy in 2000. By the end of 2010, Denmark's total installed wind capacity was 3,752 MW representing only 1.9% of the global cumulative installed capacity, however this capacity represents 21.9% of Denmark's total electrical supply[8, 9], and often western Denmark's entire electricity demand is met by wind energy.

Denmark being a small country and interconnected with neighboring countries, does not need to install additional peak-load generation or consider more operating reserves to address the issue of intermittency of wind generation. As a result, Denmark has high exports of electricity to neighboring electricity markets.

1.2.1.4 Germany

Germany is the 3rd largest country in terms of installed wind capacity, coming after China and the US with a total installed wind capacity of 27.2 GW by the end of 2010. Wind generation contributes around 7% of the Germany's electricity demand.

A FIT program was introduced in Germany in 1991 that provided incentives for renewable generation and as a result, investments in renewable energy (mainly wind energy) received a significant boost. According to the German Wind Energy Association, the German turbine manufacturers hold 30% of the global market share with over 100,000 employees. In 2009, the FIT was revised to add more incentives to wind energy and the rates for both onshore and offshore wind were increased and an additional benefit was introduced for repowering WFs by replacing aging wind turbines with new ones of double or more the capacity [7].

1.2.1.5 Spain

Spain is the second largest European country in terms of installed wind capacity, coming after Germany and the fourth globally with 20.6 GW. In 2009, 14.5% of the country's electricity demand was met by wind generation.

The Spanish Wind Energy Association estimate that by 2020 40 GW of onshore and 5 GW of offshore wind capacities could be operational, contributing almost 30% of the country's electricity demand. However, these planned developments might be difficult to achieve with the new legislation in the Spanish government from delays in approvals of projects.

1.2.1.6 India

Installed wind capacity almost tripled in India in the last five years, with its total capacity increasing to 14.1 GW in March 2011(end of country's financial year) from 5.3 GW in March 2006 [10]. India is now the second largest country in Asia in terms of installed wind capacity, coming after China and the fifth globally. According to the Indian Wind Energy Association (InWEA), India has a gross potential of wind capacity of 48.5 GW.

India's wind energy potential is hindered due to the lack of a national-wide renewable energy policy. The RPS in India is governed by individual state governments, some states have high standards up to 14% while other have lower standards with only 3%, and some other states have no goals for renewable energy at all [11].

1.2.2 Overview of Wind Energy Development in Canada

Canada's wind profile is outstanding with a bountiful wind resource, alongside its huge landmass and enormous coastlines. In 2004, a study by Helimax Energie identified 101 GW of wind resource potential in southern Quebec alone, with only 25 km of existing transmission and distribution lines [12]. Canada did not join the race of wind energy development early, and the current total installed wind capacity is 4.6 GW which contributes to 2% of the country's electricity demand. According to the Canadian Wind Energy Association (CanWEA), 20% of Canada's electricity demand could be supplied by wind energy by the year 2025.

Each province has its own independent programs for renewable energy development and incentives, but on a federal level there has only been one program called ecoENERGY for Renewable Power Program that was launched in April 2007. Unfortunately no projects are signed after March 2011, and the program is not providing funds for any new projects. The program supports 104 renewable energy projects with a total capacity of 4.5 GW over the next 14 years, with an investment of $1.4 billion [13].

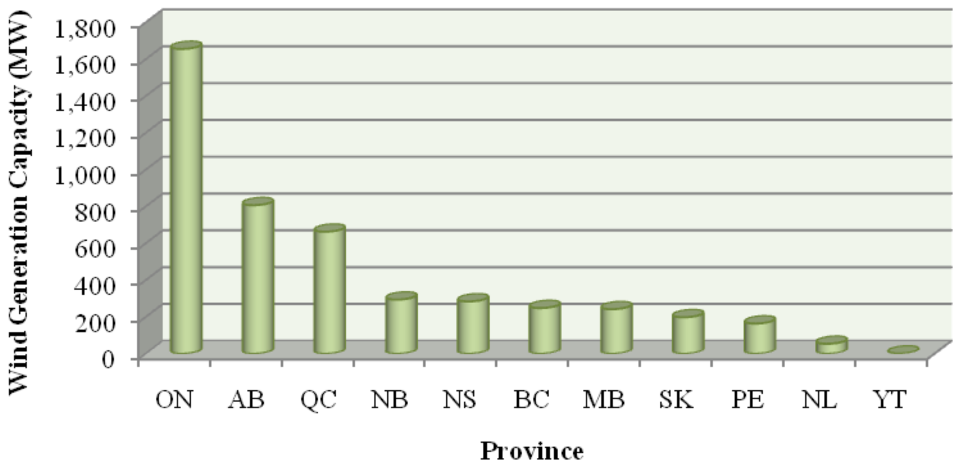


Figure1-4: Canada's Current Installed Wind Generation Capacity [2].

1.2.2.1 Wind Energy Development in Ontario

Ontario is the leader in wind energy development in Canada, with more than 2,600 MW of wind generation capacity expected to be in service by the end of 2011 [14]. According to the Integrated Power System Plan (IPSP) of OPA [15], Ontario's target for renewable resources is 15,700 MW by 2025, out of which 4,685 MW is expected to be wind generation. Wind generation is expected to be much more than what is planned for in the IPSP due to the FIT program.

A brief overview of the current and planned WFs in Ontario is presented, as they are used in various studies in this thesis. In Table 1-1, a list of Ontario's installed wind farms is provided, with their capacity in MW and their commercial operation date. In Table 1-2, a list of Ontario's wind farm projects, currently under development is presented with their capacity in MW and planned commercial operation date.

Table 1-1: Installed Wind Capacity in Ontario [16]

Wind farm	Capacity (MW)	Operational
Amaranth I, Township of Melanchthon	67.5	Mar 2006
Kingsbridge I, Huron County	39.6	Mar 2006
Port Burwell (Erie Shores), Norfolk and Elgin Counties	99	May 2006
Prince I, Sault Ste. Marie District	99	Sep 2006
Prince II, Sault Ste. Marie District	90	Nov 2006
Ripley, Township of Huron-Kinloss	76	Dec 2007
Port Alma (Kruger), Port Alma	101.2	Oct 2008
Amaranth II, Township of Melanchthon	132	Nov 2008
Underwood (Enbridge), Bruce County	181.5	Feb 2009
Wolfe Island, Township of Frontenac Islands	197.5	Jun 2009
Port Alma II (T3) (Kruger), Municipality of Chatham-Ken	101	Dec 2010
Gosfield Wind Project, Town of Kingsville	50.6	Jan 2011

Table 1-2: Wind Projects Currently Under Development [16]

Wind farm	Capacity (MW)	Expected date of commercial operation
Raleigh Wind Centre	78	2011-Q1
Talbot Wind Farm	98.9	2011-Q1
Greenwich Wind Farm	98.9	2011-Q3
McLean's Mountain Wind Farm I	50	2011-Q3
McLean's Mountain Wind Farm III	10	2011-Q3
Comber East Wind Project	82.8	2011-Q3
Comber West Wind Project	82.8	2011-Q3
Pointe Aux Roche Wind	48.6	2011-Q3

Conestoga Wind Energy Centre I	69	2011-Q4
Summerhaven Wind Energy Centre	125	2012-Q1
Bow Lake Phase I	20	2012-Q2

The location of the current and planned wind farms in Ontario are shown in Figure 1-5 [IESO]. As observed, most of the wind farms are located in southwestern Ontario, this is because of the region's wind speed profile in the region and being close to the Toronto area, which is the demand center of the province.

Figure 1-5: Wind Farms in Ontario [Source: IESO]

1.3 Objectives

Based on the discussions presented earlier, the following are the main goals of the research presented in this thesis:

- Long-term statistical trend analysis of wind generation patterns in Ontario, using various wind generation data sets of Ontario wind farms during 2007 – 2010, on hourly, monthly, seasonal and yearly time-scales.
- Examine the spatial geographic distribution effect of WF in Ontario on total wind generation, using the Pearson Product-Moment Correlation Coefficient.
- Properly model Ontario's current transmission system and planned transmission expansions and estimate Ontario's future zonal conventional and wind generation capacities, and the peak demand.
- Develop an Optimal Power Flow (OPF) model that accounts for the variability of wind generation by incorporating Monte Carlo simulations.
- Long-term system operational studies of wind penetration in Ontario power system through deterministic and probabilistic case studies to quantify the impacts of the different wind generation penetration levels.

1.4 Thesis Outline

This thesis is structured as five chapters. Following the introductory chapter a background and a literature review are presented in Chapter 2 where research publications pertaining to wind analysis and wind penetration impacts on electricity grids are discussed. Chapter 3 presents a detailed long-term trend analysis for wind generation penetration on Ontario's power system. Chapter 4 presents an OPF model which is used in examining the impacts of current and future wind generation penetration on Ontario's power system. Finally, the main conclusions, and contributions of this thesis and possible future work are highlighted in Chapter 5.

Chapter 2
Background and Literature Review

2.1 Introduction

Wind has been a source of energy for thousands of years; it was first used by the ancient Egyptians to sail their ship, and later people used it to grind up their grains or to pump water. Nowadays the same concept is applied to generate electricity. The kinetic energy in the wind is captured by the blades of the windmill and through the wind turbine it is converted into mechanical energy which is converted into electrical energy through a generator as depicted in Figure 2-1. A brief overview of the major components of the modern windmill and its modeling is presented next.

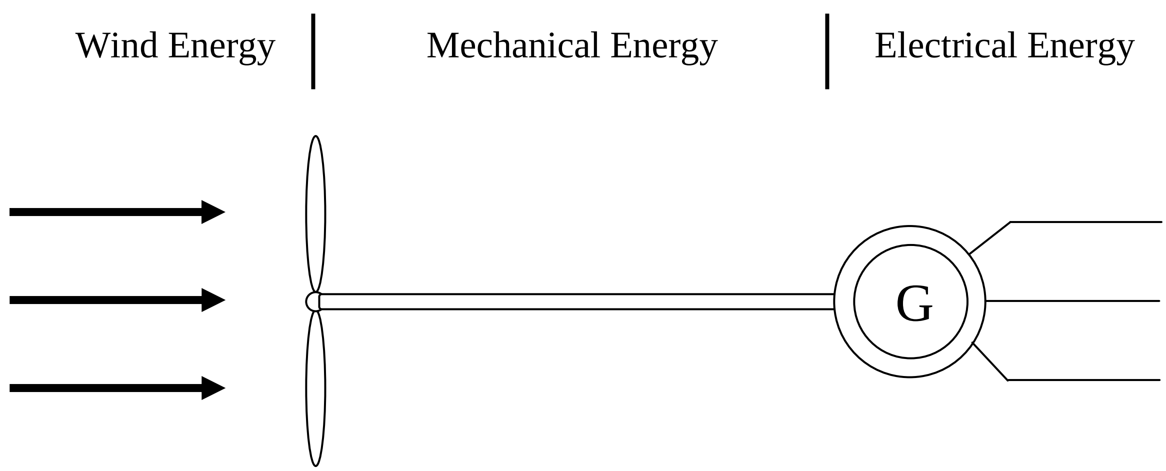


Figure 2-1: Simplified Wind Generation Process.

2.2 Wind Turbine

Wind turbines are mainly classified based on their axis of rotation, however there are other classifications within such as the wind direction (upwind or downwind), mode of operation (constant or variable speed), and number of blades (one, two, three, or multiple). Horizontal axis wind turbine (HAWT) is more dominant in the industry than the vertical axis wind turbine (VAWT).

HAWT comprises of a vertically erect tubular steel tower that ranges from 10 to 120 meters tall and above it are the blades, main rotor shaft and the generator house. The numbers of blades vary from one to three; the aerodynamic efficiency increases with increasing the number of blades, however the cost will consequently increase as well, and fewer blades are more efficient with lower wind speeds. The blade sizes ranges from 20 to 40 meters or more. HAWT have to operate facing the wind direction; upwind. A wind vane is used to change the direction of the turbine in case of small size, while in larger turbines a wind sensor coupled with a servo motor is used. The rotational speed of the rotor shaft caused by wind is stepped up to 1200-1800 rpm using a gear box, to be suitable to drive the electric generator. Some models operate at constant speed, but more energy can be collected by variable-speed turbines which use a solid-state power converter to interface with the transmission system. The electrical power output is in the range of 0.15 MW to 5 MW. All turbines are equipped with furling features to avoid damage at high wind speeds [17]. The dominant wind turbine in the industry is the 3 bladed, upwind, variable speed, pitch regulated HAWT [18].

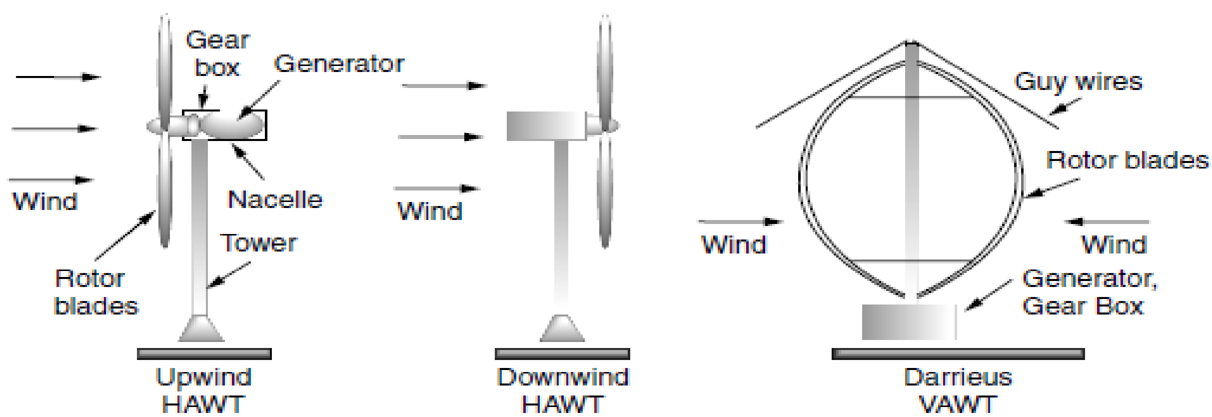


Figure 2-2: Types of Wind Turbines [17].

There are currently four types of wind generators; Type A – Type D. Type A is a squirrel cage induction generator, Type B&C are slip ring induction generators, and Type D is a synchronous generator.

2.2.1 Type A

As shown in Figure 2-3, Type A is a squirrel cage induction generator, it is mainly used with constant speed wind turbines. The generator shaft and turbine shaft are coupled through a gear box. The induction generator tends to have a high starting current, which is reduced using a soft starter. Compensating capacitors are used to provide sufficient reactive power for the induction generator.

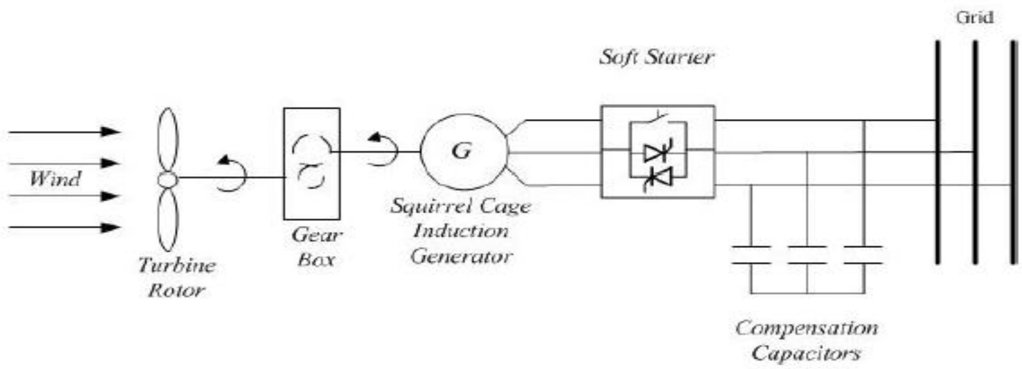


Figure 2-3: Type A - Constant Speed Wind Turbines [19].

2.2.2 Type B

As shown in Figure 2-4, Type B is a wound rotor induction generator, it is mainly used with limited variable speed wind turbines. The generator shaft and turbine shaft are coupled through a gear box. The speed of the rotor is controlled by the variable resistance added to the rotor resistances. The turbine has a limited variable speed as this speed control technique is only useful in the range of 50% to 100% of full speed. The main drawback of this Type is the power consumed by the additional resistance.

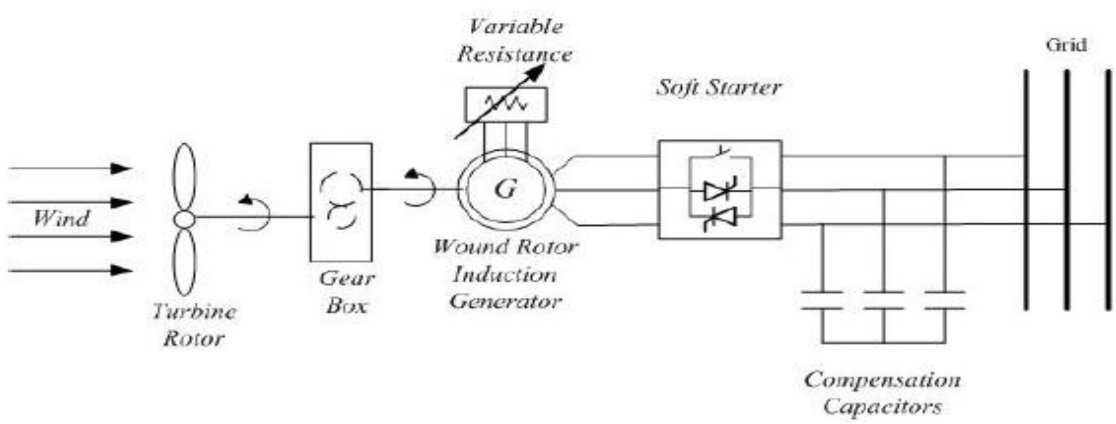


Figure 2-4: Type B - Limited Variable Speed Wind Turbines [19].

2.2.3 Type C

As shown in Figure 2-5, Type C is a Doubly Fed Induction Generator, mainly used with variable speed wind turbines. The generator shaft and turbine shaft are coupled through a gear box. The rotor windings are connected to the grid via slip rings and back-to-back voltage source converter that controls both the rotor and the grid currents. By using the converter to control the rotor currents, it is possible to adjust the active and reactive power fed to the grid from the stator independent of the generator's turning speed.

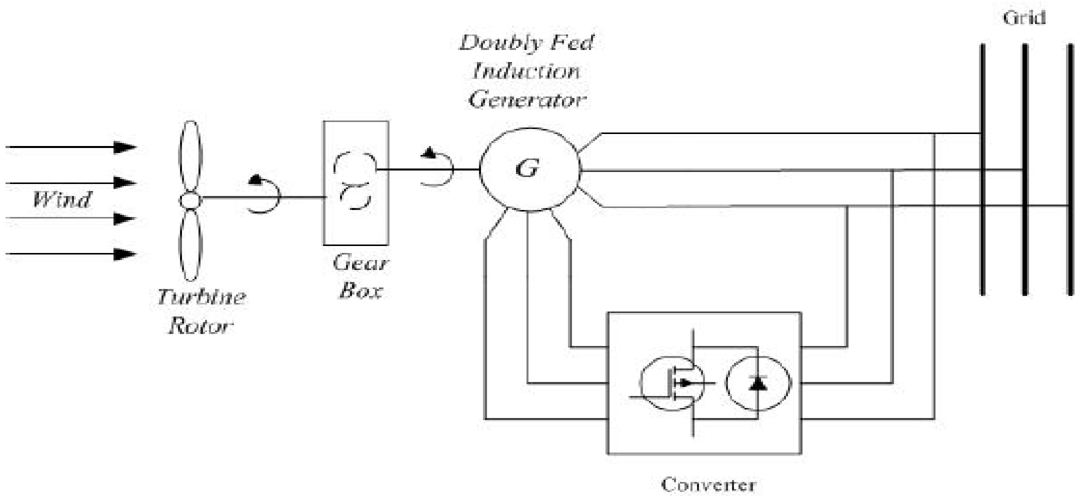


Figure 2-5: Type C - Variable Speed Wind Turbines with Partial Scale Frequency Converters [19].

2.2.4 Type D

As shown in Figure 2-6, Type D is a synchronous generator, mainly used with variable speed wind turbines. These turbines are gear-less as synchronous generators are low speed multi-pole generators, connected to the grid by a back-to-back frequency converter. By using the converter to control the rotor current, it is possible to adjust the active and reactive power fed to the grid from the stator, independent of the generator's turning speed.

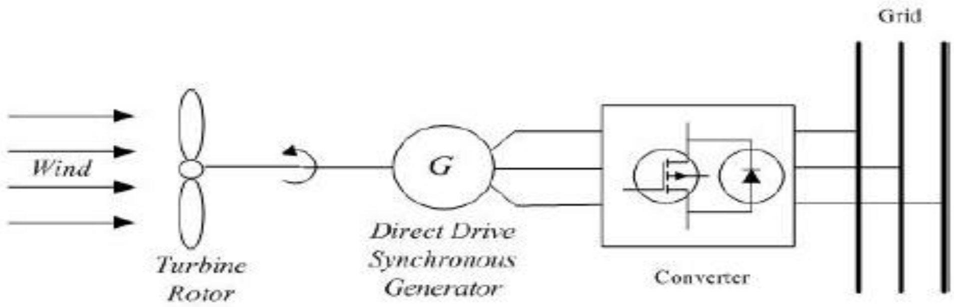


Figure 2-6: Type D - Variable Speed Wind Turbines with Full-Scale Frequency Converters [19].

2.3 Wind Modeling

2.3.1 Wind Turbine Power

A wind turbine active power output is function of the air density $\rho(kg/m^3)$, the cross-sectional area through which the wind passes $A(m^2)$, and the average wind-speed normal to this area $v(m/s)$. The relationship is given by [17] :

$$Pw = \frac{1}{2}\rho A(v^3)_{avg} \tag{2. 1}$$

The average value of the cubic power of wind speed is obtained from the wind speed's general probability density function (PDF). This function $f(v)$ can be expressed mathematically using the Weibull PDF given by,

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{2. 2}$$

Where,

k : Shape parameter.

c : Scale parameter given by $\frac{2}{\sqrt{\pi}}\bar{v}$.

$\bar{v}$: Average wind speed.

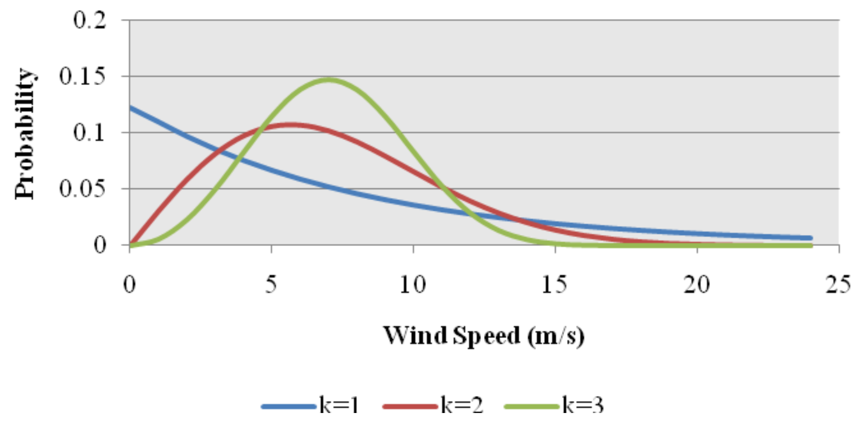


Figure 2-7: Weibull PDF with Different Shape Parameter (k).

The Weibull PDF is depicted in Figure 2-7 with a constant c of 8 and a varying k. Heuristically, it can be said that when $k = 2$ it represents best, the typical wind speed distribution, this PDF is known as the Rayleigh PDF and can be expressed mathematically as a function of the wind speed by Equation(2.3**)**. The effect of changing the average wind speed and hence the c , on the shape of the Rayleigh PDF is shown in Figure 2-8.

$$f(v) = \frac{\pi v}{2\bar{v}^{2}} \exp\left[-\frac{\pi}{4}\left(\frac{v}{\bar{v}}\right)^{2} \right] \tag{2. 3}$$

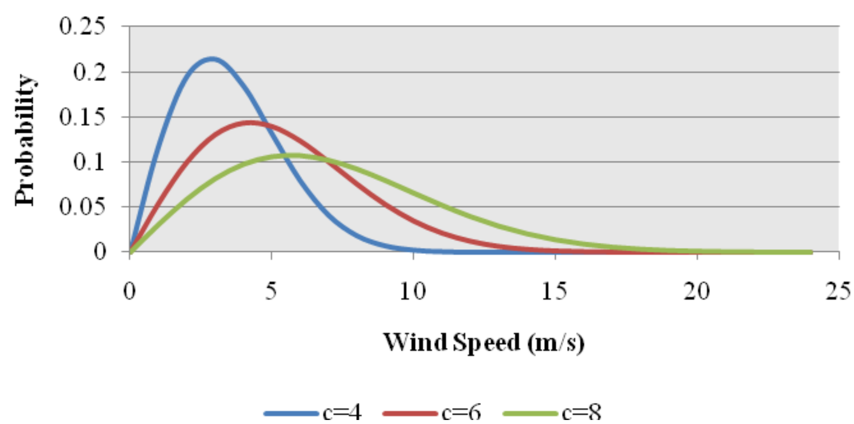


Figure 2-8: Rayleigh PDF with Varying Scale Parameter (c).

2.3.2 Wind Speed-Power Relation

Wind turbine active power production as a function of the wind-speed given below. For wind speeds below a certain value, referred to as the "cut-in" speed, the wind turbine will not generate usable active power, as it will not be able to overcome the friction in the drive-train of the turbine, and even if it rotates the generator it may not be enough to excite the generator field windings. Above the cut-in speed, the generator starts producing active power that increases as a cubic function of the wind-speed until it reaches the rated wind-speed of the turbine. The turbine produces its rated active power at the rated wind-speed, however as the wind speed increases a shedding mechanism takes place to protect the generator from exceeding its ratings. There are 3 shedding approaches for large turbines: active pitch-control system, passive stall-control design, and a combination of the two [17]. When the wind speed exceeds a certain value referred to as the "cut-out" speed, the machine is forced to shut down as a protection mechanism.

$$P_w(v) = \begin{cases} 0 & 0 \le v \le v_{ci} \\ (A + Bv + Cv^2)\,P_{rated} & v_{ci} \le v \le v_r \\ P_{rated} & v_r \le v \le v_{co} \\ 0 & v \ge v_{co} \end{cases} \tag{2. 4}$$

Where,

$$A = \frac{1}{(v_{ci} - v_r)^2}\left[v_{ci}(v_{ci} + v_r) - 4(v_{vi}v_r)\left(\frac{v_{ci} + v_r}{2v_r}\right)^3 \right] \tag{2. 5}$$

$$B = \frac{1}{(v_{ci} - v_r)^2}\left[4(v_{ci} + v_r)\left(\frac{v_{ci} + v_r}{2v_r}\right)^3 - (3v_{vi} + v_r) \right] \tag{2. 6}$$

$$C = \frac{1}{(v_{ci} - v_r)^2}\left[2 - 4\left(\frac{v_{ci} + v_r}{2v_r}\right)^3 \right] \tag{2. 7}$$

And,

$P_w(v)$: Wind turbine active power output at wind-speed v.

P_{rated}: Wind turbine rated active power output.

v_{ci}: Cut-in wind speed.

v_{co} : Cut-out wind speed.

v_r : Rated wind speed.

As illustrative example of the wind speed-power relation, an ideal wind turbine power curve, is presented in Figure 2-9 assuming that the turbine rated active power output is 1.5 MW, and 3 m/s, 16 m/s, and 24 m/s for the cut-in speed, rated wind speed, and the cut-out speed respectively.

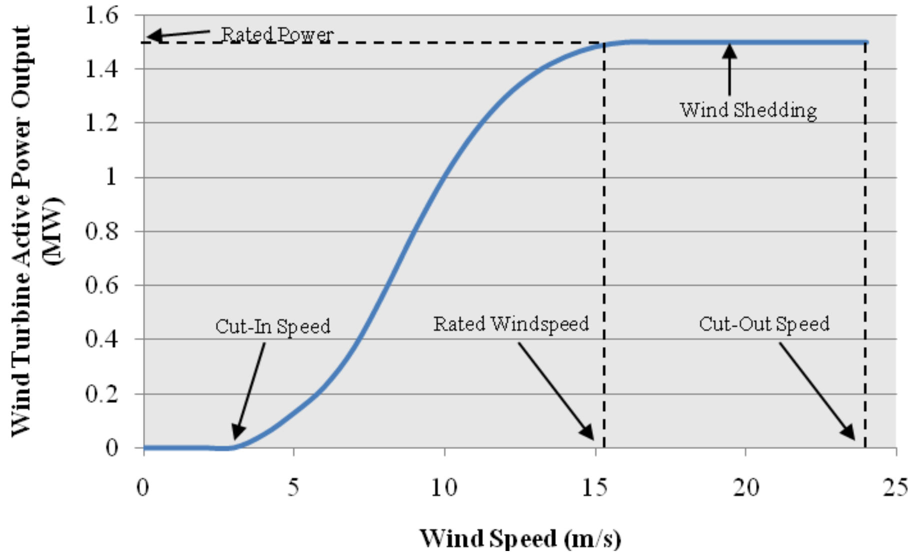


Figure 2-9: Ideal Wind Turbine Power Curve.

2.4 Operating Reserves

Operating reserve as defined by the Independent Electricity System Operator (IESO) of Ontario is the stand-by power or demand reduction that can be called upon with a short notice to deal with an unexpected mismatch between generation and load.

An important part of the reliability of an electricity grid is to always have enough energy to meet its demand. However, contingencies such as sudden increase in demand, loss of generation, or loss of a transmission element might occur that can disturb the balance of supply and demand and thus sufficient operating reserves must always be planned for, to overcome such events. The IESO classifies the operating reserves into three categories based on the time required to bring the energy into use and their sum is the total operating reserves, as follows:

- 10-minute synchronized (spinning) – 10S

- 10-minute non-synchronized (non-spinning) – 10N
- 30-minute non-synchronized – 30N

The amount of total 10-minute reserve (10S+10N) required by the IESO must be able to cover the largest single contingency that might occur, which is 900 MW, that is equivalent to the loss of the largest single generation unit in the Ontario system. Usually 25% of that is spinning (10S) and 75% non-spinning (10N). The amount of 30-minute reserve (30N) required by the IESO is equal to the greater of: half of the second largest single contingency, or the largest commissioning generating unit. These reserves are not synchronized.

One of the commonly used reliability indices used by the IESO and other power system operators, and used in this thesis is the Generation Reserve Margin (GRM), which is defined as: The capacity reserve available in the system during the peak load occurrence, as a percent of the system peak load demand [20].

$$GRM(in\,\%) = \frac{Cap^{Peak} - PD^{Peak}}{PD^{Peak}} \times 100 \qquad (2.\,8)$$

Where,

Cap^{Peak} : Capacity in service during the peak demand, in MW.

PD^{Peak} : Peak demand, in MW.

2.5 Review of Literature

Many studies on the impacts of integration of wind generation on power systems have been carried out by various organizations along with a multitude of research, have been reported in literature. The studies and researches focus on the operating reserve and their associated costs, GHG emissions and impacts on the transmission networks. A brief overview of these impacts is presented next.

2.5.1 Impact on Operating Reserve

Numerous methods have been developed by researchers in order to quantify the operating reserve requirements associated with wind generation penetration. The methods have varied widely from statistical approaches to probabilistic. The most popular statistical approach used in wind integration studies for utilities is the three-standard-deviation (3σ) of wind variability method, wherein the additional operating reserve is estimated by calculating the 3σ of the PDF of the time series of load with wind generation minus the load time series alone. In wind integration study by Manitoba Hydro the 3σ method is used to model the uncertainty of wind and hence calculate the associated operating reserves [21].

However the outcome of the study is not accepted by Manitoba Hydro as the operating reserves resulting therefrom are very low, during extreme wind changes and hence Manitoba Hydro rejected the method. The Utility Wind Integration Group (UWIG) agreed that 5σ to 7σ might be more appropriate to model the uncertainty of wind. Manitoba Hydro abandoned the 3σ method and modeled the Automatic Generation Control (AGC) and real time hydro generator response to quantify the operating reserves more accurately which results in estimated operating reserves two times greater than that obtained by the 3σ method. However in studies on the wind integration in the Nordic countries [22] and Sweden [23] only 4σ reported to be adopted.

Other approaches apply modifications to the power flow model to account for the uncertainty of wind in quantifying the operating reserves associated with wind generation penetration. In [24], a stationary power flow (SPF) is proposed to simulate and assess the impacts of large-scale wind integration on the operating reserves and uses the UK system as a case study. The SPF method is defined as the use of a sequence of stationary power flow analyses to capture slow system dynamics in the time-scale of minutes, from stationary droop response through fast reserves to scheduled generation changes, while transient dynamics are neglected. In [25], a stochastic optimal power flow method to quantify the operating reserves is presented while maintaining the system reliability and economic efficiency.

Probabilistic approaches to quantify operating reserves are vastly reported in literature. Monte Carlo simulations are applied in [26] to perform high level analysis of risks associated with varying wind penetrations. In [27], a new probabilistic approach that accounts for the uncertainty in wind generation and uses the all-Ireland system as a case study is presented. The approach links the system operating reserves at a given hour with the system reliability over the year. The study shows that the operating reserves increases moderately as the wind penetration increases. In [28], Markov-models are considered in WF modeling to account for the different wind penetration levels and machine failures. In [29], the operating reserves are probabilistically quantified using a wider reliability framework that includes conventional and well-being analyses. The well-being analysis framework provides a bridge between the deterministic and probabilistic approaches to bulk power system adequacy and security assessment using the operating states designated as healthy, marginal and at risk [30]. The well-being analysis is used in [31] in a probabilistic method that investigates the behavior of reliability indices while quantifying the operating reserves requirements associated with wind generation penetration. A sequential Monte Carlo simulation is presented in [30] to incorporate the load forecast uncertainty on case studies where wind is either added to a system or replaces some existing conventional generation. A Monte Carlo method is reported in [32] to generate random values of the hourly power output of each wind turbine to determine the availability of each wind turbine. To evaluate the adequacy of wind farms, random values are generated to compare with the availability of each wind turbine of the wind farms to determine the inclusion of each wind turbine for determining power output of wind farms. The methodology is repeated for number of iterations to obtain the LOLE. The LOLE is obtained as 164.87 hr/year, meaning the wind farm reliability contribution is 42.75% in meeting the load demand. In [33], the universal generating function technique is used to represent the system generation and load models taking into account the intermittency of wind, load uncertainty and wind turbine outages. In [34], a stochastic programming based market-clearing model that considers the network constraints and the cost of both load shedding and wind spillage is proposed. In [35], a model that combines a deterministic renewable portfolio planning module with a Monte Carlo simulation is proposed. The operating reserves are quantified such that they meet a loss of load expectation (LOLE) requirement of one day in 10 years.

Another approach to quantify the operating reserves requirements using time series analysis is reported in [36] based on Fourier analysis where the operating reserves were computed to meet a specific Loss of Load Probability (LOLP). LOLP is an index that examines the probabilities of simultaneous outages of units, that together with daily peak loads, determines the number of days per year of expected capacity shortages [20]. It is stated in [37] that wind generation can contribute to a reduction in LOLP.

A study on Xcel North system of Minnesota shows that an addition of 1,500 MW of wind capacity which correspond to 15% of the peak demand, requires an increase in the operating reserves by 8 MW [38], while another study on the New York system shows that the addition of 3,300 MW of wind capacity, corresponding to 10% of the peak demand, requires an increase in the operating reserves by 36 MW [39]. In [27], with 1,500 MW of wind capacity in the all-Ireland system the operating reserves required increased than the case with no wind by 12% in the best case scenario and by 44% in the worst. In [40], wind integration studies for different utilities around the world are reported. It is found that for 10% wind generation penetration an increase in the operating reserves to the order of 1% to 5% of the wind capacity is required, to maintain the adequacy of the system, while 20% penetration requires a 4% to 7% increase in the operating reserves. Using these results a study by Manitoba Hydro estimated that for 26% wind generation penetration an increase in operating reserves to the order of 9% of the wind capacity is required in its system to maintain the adequacy, while 35% penetration requires a 17% increase in the operating reserves [21]. In a study by General Electric presented to the OPA, IESO, and CanWEA [41] additional operating reserves required are found to be negligible with 5,000 MW of wind generation capacity or less, and only becomes more significant with higher wind penetration. It is found that a 10,000 MW installed wind generation capacity requires an increase in the operating reserves by 11%. In a wind integration study on the four Nordic countries by [22], the increased operating reserves are determined to be 1.5% to 4% of the installed wind generation capacity at a 10% wind generation penetration [22].

2.5.2 Impacts on Operation Costs

Unlike the operating reserves, the studies on the impact on the system operation costs associated with wind integration on power systems are inconclusive, some studies show that as wind generation penetration increases the operation cost increases, while some studies show that they decrease. The operation costs changes with wind generation penetration as a result of wind intermittency and uncertainty. Wind generation penetration in the order of 20% to 30% is investigated in numerous studies and are found to raise economic issues more than physical ones [37]. According to [34, 42-45] the operation costs decreases with the increase in wind generation penetration. In [34], it is stated that the reduction in operation costs may be hindered as a result of network bottlenecks caused by wind generation. In [45], it is mentioned that the operation costs tends to drop when more wind generation capacity is added to the system, however this reduction is because of the assumed zero costs for WFs. In [44], the medium term operation costs are reportedly reduced with wind penetration but it is only a transient phenomenon and is expected to increase in the long term. A study in [43] on the Belgium system shows that the operation costs reduce by 56K €/MW of installed wind generation capacity per year, it was also stated that wind speed forecast errors do not have a significant effect on this cost. A major aspect of operation cost changes due to wind is because of forecasting errors. In [42], it is estimated that by reducing the forecasting errors by 20% a cost reduction of 15M €/year is achieved in Germany.

According to [26, 27, 37, 46-49] the operation costs increases with the increase in wind generation penetration. In [26], it was found that the expected cost of most of the generation portfolios increases as wind penetration increase, while their cost uncertainty decrease. In [37], it is found that wind uncertainty increases the operation costs by 5 $/MWh at wind generation penetration of 20% to 30%. In [49], it is found that the operation costs increase by about 10% of the wholesale value of wind generation at a 20% wind generation penetration. In [27], it is estimated that the operation costs are 2 $/MWh to 4 $/MWh for low penetration levels, whereas they may be up to 6 $/MWh for high penetration levels. In a study carried out on the UK electricity system [46] it is noted that extending the penetration of renewable generation to 20% or 30% of the demand by 2020 would increase system costs. Another wind integration study on the UK electricity system carried out in [48], concludes that 20% wind generation penetration would increase the current cost by 5%.

According to [47, 50] the operation costs increase for a country importing more wind generation because its exporting possibilities decrease. In [50] it is stated that Germany has the highest integration costs as its wind generation capacity is not geographically dispersed in the country with north-western Germany having the highest share of wind generation. The operation costs of Denmark, which has the highest wind penetration, in Europe, is found to be much lower than that of Germany, as Denmark has excellent export possibilities to neighboring countries. In [47], it is suggested that wind generation facilities should be geographically dispersed to reduce the operation costs, especially when transmission capacity is limited.

2.5.3 Impacts on Transmission Network

The impacts of wind generation penetration on the transmission network depends on its distribution across the network, its location with respect to the demand, and the correlation between wind generation output and demand consumption. Wind generation may change the power flow direction, reduce or increase power losses and bottlenecks [51]. In [45], it is found that wind generation impact depends on its location and network constraints, and as wind generation penetration increases, the total network losses decrease. In [52], it is noted that large-scale wind generation will not reach its potential without a corresponding significant expansion of the electric transmission infrastructure.

2.6 Concluding Remarks

This chapter presents an overview of wind energy generation penetration. The major technologies utilized in harnessing wind energy are discussed; different types of wind turbines and wind generators, and is concluded that the dominant wind turbine in the industry is the 3 bladed, upwind, variable speed, pitch regulated horizontal axis wind turbine. Wind modeling is also discussed, wherein turbine power and wind speed-power relationship are presented in detail.

A brief literature review of wind integration studies, assessing the impact of wind generation penetration on power systems is presented, with the different methodologies used. It is concluded that an increase in the requirements of operating reserves is required with the increase in wind generation penetration. Unlike the operating reserves, the studies on the impact on the system operation costs associated with wind integration on power systems are inconclusive, some studies show that as wind generation penetration increases the operation cost increases, while some studies show that they decrease.

Chapter 3

Long-term Statistical Analysis of Wind Generation in Ontario

3.1 Introduction

Ontario's goal is to develop a cleaner energy economy and to this effect, the Government of Ontario has set a goal of eliminating all coal-fired generation by the end of the year 2014. Wind energy is one of the most mature amongst the renewable energy technologies; it is clean and abundant. With Canada's wind profile and wind energy potential, Ontario has focused upon increasing the wind generation penetration in its electrical grid to compensate for the phased-out coal-fired generation. According to the Canadian Wind Energy Association (CanWEA), 20% of Canada's electricity demand could be supplied by wind energy by the year 2025. Expansion of wind generation capacity requires a closer examination of the location and quality of wind resources and a detailed understanding of its operational impacts on the transmission grid.

Ontario's current electricity market has an installed generation capacity of 34,731 MW, out of which 3.6% is wind generation (Figure 3-1). This chapter is focused on analyzing the wind generation behavior and trends in the Ontario electricity market. These analyses are carried out to provide critical input and guidelines to planners and policy makers on the role that wind can play in the supply mix of Ontario when coal-fired generating units are replaced with wind generation.

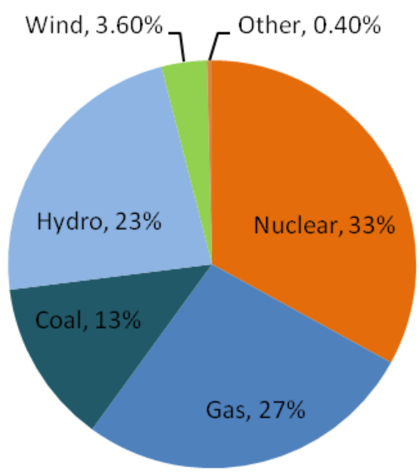


Figure 3-1: Ontario's Current Electricity supply mix (Feb 20, 2011).

3.2 Long-Term Wind Generation Capacity Factor Trends in Ontario

In this section, the long-term wind generation trends in Ontario are analyzed using different approaches and techniques to present a better understanding of wind generation patterns and how its intermittence, variability and availability affect Ontario's electricity grid. For detailed comprehension of wind generation effects, the long term trends analysis is carried out on yearly, seasonal and monthly basis. To understand how wind generation in Ontario varies throughout the year, this section examines overall wind generation CF trends in Ontario and then by specific wind farms.

The CF of a power plant is defined as the ratio of the electrical energy produced in a given period of time to the electrical energy that could have been produced at continuous maximum power operation during the same period [53].

$$CF\ (in\,\%) = \frac{ACTUAL\ ENERGY\ PRODUCTION}{POSSIBLE\ ENERGY\ PRODUCTION} \times 100$$

The CF for conventional fossil-fuel BASED power stations can be accurately estimated, as their power output depends on the available fossil-fuel and downtime, be it either due to maintenance or contingencies. This is not the case for wind energy, as wind generation depends on wind, which by nature is variable and intermittent. The wind turbine rated capacity is the maximum power it can deliver when operating at its optimum wind speed, but that rated capacity will most likely not be reached. So the CF indication is in order to relate the actual output to the rated output of the wind generator. Wind CF is defined as the wind generation production over the current installed wind generation capacity.

3.2.1 Wind Generation CF Trends for Total Installed Wind Generation Capacity

According to Bruno De Wachter [54], as the wind generation penetration increases in a system, the average CF will decrease accordingly. It has been observed that countries with high penetration levels of wind generation tend to have lower average CF than those with less penetration levels. The average CF differs significantly between countries. Bruno De Watcher in [54] stated that Germany, for instance, has a CF of only 16.9%. That is because the most viable sites for wind generation get developed first and subsequent development takes place in sites with poorer wind speed characteristics, thus reducing the average CF. The U.S. has a significantly large amount of installed wind capacity, but also a high CF (28.8%) for wind generation, thereby implying that it still has a large remaining wind development potential to exploit. Figure 3-2 presents Ontario's annual average wind generation CF over the past four years (2007 to 2010). It is observed that the annual average wind generation CF has been reducing since the penetration of wind generation in 2006. However this reduction is not as significant as that in other highly penetrated countries, nor has it attained a steady state value. Thus implying scope for further investments as wind generation in Ontario still has more capability to provide electricity to the electrical grid.

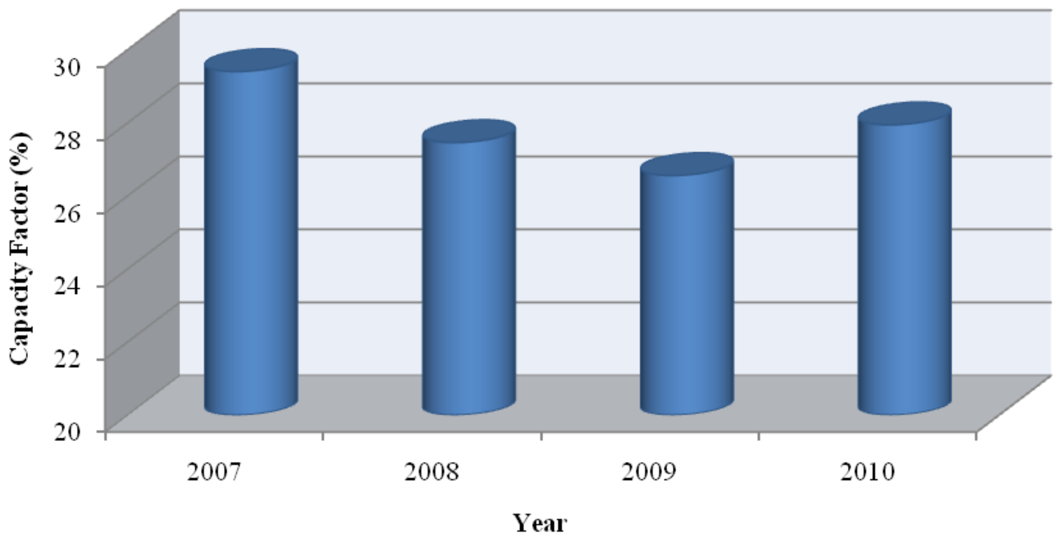


Figure 3-2: Annual-Average Wind Generation CF in Ontario.

Figure 3-3 presents Ontario's seasonal average wind generation CF over the past four years (2007 to 2010). It is observed that the wind generation CF tends to be the lowest during the summer with an average of 16.1%, and the highest during the winter with an average of 34.5%, while it is approximately similar for the spring and fall with an average of 31.5% and 29% respectively.

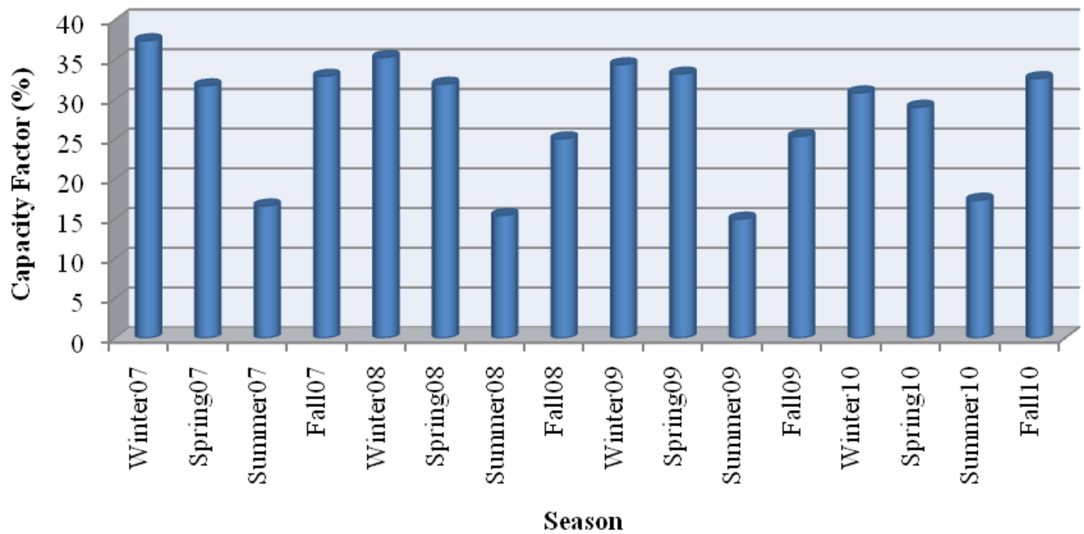


Figure 3-3: Seasonal-Average Wind Generation CF in Ontario.

Figure 3-4 presents Ontario's monthly average wind generation CF over the past four years (2007 to 2010). It is observed that the wind generation CF tends to be the lowest during the summer months: June, July and August.

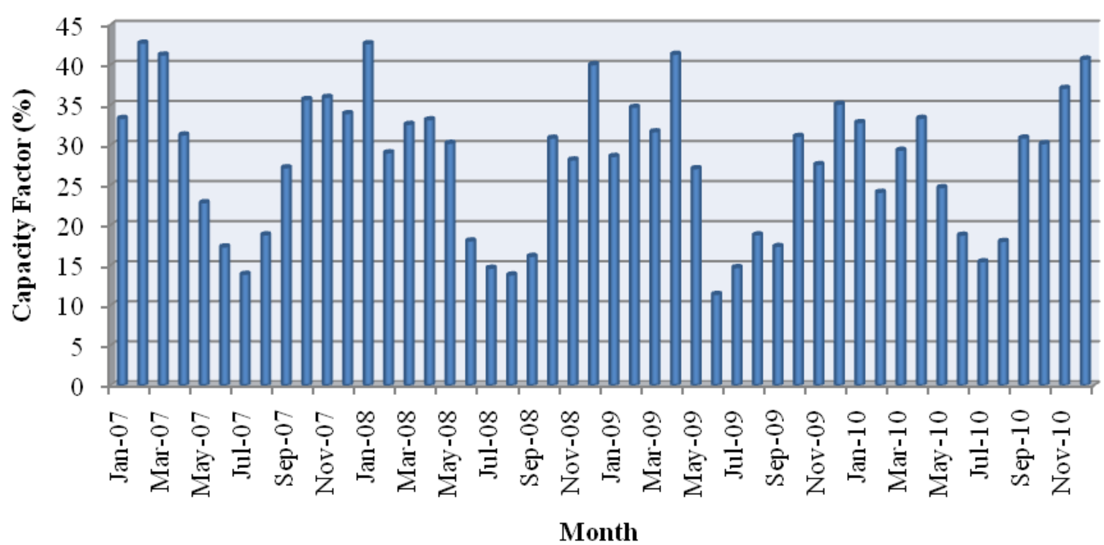


Figure 3-4: Monthly-Average Wind Generation CF in Ontario.

3.2.2 Wind Generation Capacity Factor Trends of Ontario's Wind Farms

Figure 3-5 presents Ontario's wind-farms (WFs) annual average CF for the year 2010. The analysis has been done for the year 2010 only, as the WFs have different dates for first commercial operation and only the year 2010 has all WFs operational. It can be noticed that most of the WFs in the southwestern region (Ripley South, Underwood, Kingsbridge, Port Alma) tend to have higher annual average CF among Ontario's WFs.

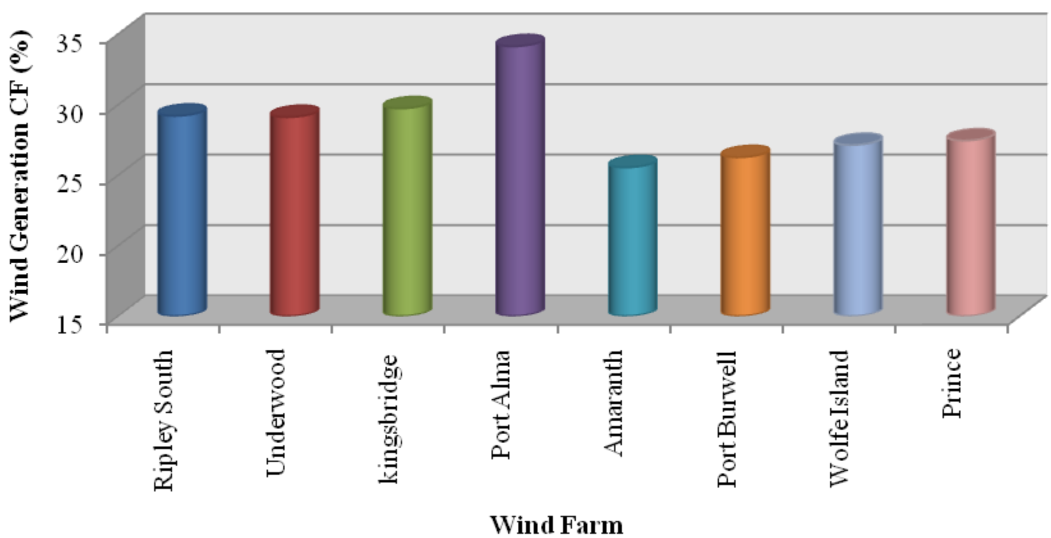


Figure 3-5: Ontario's Wind-Farms' CFs (2010).

3.2.3 Long-Term Wind Generation Variability Trends

To arrive at a better understanding of the wind generation intermittency and variability in Ontario, long term wind generation variability trends are presented. Figure 3-6 presents the wind generation CF variations based on a daily, weekly, monthly and yearly basis, to illustrate the degree of intermittence. The wind generation intermittency is observed with the CF changing significantly on a daily basis. Furthermore dissection of daily variations is presented next.

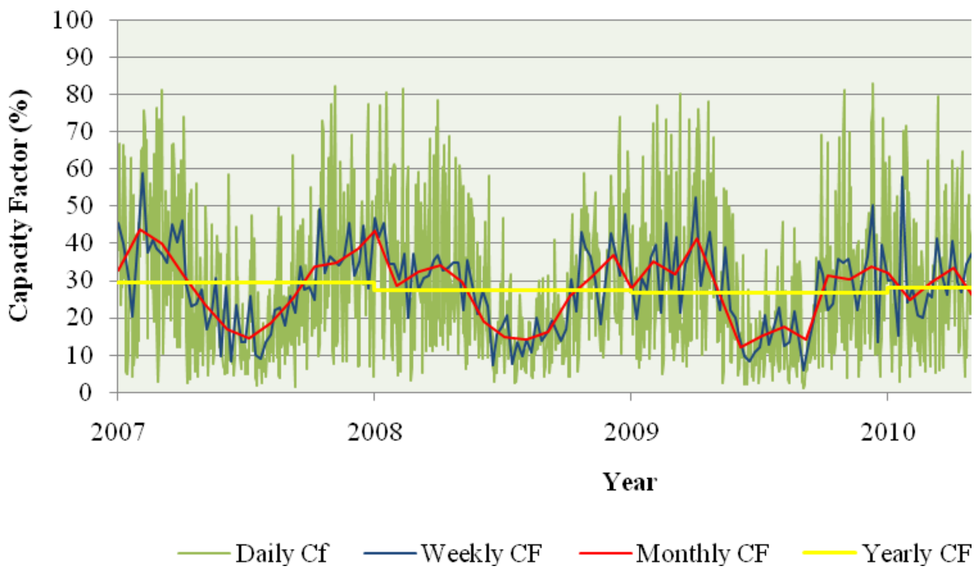


Figure 3-6: Wind Generation CF Variations (2007-2010) in Ontario.

A histogram of the absolute daily change in wind generation CF from the year 2007 to 2010 is presented in Figure 3-7. The absolute daily change ranges from 0% to about 70 % during 2007 to 2010. However it is observed that the absolute daily change is 30% or less for 85% of the year in 2007 and increased through the years to become 89 % in 2010. As an illustrative example of wind generation's extreme daily changes in CF, 4 cases are presented in Figure 3-8 to Figure 3-11, one representing each year from 2007 to 2010, where each case is the most extreme of that year.

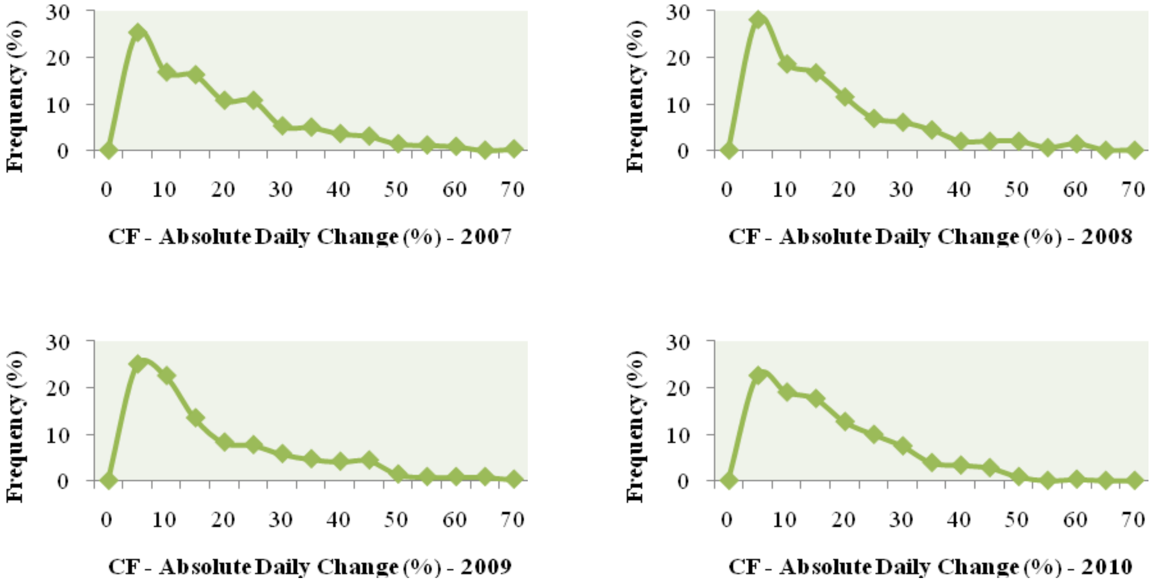


Figure 3-7: Histogram of the Wind Generation CF Absolute Daily Change (2007-2010).

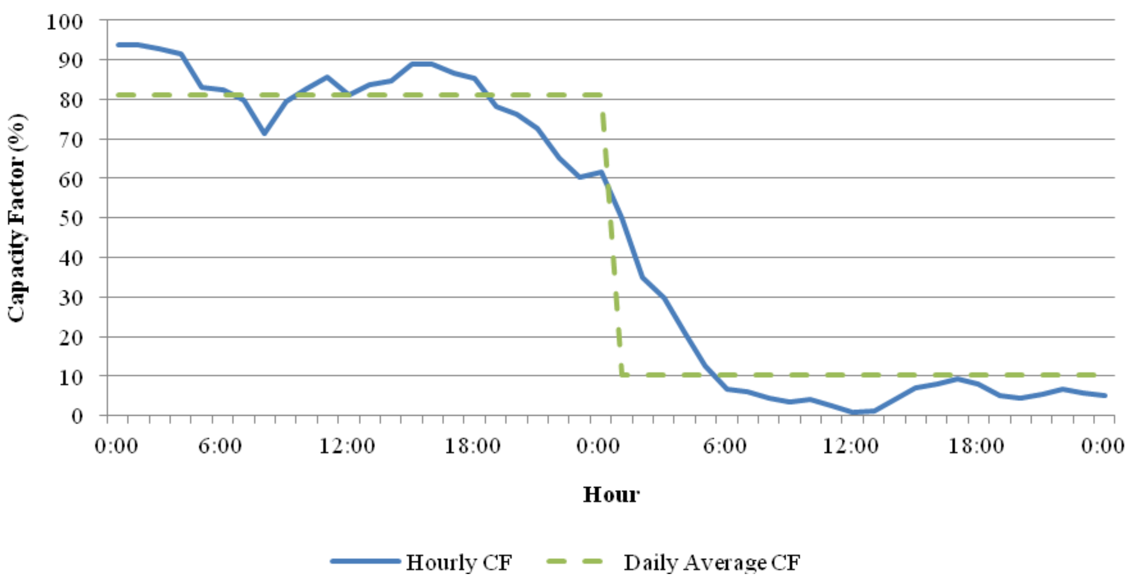


Figure 3-8: Extreme Variation in Wind Generation CF: 5th -6th Mar 2007.

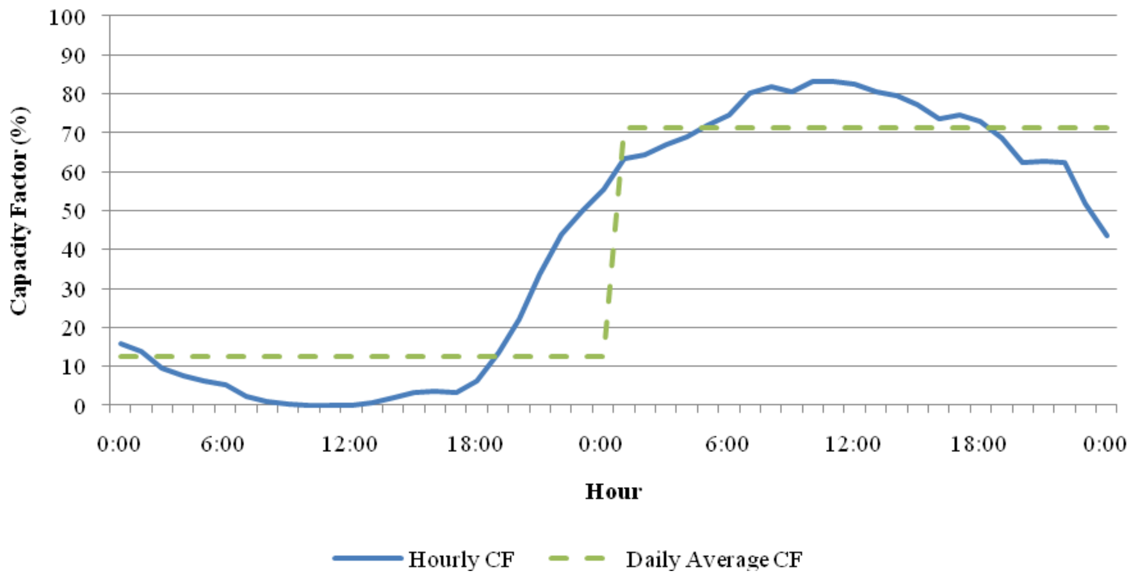


Figure 3-9: Extreme Variation in Hourly Wind Generation CF: 29th to 30th Mar 2008.

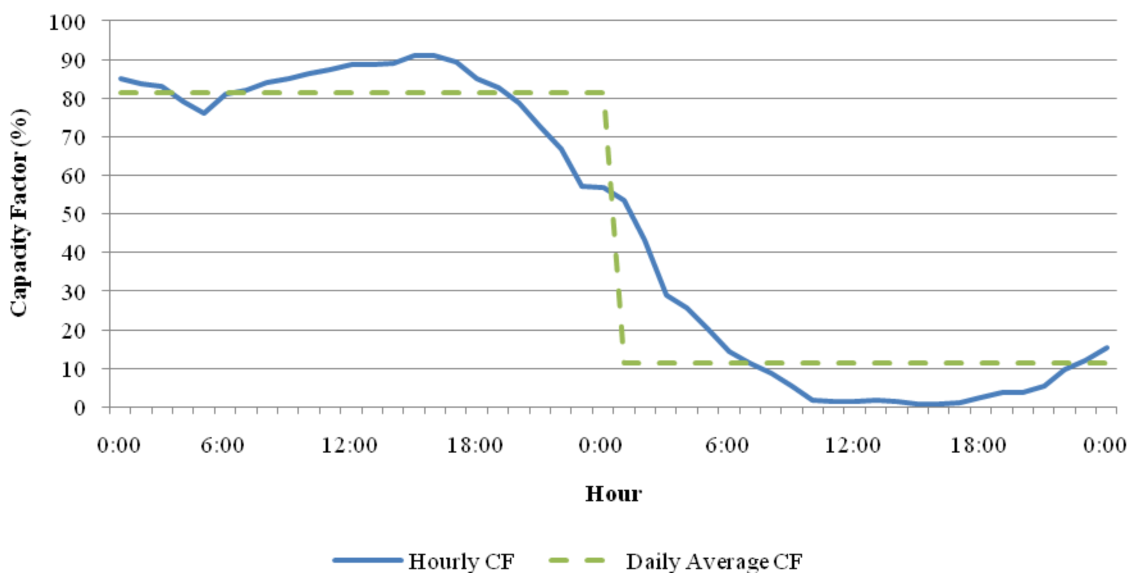


Figure 3-10: Extreme Variation in Hourly Wind Generation CF: 31st Oct - 1st Nov 2009.

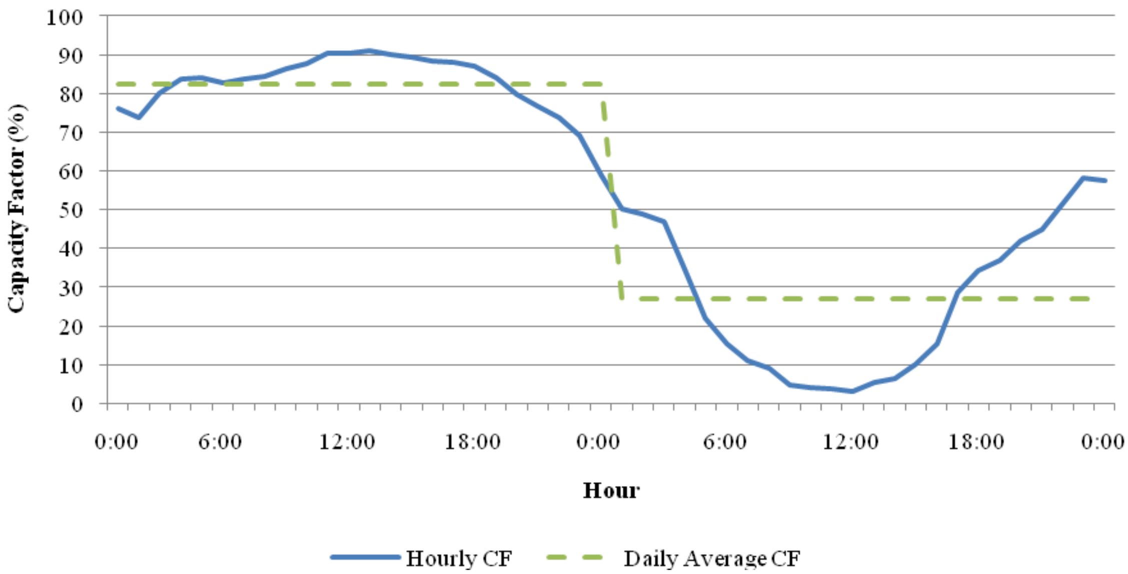


Figure 3-11: Extreme Variation in Hourly Wind Generation CF: 23rd – 24th Nov 2010.

As observed from Figure 3-8 to Figure 3-11, the interdaily change in wind generation CF can be severe, where a high wind generation CF in a day drops to almost zero in the next day, or vice-versa. With an increase in the wind generation penetration level, such intermittency can reduce the reliability of the power system, and consequently increasing the need for adequate operating reserve.

3.3 Spatial Effect on Wind Generation Correlation

3.3.1 Pearson Product-Moment Correlation Coefficient

In statistics, correlation is defined as any broad class of relationships between two or more random variables or observed data sets. In this chapter the observed data from the Ontario power grid which are relevant to wind generation are considered for determining such statistical relationships.

The statistical method used for correlation analysis in this chapter is the Pearson Product-Moment Correlation Coefficient, which measures the correlation between two random variables X and Y, giving a value in the range of -1 to +1. A value of +1 implies that a linear equation describes the relationship between X and Y perfectly, with all data points lying on a line for which Y increases as X increases. A value of −1 implies that all data points lie on a line for which Y decreases as X increases. A value of 0 implies that there is no linear correlation between the variables [55].

The mathematical formula of the Pearson Product-Moment Correlation Coefficient is given as:

$$\rho_{X,Y} = \frac{\operatorname{cov}(X,Y)}{\sigma_X \sigma_Y} \tag{3.1}$$

Where,

$$\operatorname{cov}(X,Y) = E[(X - \mu_X)(Y - \mu_Y)] \tag{3.2}$$

$$\sigma_X = \sqrt{E[(X - E(X)^2)]}\ ,\ \sigma_Y = \sqrt{E[(Y - E(Y)^2)]} \tag{3.3}$$

$$\mu_X = E(X)\ ,\ \mu_Y = E(Y) \tag{3.4}$$

Where $\rho_{X,Y}$ is the correlation coefficient, $\operatorname{cov}(X,Y)$ is the covariance between X and Y, σ_X and σ_Y is the standard deviation of X and Y respectively, μ_X and μ_Y is the mean of X and Y respectively, and $E(X)$ and $E(Y)$ is the expectation of X and Y respectively.

The two statistical data sets used in the present analysis are the wind generation and the corresponding electricity system demand in Ontario. Table 3-1 presents the relationship interpretations for a general class of statistical data sets and the range of correlation coefficients.

Table 3-1: Correlation Range Interpretation

Correlation	Negative	Positive
None	-0.09 to 0.0	0.0 to 0.09
Small	-0.3 to -0.1	0.1 to 0.3
Medium	-0.5 to -0.3	0.3 to 0.5
Large	-1.0 to -0.5	0.5 to 1.0

3.3.2 Correlation between Ontario's WFs

The correlation between the CFs of Ontario's WFs is examined using the Pearson Product-Moment Correlation Coefficient and presented in Table 3-2. The data used are the hourly WF generation output made publicly available by the IESO [14]. The correlations between the WF CFs are presented in the form of a matrix. Correlation coefficients close to 1 indicate a strong positive relation between the two WFs examined, meaning that their output changes coherently. As observed, the correlation is always positive between the WF CFs, which indicates that WFs all in Ontario have similar generation patterns but with small or large variations, depending on how much they deviate from the value 1. In an attempt to understand these variations, the correlation between the WF CFs is plotted against their distances from one another, as presented in Figure 3-12. The approximate distance between each WF is given in Table 3-3. These distances are measured based on the approximate geographic coordinates of the WFs location presented, in Table 3-4.

As observed, the correlation between the WF CFs with respect to their distances is a decaying exponential, with an exponential rate of change of $C = e^{-d/d_o}$, where d is the separation between the WFs in kilometers, and d_o is a constant of 609. As the distance between two WFs increase, the correlation of their output decreases. Low correlation between WFs' outputs is required in order to smooth-out the variability in total wind generation output. Hence a 0.5 correlation or less between WFs' outputs is recommended. From Figure 3-12 it can be noticed that the correlations between WFs' outputs is less than 0.5 if they are separated by 320 km or more. Therefore it is recommended for future wind investments from a grid reliability point of view that the WFs should be geographically dispersed all over the province. The benefits of geographic diversity for WFs are presented next.

Table 3-2: Correlation between Ontario Wind-Farms' CFs

	Ripley South	Under-wood	Kings-Bridge	Port Alma	Amaranth	Port Burwell	Wolfe Island	Prince
Ripley South	1							
Underwood	0.899	1						
Kingsbridge	0.928	0.876	1					
Port Alma	0.663	0.641	0.696	1				
Amaranth	0.696	0.752	0.693	0.591	1			
Port Burwell	0.633	0.645	0.671	0.725	0.651	1		
Wolfe Island	0.467	0.491	0.471	0.399	0.539	0.533	1	
Prince	0.468	0.489	0.496	0.379	0.397	0.292	0.235	1

Table 3-3: Approximate Distances between Ontario's Wind-Farms in Kilometers

	Ripley South	Under-wood	Kings-Bridge	Port Alma	Amaranth	Port Burwell	Wolfe Island	Prince
Ripley South	0							
Underwood	35	0						
Kingsbridge	20	53	0					
Port Alma	219	254	201	0				
Amaranth	112	103	127	289	0			
Port Burwell	172	202	161	129	191	0		
Wolfe Island	382	369	397	526	270	400	0	
Prince	349	327	356	513	408	516	609	0

Table 3-4: Approximate Latitudes and Longitudes of Ontario's Wind-Farms

Wind Farm	Latitude, Longitude
Ripley South	44.08, -81.57
Underwood	44.40, -81.49
Kingsbridge	43.94, -81.70
Port Alma	42.18, -82.24
Amaranth	44.31, -80.20
Port Burwell	42.65, -80.80
Wolfe Island	44.88, -76.89
Prince	46.54, -84.35

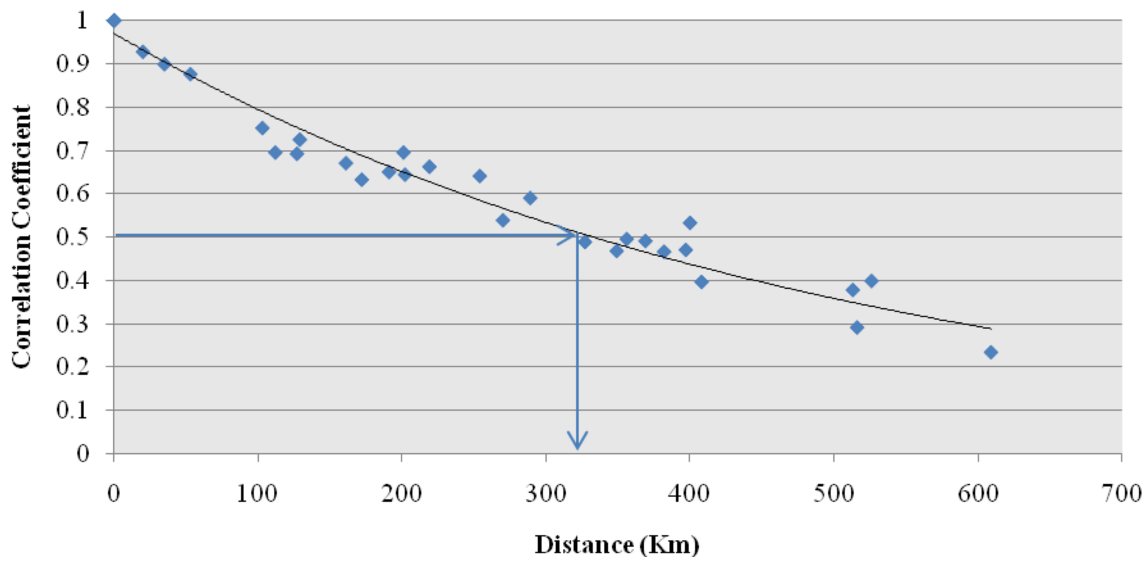


Figure 3-12: Correlation of Ontario Wind-Farms' CFs against their Distances (2010).

In order to quantify the impact of geographic diversity of WFs on the variability of the total wind generation output, a histogram of the absolute hourly change in total wind generation CF from the year 2007 to 2010 is presented in Figure 3-13, and a histogram of the absolute hourly change in each WF CF for the year 2010 is presented in Figure 3-14.

As observed, the absolute hourly change in total wind generation CF ranges between 0% to about 14 % or less from 2007 to 2010. However it is observed that the histograms distributions are gradually concentrating in the lower CF ranges, given that the absolute hourly change in CF is 5% or less for 75% of the hours in 2007 that increased to 83% of the hours in 2010. This is due to the fact that wind generation became sparser in its penetration while its installed capacity in Ontario increased from 395 MW (in 2007) to 1234 MW (in 2010). This is confirmed in Figure 3-14 by comparing the absolute hourly changes in the CF of total generation with that of each WF. The absolute hourly change of the CF of each WF ranges between 0% to about 40% in 2010, whereas that for total wind generation ranges between 0% to about 14 % in the same year. Moreover, the absolute hourly change in total wind generation of 10% or more only occurred for 2.3% of the hours in 2010, while that for each WF in Ontario occurred on average 17.4% of the hours in 2010. Hence the variation in the total wind generation output in Ontario has significantly smoothed as the wind generation penetration level increased and geographic diversity increased.

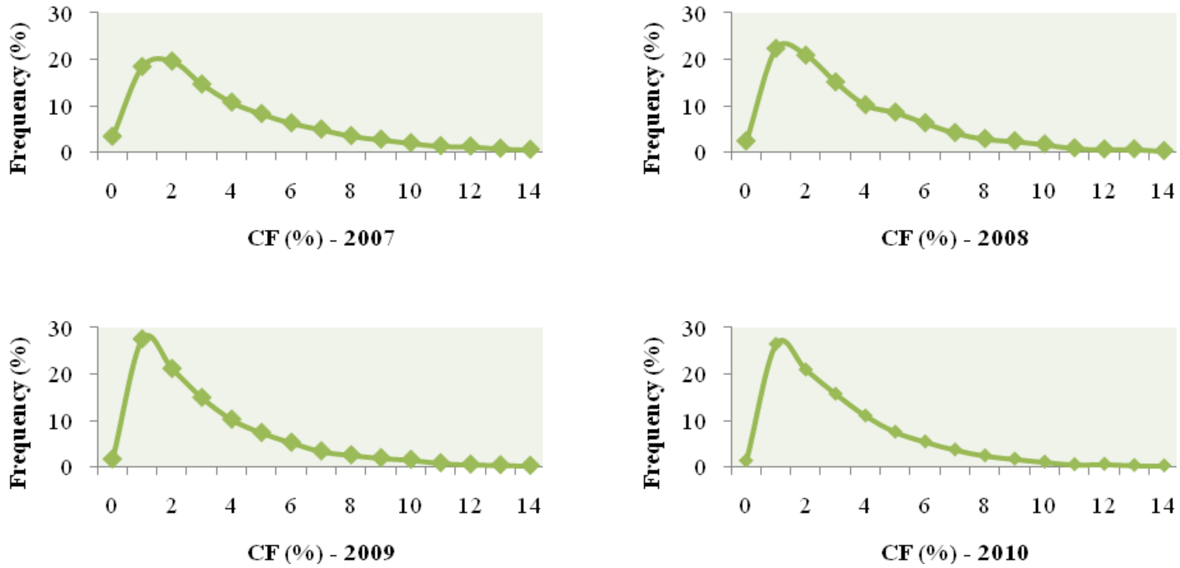
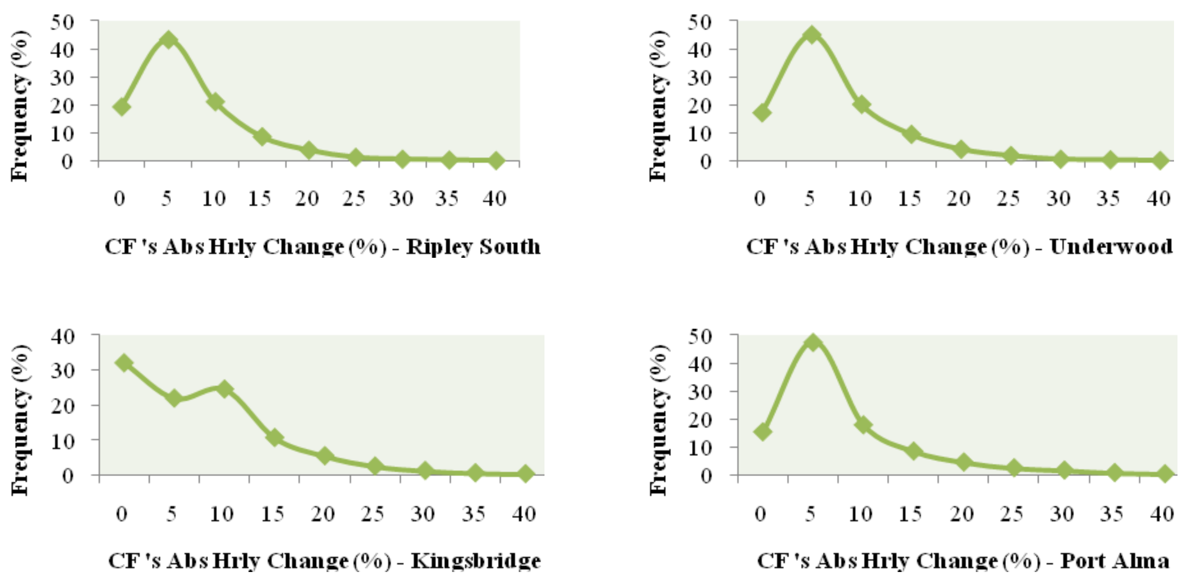


Figure 3-13: Histogram of the Wind Generation CF Absolute Hourly Change (2007-2010).



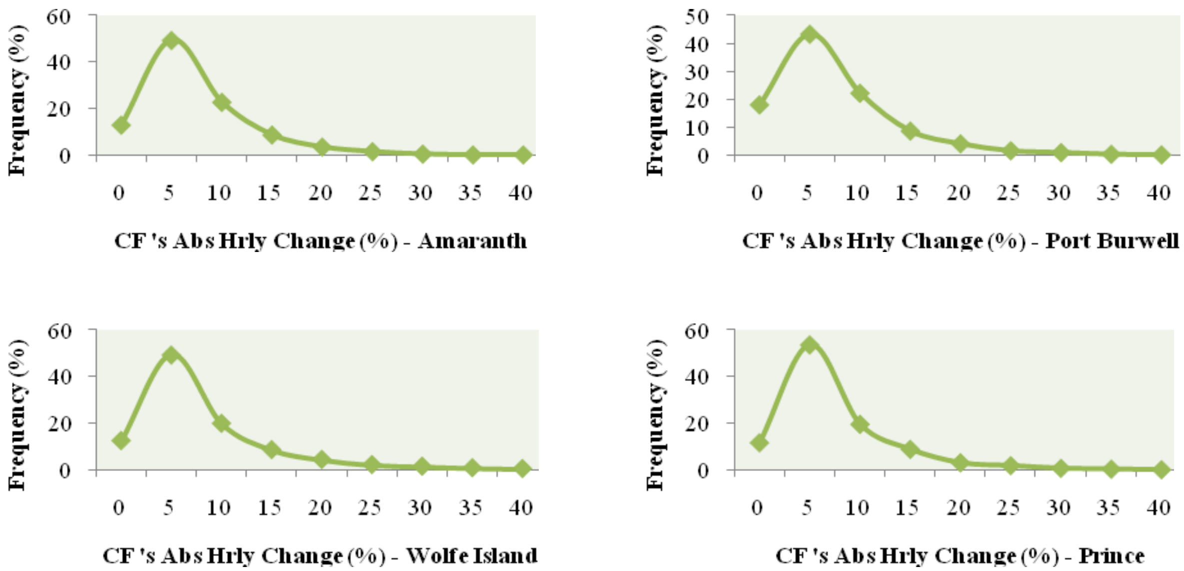


Figure 3-14: Histogram of the Absolute Hourly Change in Ontario WF CFs (2010).

3.4 System Demand On & Off-Peaks Analysis

Wind generation has been penetrating the Ontario electricity market since March 2006 and its capacity is continuing to grow. With a low level of penetration of wind generation, the impact on Ontario's spinning reserves requirements are expected to be insignificant. But as wind generation penetration level increases, Ontario's spinning reserves requirements and their proper procurement and availability is becoming a planning issue. This is due to the variability and intermittency of wind. The operating reserves, either spinning or non-spinning, depend greatly on the peak demand levels. For integration of wind generation with high penetration levels, the planners need to have a clear insight on the system peak demand and its correlation with wind generation.

In this section, the electricity system demand for on- and off-peak periods is analyzed to examine the contribution of wind generation during these periods. The on- and off- peak system demands are defined as the maximum and minimum hourly system demand for a certain day respectively. A histogram for the occurrence of these peaks is presented in Figure 3-15 and Figure 3-16 respectively, to illustrate when these peak demands occur in the Ontario system. As observed, the occurrence of the daily system on-peak demand in Ontario is typically between the hours of 6 PM to 8 PM at a frequency of almost 52% of the time from the year 2007 to 2010, whereas the daily system off-peak demands occur in Ontario between the hours of 3 AM to 4 AM at a frequency of more than 65%.

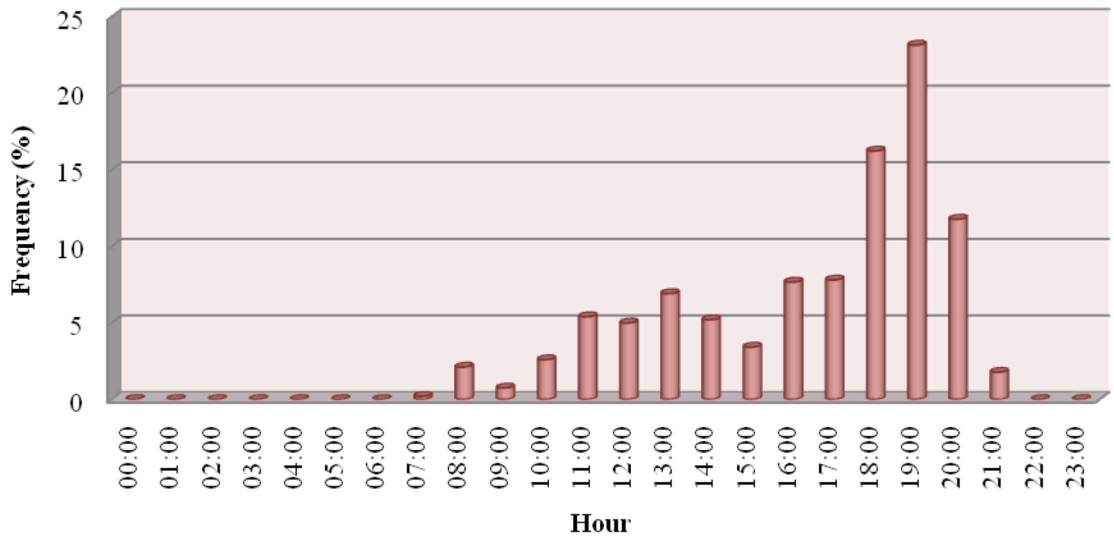


Figure 3-15: Histogram of the Occurrence of Daily System On-Peak Demand (2007-2010) in Ontario.

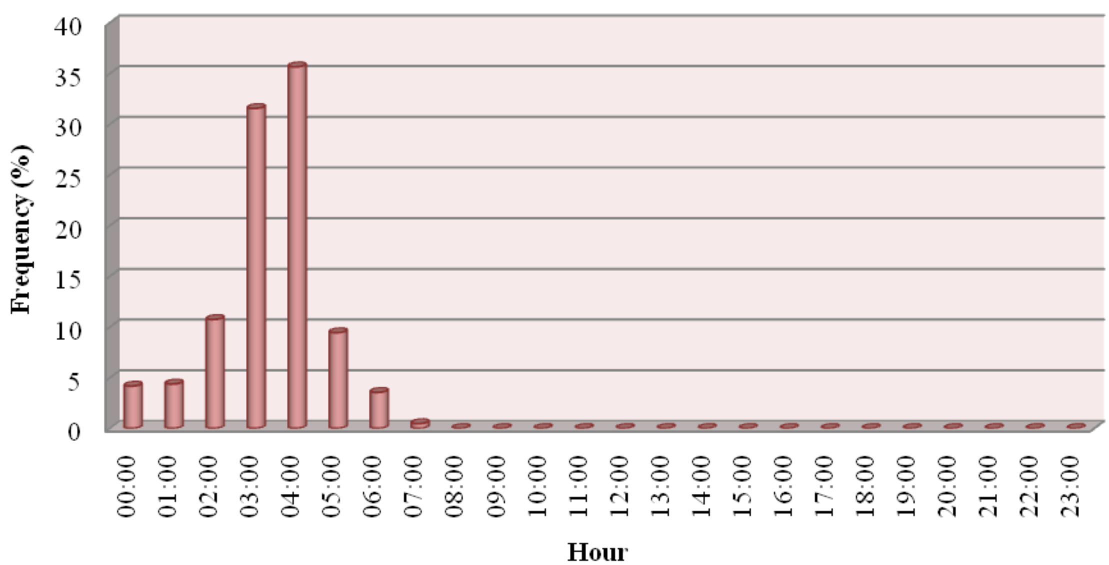


Figure 3-16: Histogram of the Occurrence of Daily System Off-Peak Demand (2007-2010) in Ontario.

The daily wind generation coincident with the on-peak system demand is averaged on a yearly basis, to obtain the annual average wind generation CF during On-Peak system demand. Similar values are obtained for the Off-Peak system demand and normal system demand cases (Figure 3-17).

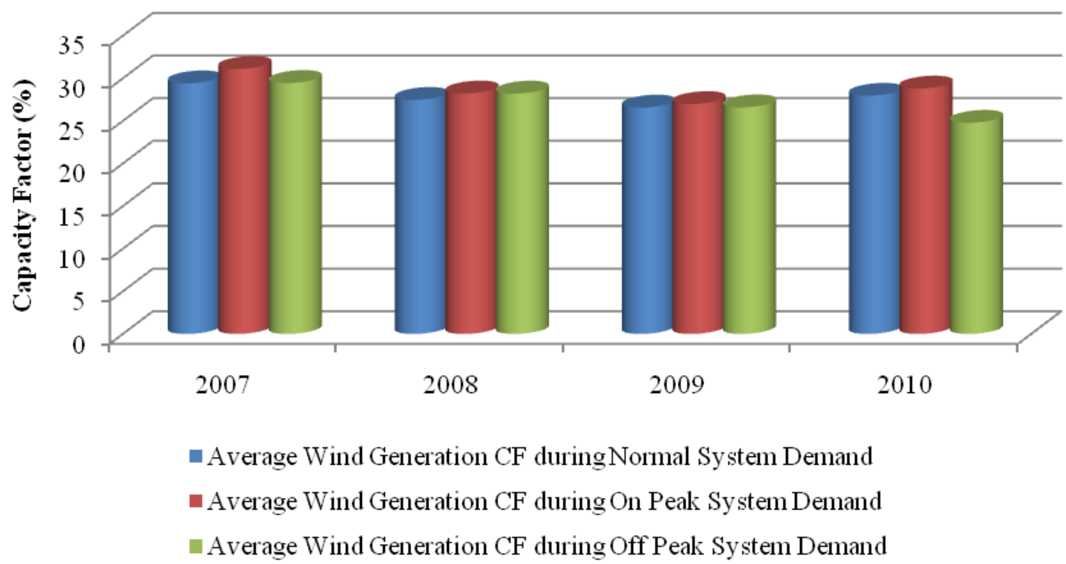


Figure 3-17: Annual-Average Wind Generation CF in Ontario at Various Demand Blocks.

As observed from Figure 3-17, the annual average wind generation CF during on-peak and off-peak system demands do not differ much from that during normal system demand. Interestingly enough, one would expect the average wind generation CF during the off-peak system demands to be higher than that during normal system demand, and the wind generation CF during the on-peak system demand to be lower than that during the normal system demand. This is expected because the wind speed is usually higher at night when there is low system demand, while the wind speed is lower in the afternoon when system demand is high. Further dissection of the data is needed to extract the underlying information that is lost during the annual averaging, which is presented next.

A histogram for the CF of wind generation that is coincident with the system on and off-peak demands are presented in Figure 3-18 and Figure 3-19 respectively, to clearly exhibit how much wind generation takes place during such peak demands in the Ontario system.

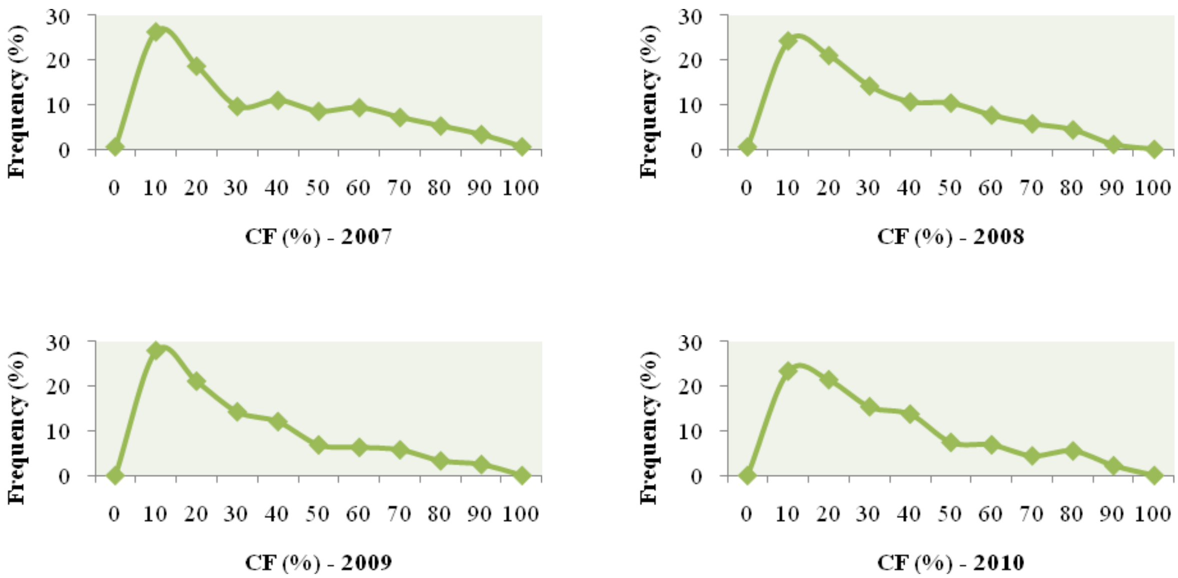


Figure 3-18: Histogram of Wind Generation CF Coinciding with Daily On-Peak System Demand (2007-2010).

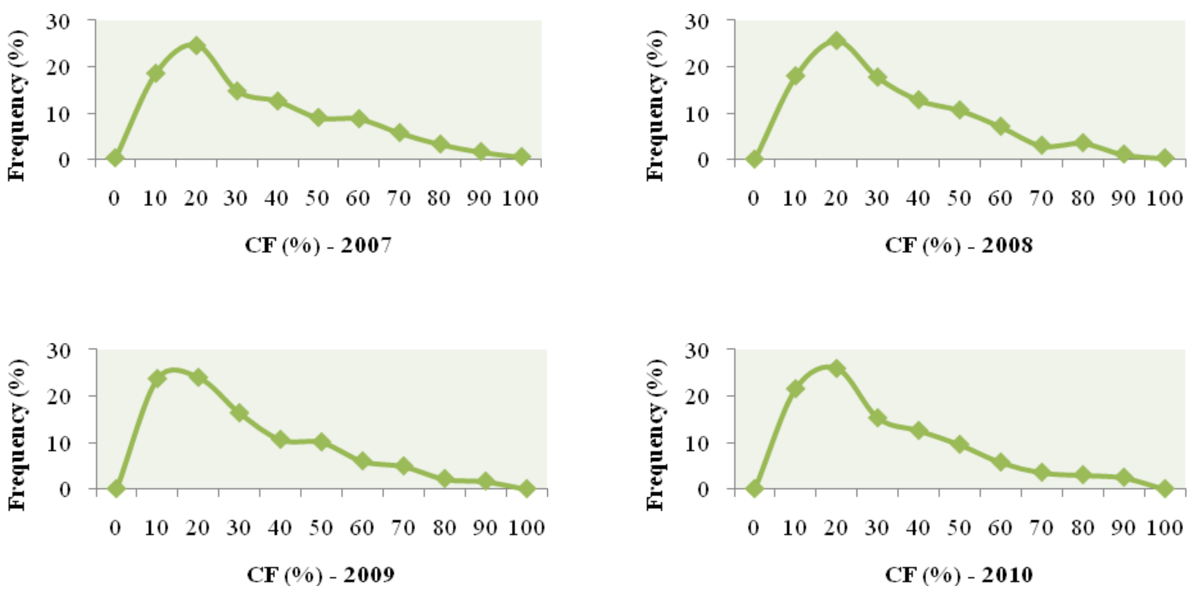


Figure 3-19: Histogram of Wind Generation CF Coinciding with Daily Off-Peak System Demand (2007-2010).

As observed from Figure 3-18 and Figure 3-19, the wind generation CF during system on and off-peak demands ranges between 0% to just about 100%, which justifies their yearly averages being almost same as that during normal system demand. However, it is observed that CFs in the range of 10-30% occurs for about 60% of the time. But their distribution differs in each case, for example, the wind generation CF during the on-peak system demand is between 0-10% for 26% of the year and between 10-20% for 20% of the year. This is reversed in case of off-peak, when wind generation CF is in the range of 0-10% for 20% of the year and from 10-20% for 25% of the year. It is also observed that the occurrence of wind generation CF of 5% or less is quite different for the on-peak and off-peak system demands cases. During the on peak, the CF is lower than 5% for 11% of the year with an average of 39 days, but during the off peak, the CF is lower than 5% for 8% of the year with an average of 29 days.

3.5 Long-Term Wind Generation Correlation with System Demand

3.5.1 Yearly Analysis of Correlation

In this section, the wind generation data for Ontario is aggregated by taking the hourly averages over a year, meaning that the daily wind generation data for a certain hour, say 6 PM, over the whole year is averaged to obtain the average wind generation for 6 PM for this year. Similarly, the annual average hourly system demand for Ontario is also obtained. From these, the hourly wind generation as a percentage of the system demand is also obtained and analyzed alongside (Figure 3-20 to Figure 3-23).

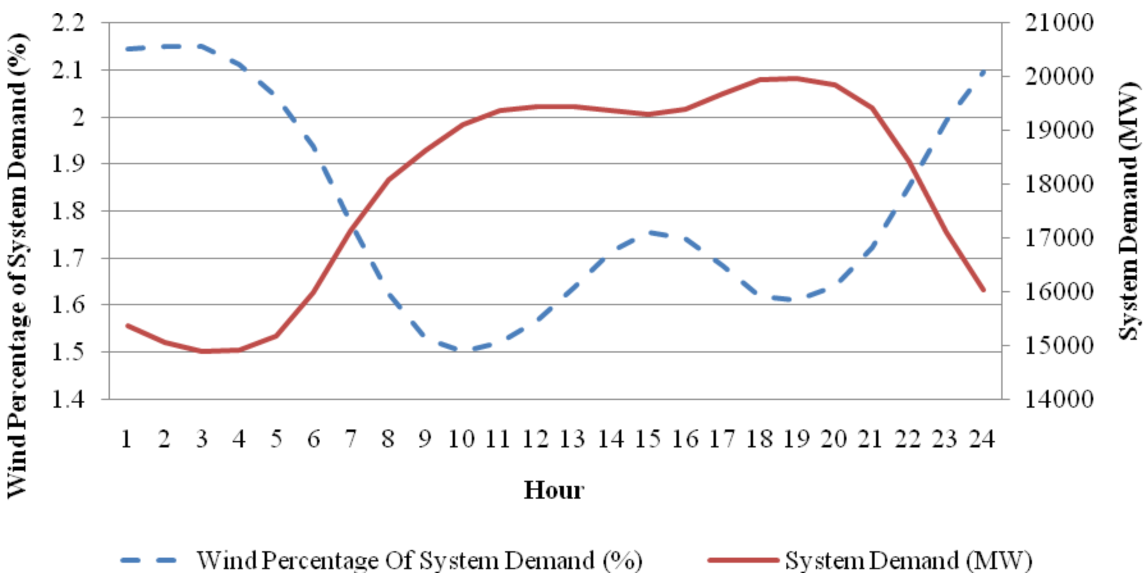


Figure 3-20: Yearly Average Wind Generation vs System Demand 2010.

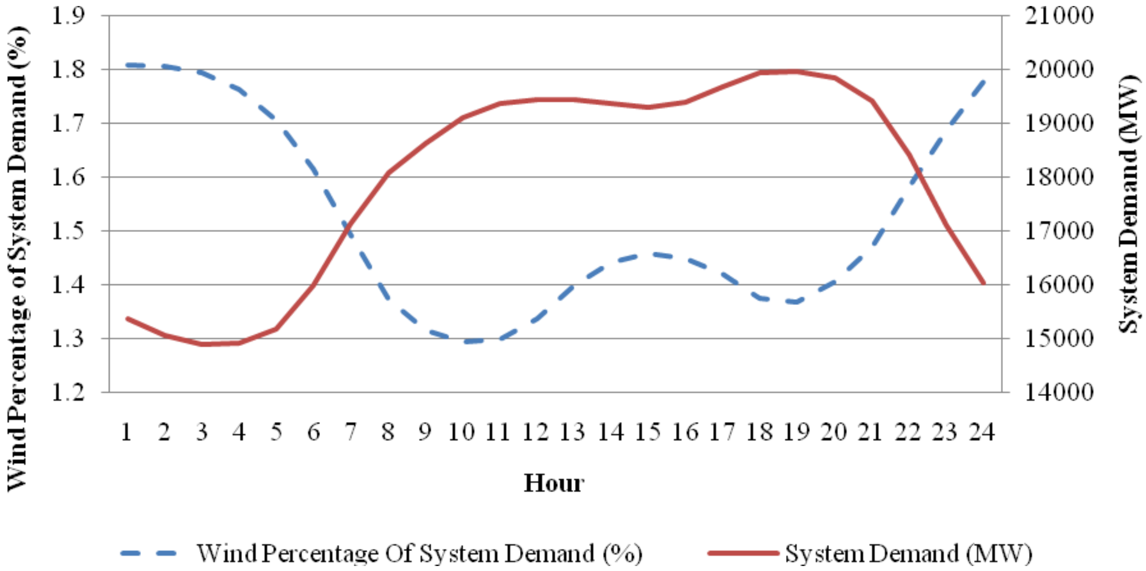


Figure 3-21: Yearly Average Wind Generation vs System Demand 2009.

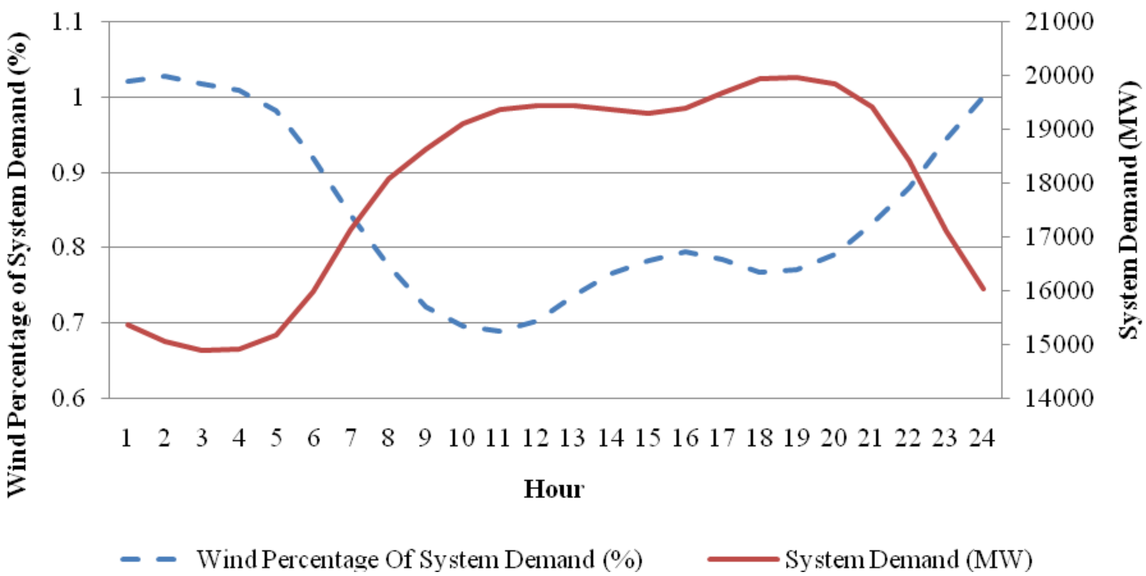


Figure 3-22: Yearly Average Wind Generation vs System Demand 2008.

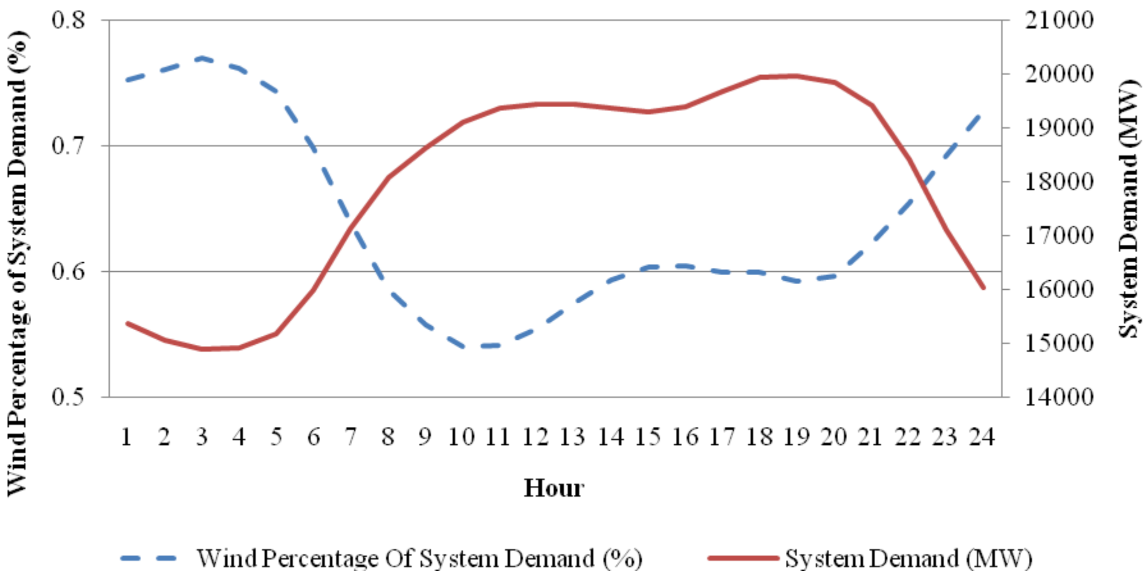


Figure 3-23: Yearly Average Wind Generation vs System Demand 2007.

As observed from Figure 3-20 to Figure 3-23, the yearly average system demand in Ontario for all years is in the range of 15,000 to 20,000 MW, while the average wind generation as a percentage of the system demand varies significantly throughout the years because of the increase in installed capacity in Ontario from 395 MW (in 2007) to 1234 MW (in 2010). The wind generation as a percentage of system demand indicates the wind penetration level. It is observed that the highest wind penetration level occurs during the hours of 10 PM to 2 AM, while the lowest penetration occur during the hours of 9 AM to 11 AM.

Table 3-5 presents the correlation analysis for wind generation versus system demand in Ontario. It is observed from the analysis that the correlation coefficients for the years 2007 to 2010 are almost -0.9, which according to Pearson Product-Moment Correlation Coefficient means that there is a large inverse correlation between wind generation and system demand in Ontario. As the wind generation increases, the system demand tend to decrease and when wind generation decreases the system demand tend to increase.

Table 3-5: Wind Generation versus Ontario System Demand Correlation Coefficients - Yearly

Year	Correlation Coefficient
2007	-0.927
2008	-0.926
2009	-0.920
2010	-0.902

3.5.2 Seasonal Analysis of Correlation

In this section the analysis is carried out for the four seasons of the year: Winter, Spring, Summer and Fall. The wind generation and system demand data is aggregated for a season by taking its seasonal average for a certain hour. For example, the wind generation data for 6 PM all through a season is averaged, thereby resulting in an average generation profile for the season. This is then averaged over the 4 years under study.

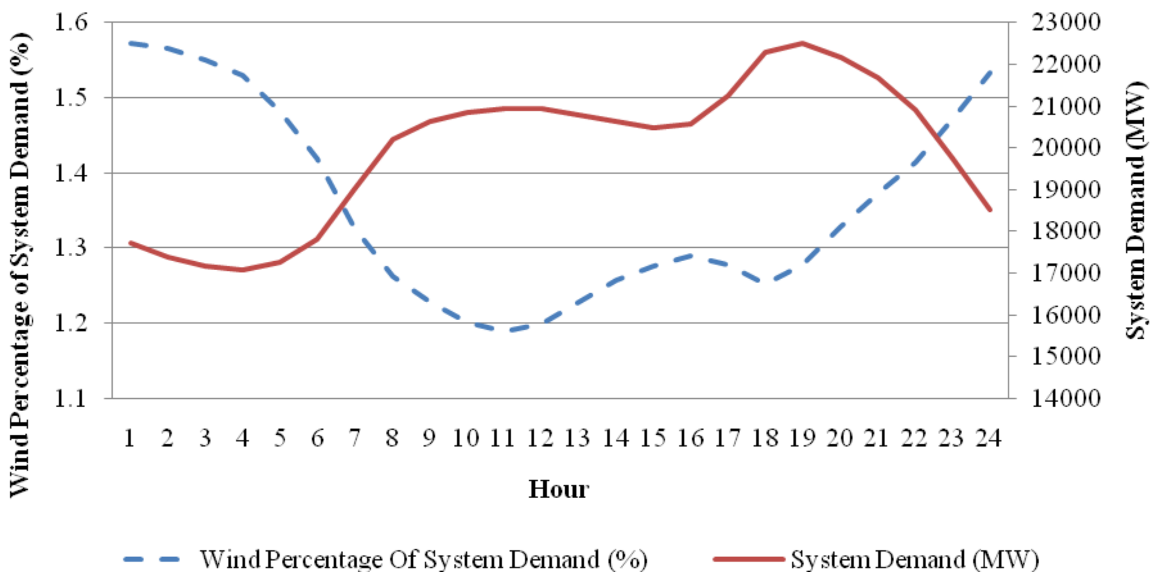


Figure 3-24: Seasonal Average Wind Generation vs System Demand, Winter (2007-2010).

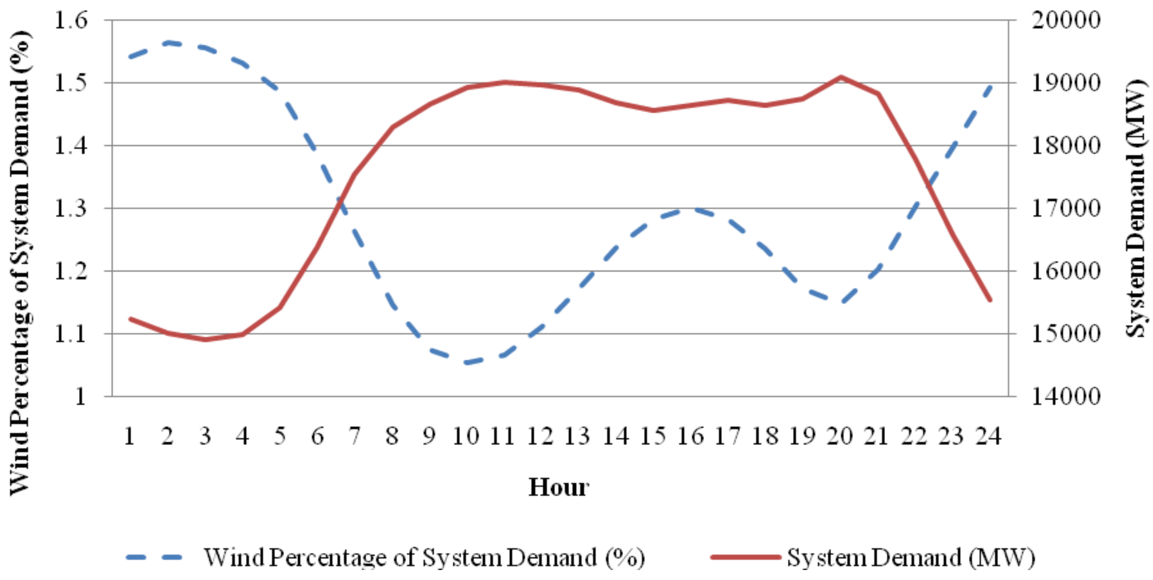


Figure 3-25: Seasonal Average Wind Generation vs System Demand, Spring (2007-2010).

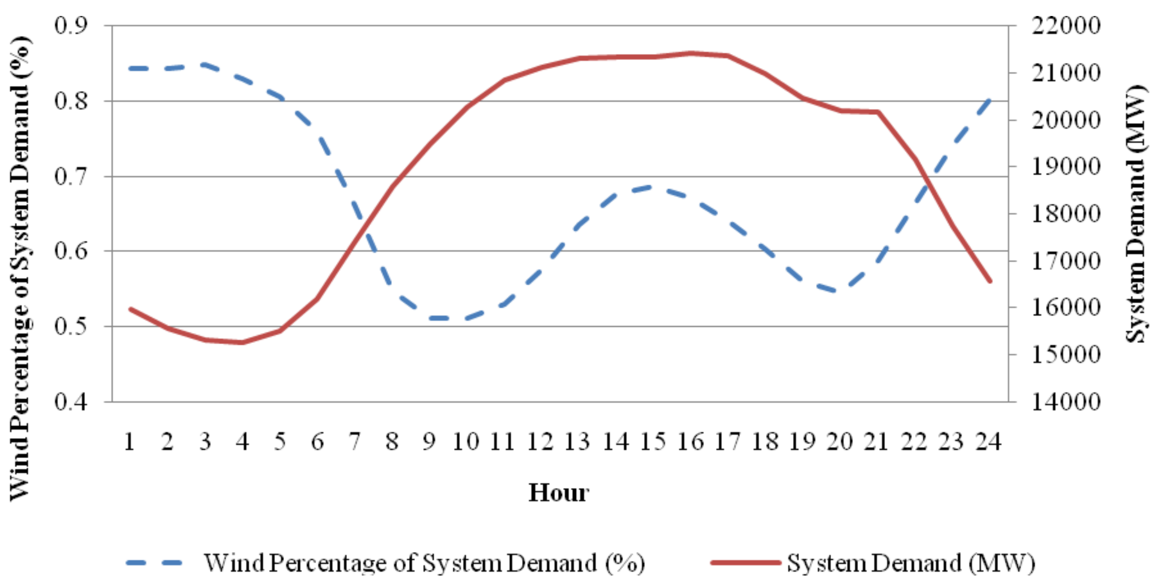


Figure 3-26: Seasonal Average Wind Generation vs System Demand, Summer (2007-2010).

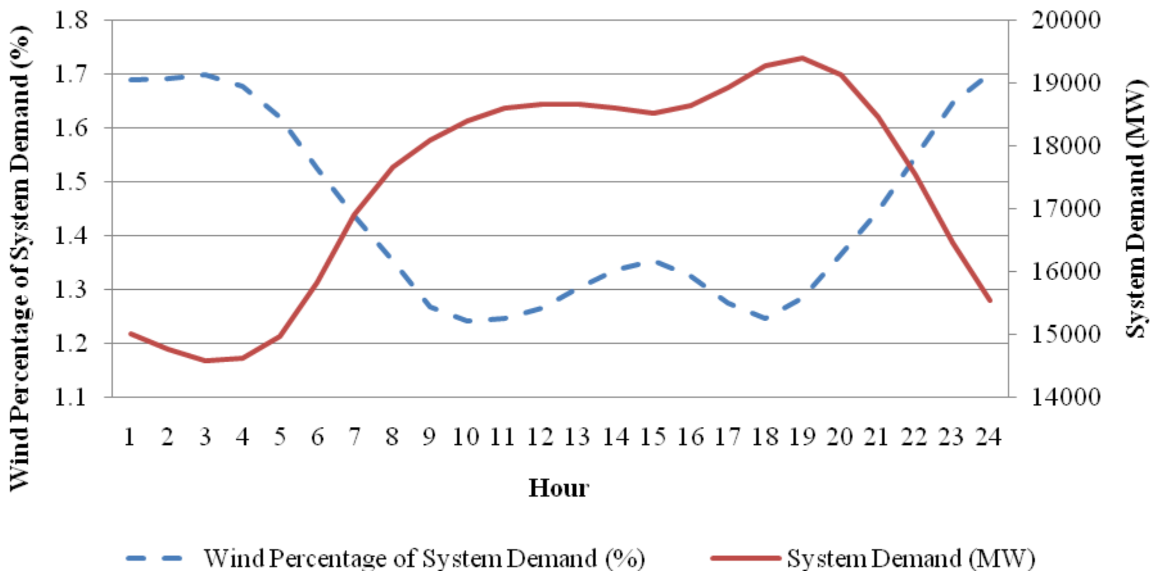


Figure 3-27: Seasonal Average Wind Generation vs System Demand, Fall (2007-2010).

As observed from the seasonal plots (Figure 3-24 to Figure 3-27), the average system demand in Ontario for all seasons is in the range of 15,000 to 20,000 MW, while the average wind generation varies significantly across the seasons. The wind generation as a percentage of system demand indicates the wind penetration level. It is observed that the highest wind penetration level for all seasons usually occurs during the hours of 10 PM to 2 AM, while the lowest penetration usually occurs during the hours of 9 AM to 11 AM. Moreover, it is observed that the highest wind penetration level occurs during the Fall as it ranges from 1.24% to 1.7% and the lowest occurs during the Summer as it ranges from 0.51% to 0.85%, while it is approximately similar for the Winter and Spring as they range from 1.19% to 1.57% and 1.05% to 1.57% respectively.

3.6 Concluding Remarks

This chapter presents a long-term statistical trend analysis of wind generation patterns in Ontario. Using various wind generation data sets of Ontario wind farms during 2007 – 2010, on hourly, seasonal and yearly time-scales, some important insight is presented. It is concluded that as the wind generation penetration increases in a system, the average CF will decrease accordingly, that is because the most viable sites for wind generation get developed first and subsequent development takes place in sites with poorer wind speed characteristics, thus reducing the average CF. From the analysis presented it is observed that geographical dispersion of wind farm investments is recommended in order to reduce the variability and fluctuations in wind generation output. It has been found that in order to smooth-out the variability in total wind generation output, low correlation between WFs' outputs is required, which in case of Ontario can be achieved by separating WFs or groups of WFs by 320 km or more. It is also concluded that the long-term total wind generation CF are not sufficient for investment or operational planning decisions because the intermittency and variability of the energy output in the short-term do not provide a solid basis, as demonstrated in the chapter.

Wind generation in Ontario can only be relied upon if there is an adequate back-up operating reserve to account for its shortfalls. Generally there are two types of operating reserves, spinning reserves which can promptly be brought online to account for any sudden and unexpected changes in the system demand-supply balance within 10 minutes or less, and non-spinning reserves for slower changes within 10 to 30 minutes. Spinning reserves are typically the difference between the maximum outputs of operating power plants and their actual output, such that they can rapidly restore the balance between supply and demand. The primary choice of system operators for spinning reserves are hydroelectric plants, as their output does not require fuel and can be quickly changed. In cases where hydroelectric generation is of limited capability, gas-fired generation plants are the best alternative. Gas-fired generation plants can rapidly increase and decrease their generation with only minimal loss of efficiency.

In the next chapter, an estimate for the expected increase in operating reserves arising from different levels of penetration of wind generation is presented.

Chapter 4
Long-Term System Operational Impacts of Wind Penetration in Ontario Power System

4.1 Introduction

In Chapter 3, the long-term wind generation trends are analyzed with different techniques and approaches to present a better understanding of wind generation and how its intermittency, variability and availability affect Ontario's electricity grid. The output of these analyses are then used in this chapter to analyze wind generation impact on the electricity grid by incorporating them in a power flow model to observe the changes that occur due to the presence and growth of wind generation in Ontario. In the following section, a brief overview of the Ontario electricity system is presented. Therefore, an adequate simplified model for Ontario's electricity system is developed and used in a deterministic as well as a probabilistic case study to determine the impact of different wind generation penetration levels on the Ontario system, and consequently, the estimated changes in operating reserves and delivered electricity cost.

4.2 Ontario Electricity System

The Ontario electricity network with voltages higher than 50 kV is controlled by Ontario's Independent Electricity System Operator (IESO). Ontario's electricity network mainly comprises a 500 kV transmission network, a 230 kV transmission network, and several 115 kV transmission networks. Ontario's electricity network is synchronously interconnected to the province of Manitoba, Canada and to the neighboring US utilities in the states of New York, Minnesota, Michigan, and to the province of Manitoba and non-synchronously to the province of Quebec, Canada. The IESO represents the Ontario electricity network with ten zones, which is also adopted in this study to develop a simplified 10-bus model of Ontario's electricity network as presented in Figure 4-1.

The simplified model is the 500 kV network, with a 230 kV interconnection between Northeast (NE) and Northwest (NW), and the 115 kV network is neglected for simplicity. The transmission line parameters and loading limits of the model are assessed based on several factors; transmission line voltage, length, capacity and per unit surge impedance loading [56]. Planned transmission corridor enhancements in Ontario are given in Table 4-1.

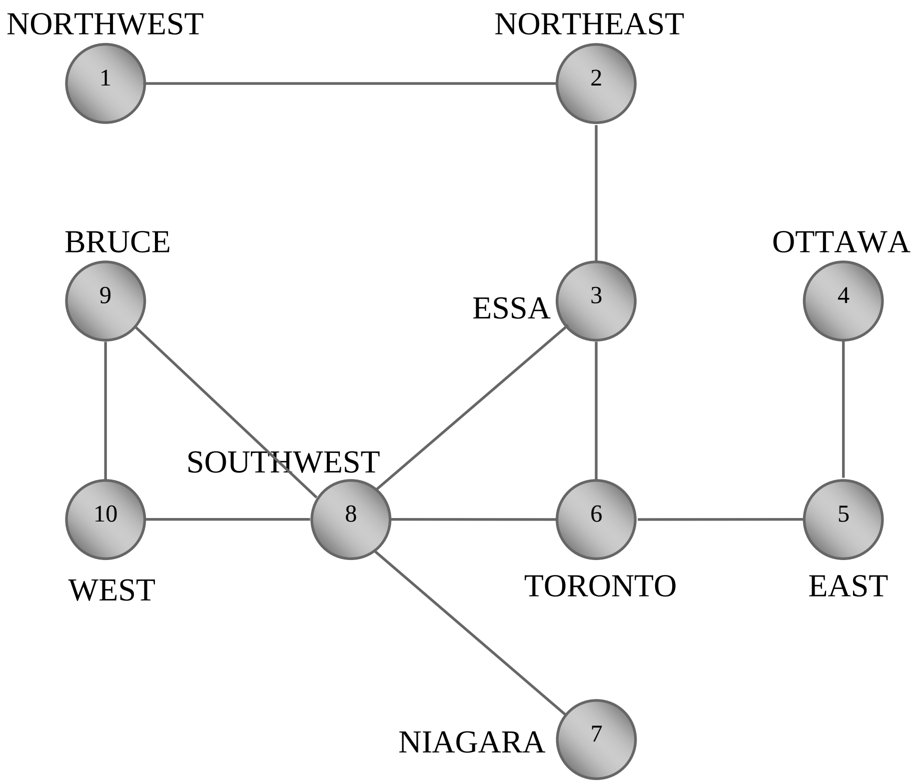


Figure 4-1: Simplified Ontario Transmission Network.

Table 4-1: Planned transmission corridor enhancements in Ontario (2012 - 2017)

Year	Corridor	Current MW	Planned MW
2012	Bruce-SW	2560	4560
2012	SW-Toronto	3212	5212
2013	NE-NW	350	550
2015	Bruce-West	1940	2440
2017	Toronto-Essa	2000	2500
2017	Essa-NE	1900	2400

4.3 Supply Mix Estimates for Ontario

The zonal generation capacity for the three years under study, 2010, 2015 and 2025, is developed based on Ontario's Integrated Power System Plan (IPSP) and information made publicly available by the IESO [14, 15]. The supply mix of generation resources in Ontario considered in this model includes nuclear, wind, hydro, gas-fired generation and coal-fired generation, as presented in Figure 4-2 to Figure 4-4.

According to the IPSP, Ontario's 2025 target for renewable resources is 15,700 MW, out of which 4685 MW is wind generation. Wind generation is expected to be much more than what is planned for in the IPSP due to the Feed-in Tariff (FIT) program associated with the Green Energy Act (GEA) of 2009. In the OPA's report for wind integration study [41], one of the key findings is the impact of wind generation penetration on the operating reserves. It is stated that the additional operating reserve requirement is considered negligible, with 5,000 MW of wind capacity or less, and would become more significant with higher wind generation penetration. Hence, different wind generation targets have been set for the years under study.

In the IPSP, wind generation development is proposed through small and large sites. Small wind sites are included in this study on the basis of expected response to the Renewable Energy Standard Offer Program (RESOP) and the FIT program. Large wind sites are used to provide the remaining resources needed to meet the set targets. The zonal wind generation capacities for 2015 and 2025 are extracted from the IPSP with the aid of the analysis of future wind farm development in Ontario carried out by Helimax [57] and the results are presented in Figure 4-5. The study [57] identifies 60 potential sites for wind generation across Ontario, and considers some constraints on site selection, such as being under the 50^{th} parallel latitude, not an off-shore site, and not being in national parks or provincial parks or important bird area. A buffer zone for the potential sites is enforced between the site and existing wind projects, hydrographic sites, airports, roads, railways, and buildings. Moreover, sites with wind speed less than 6.5 meters/second, at 80 meters above ground level, are not considered. The 60 identified sites have a cumulative capacity of 7,570 MW. The OPA presented in the IPSP a list of potential small wind sites with a cumulative capacity of 2,787 MW, each site's capacity is less than 10 MW. These wind sites are projected based on applications that Hydro-One Inc., received from proponents. The OPA identified in the IPSP the location and capacity of planned wind sites to be in service before 2020. The total capacity of planned wind sites is 3039 MW, of which 1,148 MW of small wind sites from RESOP and the rest are large wind sites from the 60 sites identified in [57].

The wind generation capacity used in this study for 2010 is the actual capacity which is 1,234 MW. For 2015, the planned wind generation capacity is assumed to be all of the 3,039 MW identified by the OPA to result in a total capacity of 4,272 MW when added to the 2010 installed capacity. For 2025, the planned wind generation capacity is assumed to be the 7,570 MW, from all the 60 large wind sites identified in [57], plus the 2,787 MW of small wind sites identified by the OPA without the 277 MW planned for Orangeville, resulting in 11,314 MW capacity when added to the 2010 installed capacity. The total zonal wind generation capacity for 2010, 2015 and 2025 is presented in Figure 4-5.

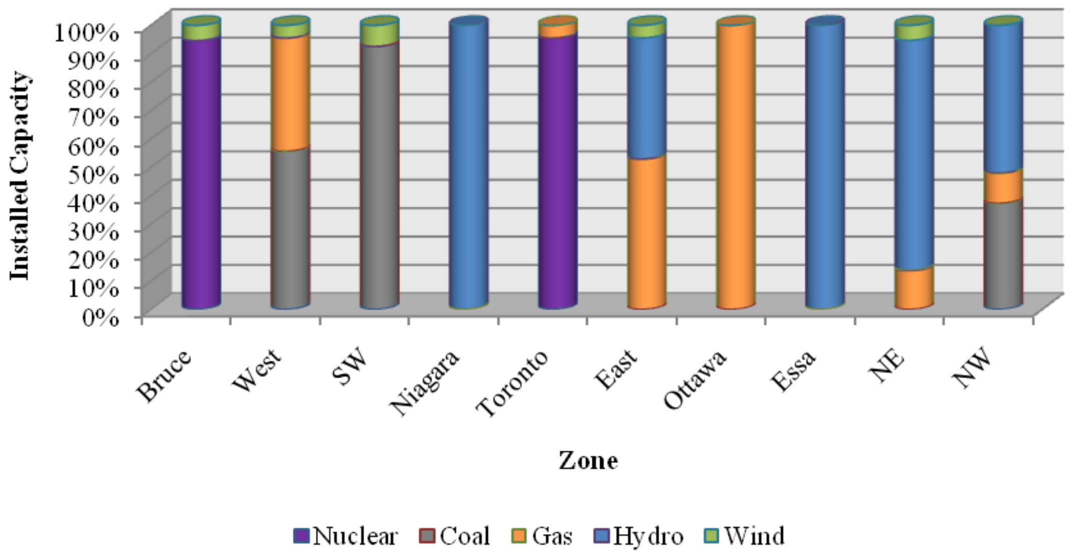


Figure 4-2: Ontario's Existing Zonal Supply Mix (2010).

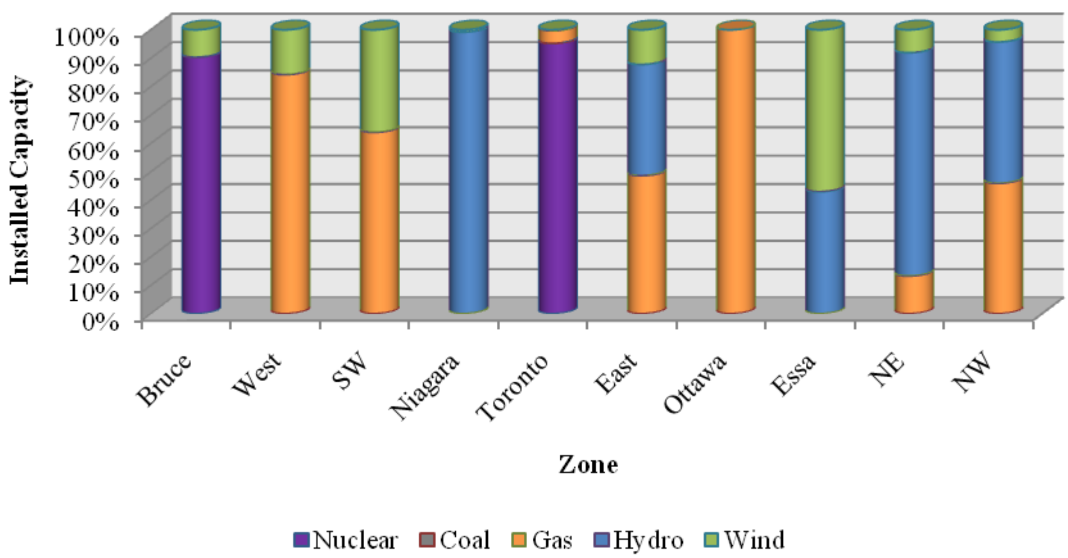


Figure 4-3: Ontario's Planned Zonal Supply Mix (2015).

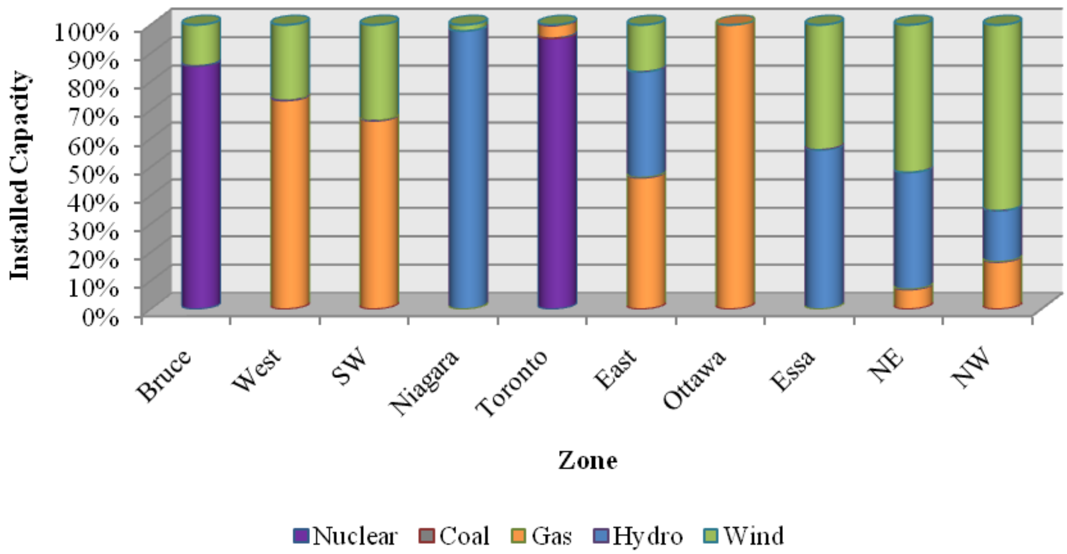


Figure 4-4: Ontario's Planned Zonal Supply Mix (2025).

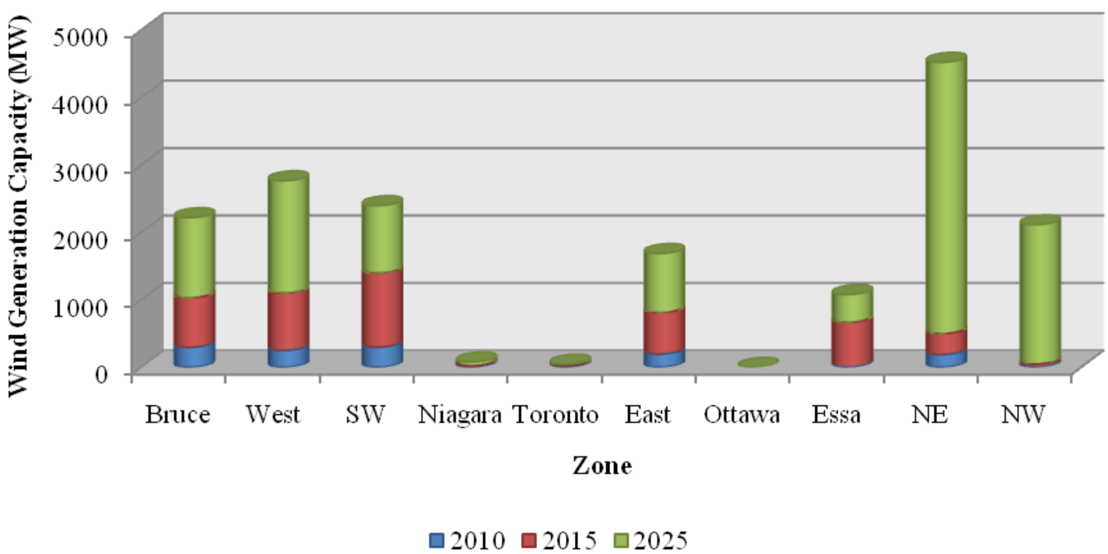


Figure 4-5: Ontario's Zonal Existing and Planned Wind Generation Capacity (2010-2025).

4.4 Demand Estimates for Ontario

The zonal peak demand forecasts for this study are obtained from the ten-year demand forecast provided by the IESO for the period of 2006-2015 [58]. The zonal peak demand average annual growth rates (AGR) are calculated from the forecast as shown in Table 4-2 and then applied to the actual Ontario zonal peak demand of 2010 to estimate the 2015 and 2025 zonal peak demands. Figure 4-6 presents the zonal peak demands estimates, and Figure 4-7 presents the overall system peak demand estimates for the years 2010, 2015 and 2025 adopted in this study.

Table 4-2: Zonal Peak Demand Annual Growth Rate

Zone	Bruce	West	SW	Niagara	Toronto	East	Ottawa	Essa	NE	NW	System
AGR (%)	0.98	1.27	1.38	0.49	0.83	0.77	1.49	1.33	-0.47	0.06	0.95

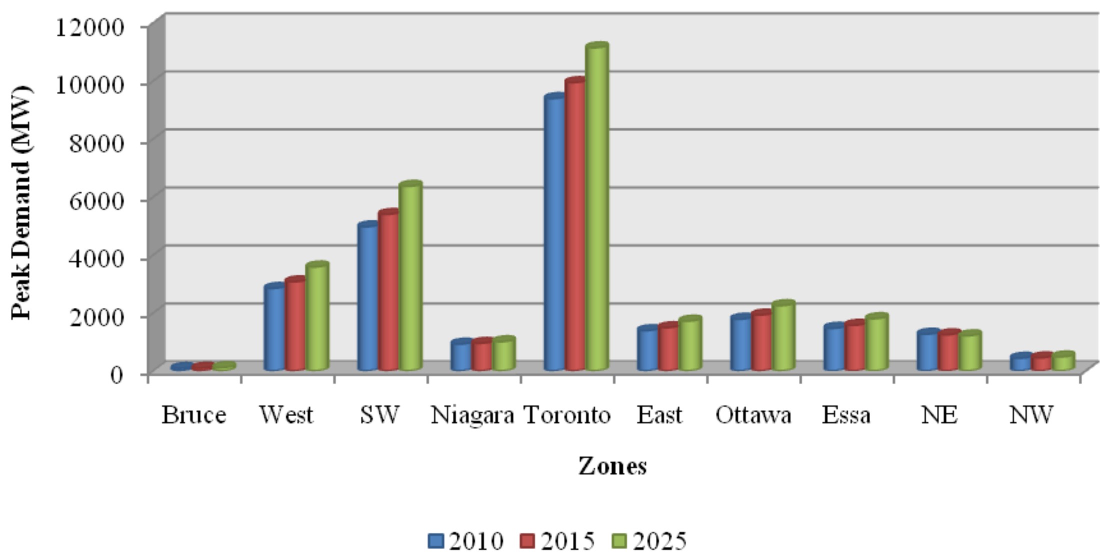


Figure 4-6: Zonal Peak Demand Estimates for Ontario (2010-2025).

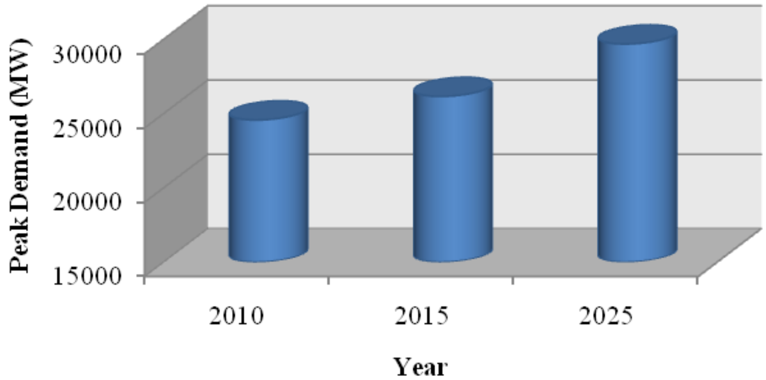


Figure 4-7: Existing Estimates of Peak Demand for Ontario (2010-2025).

4.5 Operational Planning Model for Ontario

Optimal power flow (OPF) is a typical nonlinear programming (NLP) problem that, in most cases, can be mathematically stated as

Minimize $F(\mathbf{u}, x)$

Subject to $h(\mathbf{u}, x) = 0$

$g(\mathbf{u}, x) \leq 0$

Where, **u** is a vector of controllable variables in the system and **x** is the vector of state variables. For example, **u** consists of generator voltage, generator active power output except at the slack bus, transformer tap settings and shunt VAR compensations; **x** consists of slack bus power, load bus voltages, generator reactive power outputs and transmission line loadings. $F(\mathbf{u}, x)$ is a scalar objective function. Equality constraints $h(\mathbf{u}, x)$ are derived from conventional power balance equations. Inequality constraints $g(\mathbf{u}, x)$ are the limits on control variables u and the operating limit on the other variables of the system. The objective function and the constraints are presented and discussed in detail.

4.5.1 Objective Function

The objective function is to minimize the total cost of generation. The cost of generation is approximated by a linear function in order to reduce the computational burden of the optimization problem. Conventional and wind generation costs are represented as constants derived from the generators' full load average costs [59]. The wind generation CF is incorporated in the wind generation cost to incorporate the Monte Carlo simulations in the cost function. The costs of reactive power compensation are also incorporated in the cost function, although it is noted that these costs are a small proportion of the total cost.

$$Cost = \sum_{k=1}^{K} a_k (PG_k^{\min} + \Delta PG_k) + \sum^{N} (b_i Wcf_i Pw_i + c_i Qc_i) \quad (4.\ 1)$$

4.5.2 Demand-Supply Balance

This constraint ensures that there is enough active and reactive power generation to meet the demand at any given instant while accounting for the transmission losses. The capacity of wind generation active and reactive power, Pw_i and Qw_i respectively, are constants, given the wind capacity in each zone depending on the level of wind generation penetration, having an assumed power factor of 0.95 p.u.. The Wcf_i is a random value assigned by the Monte Carlo simulation with a lognormal probability density function with a given range. The demand is assumed to have a constant power factor of 0.9 in each zone.

$$P_i + Wcf_i Pw_i - Pd_i - P_{LOLU} = \sum_j |V_i||V_j||Y_{ij}| \cos(\theta_{ij} + \delta_j - \delta_j) \quad (4.\ 2)$$

$$Q_i + Wcf_i Qw_i + Qc_i - Qd_i = -\sum_j |V_i||V_j||Y_{ij}| \sin(\theta_{ij} + \delta_j - \delta_j) \quad (4.\ 3)$$

4.5.3 Generation Limits

This constraint ensures that any generator with output less than its minimum capability is not being selected.

$$PG_k^{\min} W_k \le PG_k \le PG_k^{\max} W_k \quad (4.\ 4)$$

$$QG_k^{\min} W_k \le QG_k \le QG_k^{\max} W_k \quad (4.\ 5)$$

$$Qc_i^{\min} \le Qc_i \le Qc_i^{\max} \quad (4.\ 6)$$

Where,

$$PG_k = PG_k^{\min} W_k + \Delta PG_k \quad (4.\ 7)$$

4.5.4 Network Power Losses

Computes the total network losses as a result of power flow.

$$Ploss = 0.5 \sum_{ij} G_{ij} (V_i^2 + V_j^2 - 2V_i V_j) \cos(\delta_j - \delta_i) \quad (4.\ 8)$$

4.5.5 Line Flow Limits

Ensures that the transmission lines connecting the different zones are not overloaded by exceeding their maximum power transfer limits.

$$\left|P_{ij}\right| \leq P_{ij}^{\max} \quad (4.9)$$

Where,

$$P_{ij} = V_i (Ir_{ij} \cos(\delta_i) + Ii_{ij} \sin(\delta_i)) \quad (4.10)$$

$$Q_{ij} = V_i (Ir_{ij} \sin(\delta_i) - Ii_{ij} \cos(\delta_i)) \quad (4.11)$$

And,

$$Ir_{ij} = V_i Y_{ij} \cos(\theta_{ij} + \delta_i) - V_j Y_{ij} \cos(\theta_{ij} + \delta_j) - V_i (B_{ij} / 2) \sin(\delta_i) \quad (4.12)$$

$$Ii_{ij} = V_i Y_{ij} \sin(\theta_{ij} + \delta_i) - V_j Y_{ij} \sin(\theta_{ij} + \delta_j) + V_i (B_{ij} / 2) \cos(\delta_i) \quad (4.13)$$

4.5.6 Voltage Limits

Ensures that the terminal voltage at each zone, which is modeled as a single bus, is within the acceptable range.

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad \forall \in N \quad (4.14)$$

4.5.7 Adequacy Constraint

Ensures that there is enough generation capacity to meet the peak demand while maintain adequate spinning reserves to account for actual wind generation output.

$$\sum_{k=1}^{K} ((PG_k^{\max} W_k) - PG_k) \geq \sum^{N} Wcf_i Pw_i \quad (4.15)$$

4.5.8 Generation Emissions

Computes the weight of Green-House-Gas emissions of the generating units expressed with carbon dioxide equivalent (CO2e), and the associated cost of carbon emissions (C_{CO2}).

$$CO2e = \sum_{k=1}^{K} e_k (PG_k^{\min} + \Delta PG_k) + \sum^{N} (d_i Wcf_i Pw_i) \quad (4.16)$$

$$C_{co2} = (SCC)(CO2e) \tag{4. 17}$$

Table 4-3: Model parameters [59]

Type of Generation	Delivered Electricity Cost (₵/KWh)	CO2 Emission Rate (ton/MWh)
Nuclear	6.35	0.01
Coal	13.34	1
Gas	10.37	0.54
Hydro	7.22	0.008
Wind	11.69	0.012

4.6 Results and Discussions: Deterministic case study

The optimal power flow model developed in Section 4.5 is used in a deterministic and probabilistic case study. The model is a Mixed Integer Nonlinear Programming (MINLP) and is solved using the COINBOINMIN solver [60] in the General Algebraic Modeling System (GAMS) platform. The results of both case studies are presented and analyzed in the next sections.

A deterministic case study is carried out on the Ontario grid at the peak demand hour to quantify the impact of the different penetration-levels of wind generation. The case study is carried out for the years 2010, 2015 and 2025 with 1,234 MW, 4,273 MW and 11,314 MW of installed wind generation capacity respectively.

The total average wind generation CF of the Ontario system is assumed to be a constant, but differs across the zones. The demand for 2010, as stated in Section 4.4, is the actual peak demand in Ontario for that year. Thus the total average wind generation CF used in the model, is the actual coincident value at that hour, of 27%. The wind generation CF for 2015 and 2025 are assumed to be continuously reducing from that of 2010, as per the discussion in Chapter 3, about how as the wind generation penetration increases in a system the average wind generation CF decreases. Based on the wind generation installed capacity of 2015 and 2025, their wind generation CF are estimated to be 24% and 20% respectively. The zonal wind generation CF is calculated based on the correlation between the wind generation CF of each zone. The correlation between the zonal wind generation CF, is calculated in this work, from the historical hourly wind generation data provided by IESO [14], as shown in Table 4-4. The zonal wind generation CF is obtained by fixing the wind generation CF of a single zone and correlating the rest of the zones' wind generation CFs to it. The fixed wind generation CF is chosen such that when correlating the rest of the zones' wind generation CF, it results in the total average wind generation CF required. In this study the fixed zone is Bruce. As for 2015 and 2025, the zones that do not have historical data of wind generation, their correlations are calculated from the correlation formula developed in chapter 3. The formula is $C = e^{-d/d_o}$, where d is the separation between the zones in kilometers, and d_o is a constant of 609.

Table 4-4: Current Ontario zonal wind generation's CF correlation matrix

	Bruce	*West*	*SW*	*East*	*NE*
Bruce	1				
West	0.673312	1			
SW	0.796224	0.698741	1		
East	0.503853	0.403997	0.603194	1	
NE	0.524958	0.386255	0.407074	0.242519	1

4.6.1 System Operation in 2010

Figure 4-8 presents the zonal generation, demand and transmission corridor power flows of the base case (2010). The following observations can be made:

- The Toronto zone has the highest demand in Ontario, and is mainly served from the nuclear generation within the Toronto zone (Pickering and Darlington: 6,600 MW), the nuclear generation in the Bruce zone (Bruce: 4,846 MW), and the hydroelectric plants in the Niagara zone (2,290 MW). The output of Bruce zone is at the limit of its capacity, this being a predominantly nuclear generation zone and is very cheap. Hence the transmission corridor connecting Bruce to the SW zone to serve the high demand in the Toronto zone is heavily loaded (90% of its capacity).
- As for the province capital, the Ottawa zone has a low generation capacity of 73 MW whereas its demand is 1,784 MW. Therefore the load is mainly served from the generation of the East zone which comprises a mix of gas and hydroelectric plants with a gross capacity of 2,474 MW and 1,991 MW, respectively. Accordingly the transmission corridor connecting the generation in the East zone with the demand in Ottawa is heavily loaded at 92% of its capacity.
- The total wind generation capacity is 1,234 MW.

- The wind generation output from the southwestern region i.e., Bruce, Southwest and West, as determined from the model, is 78% of the total wind generation output in the system.

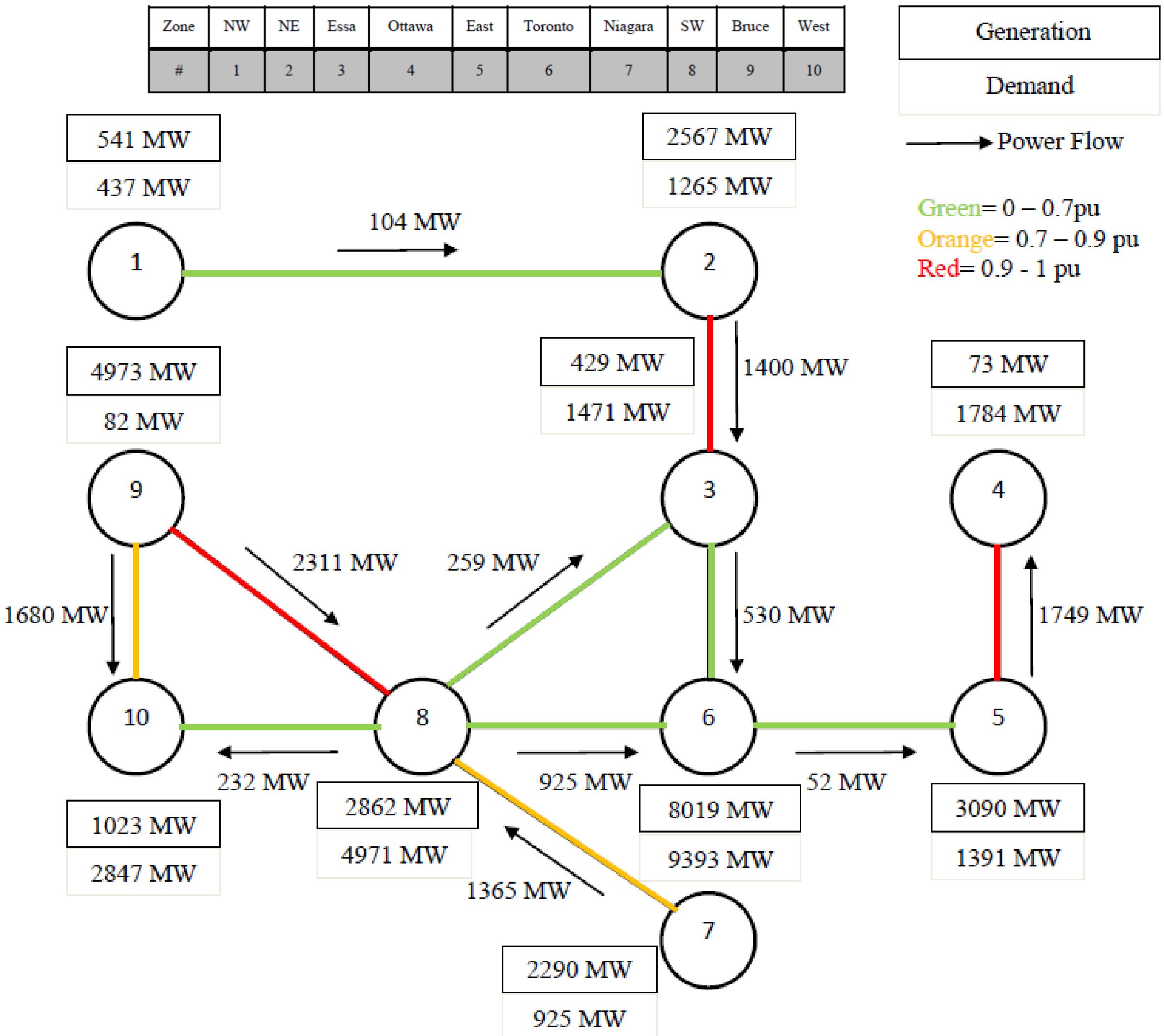


Figure 4-8: Zonal generation, demand and corridor power flows in Ontario (2010).

4.6.2 System Operation in 2015

Figure 4-9 presents the change in the zonal generation, demand and transmission corridor power flows for the year 2015 from that of the base case (2010). The following observations can be made:

- The capacity of the transmission corridor connecting Bruce to West has increased by 500 MW as a result of transmission expansion, as shown in Table 4-1.
- Transmission expansion planned between Bruce and the SW zone in 2012, as shown in Table 4-1, results in two more 500 kV circuits to support the additional 1,400 MW of nuclear generation to Bruce zone.
- The generation in SW and Toronto zones are reduced by 943 MW and 315 MW respectively due to the decommissioning of the coal-fired generating units of Nanticoke power station located in SW (2,760 MW) and the planned refurbishment of Pickering B (Toronto) nuclear generation station (2,064 MW) in 2014. Thus the cheap hydroelectric generation of Niagara is used to meet the demand of southwestern Ontario along with the increased generation capability from Bruce. Hence the transmission corridor connecting the Niagara and SW zones are more congested with the power flowing through it increasing from 78% to 99% of its capacity.
- The transmission corridor connecting the Ottawa and East zones are more congested with an increase in the power flowing through them from 92% to 95% of its capacity, to account for the 144 MW demand increase in Ottawa in 2015 whereas Ottawa's generation only increases by 97 MW.
- The demand of NE and NW zones are much less than their generation capability and thus the cheap hydroelectric generation of both zones are utilized at their capacities to serve zones with higher demands, at a low generation cost, at 88% and 80% of their capacity respectively, resulting in the congestion of the transmission corridor connecting the NE and Essa zones.
- The wind penetration level increased from 1,234 MW to 4,273 MW, with a 670 MW of extra wind generation injected at the zones as determined from the model.
- It is noted that, 70% of the wind generation output is coming from the southwestern region i.e., Bruce, Southwest and West.
- As the wind generation capacity in the West zone increases from 250 MW to 754 MW, yielding an increase in wind generation output of 123 MW, the power flowing from Bruce to West decreases by 11 % on the transmission corridor connecting the two zones.
- As the wind generation capacity in the Bruce and SW zones have increased from 297 MW and 298 MW to 774 MW and 1,159 MW respectively, yielding in a 547 MW increase in wind

generation output in these zones, the power flowing from Bruce to SW decrease by 10% on the transmission corridor connecting the two zones.

- With the decommissioning of the Lambton coal power station (950 MW), the change in zonal generation is still positive, a portion of that increase can be attributed to the 196 MW of wind generation output in that zone which is approximately 19% of the total output of wind generation at that hour.

Zone	NW	NE	Essa	Ottawa	East	Toronto	Niagara	SW	Bruce	West
#	1	2	3	4	5	6	7	8	9	10

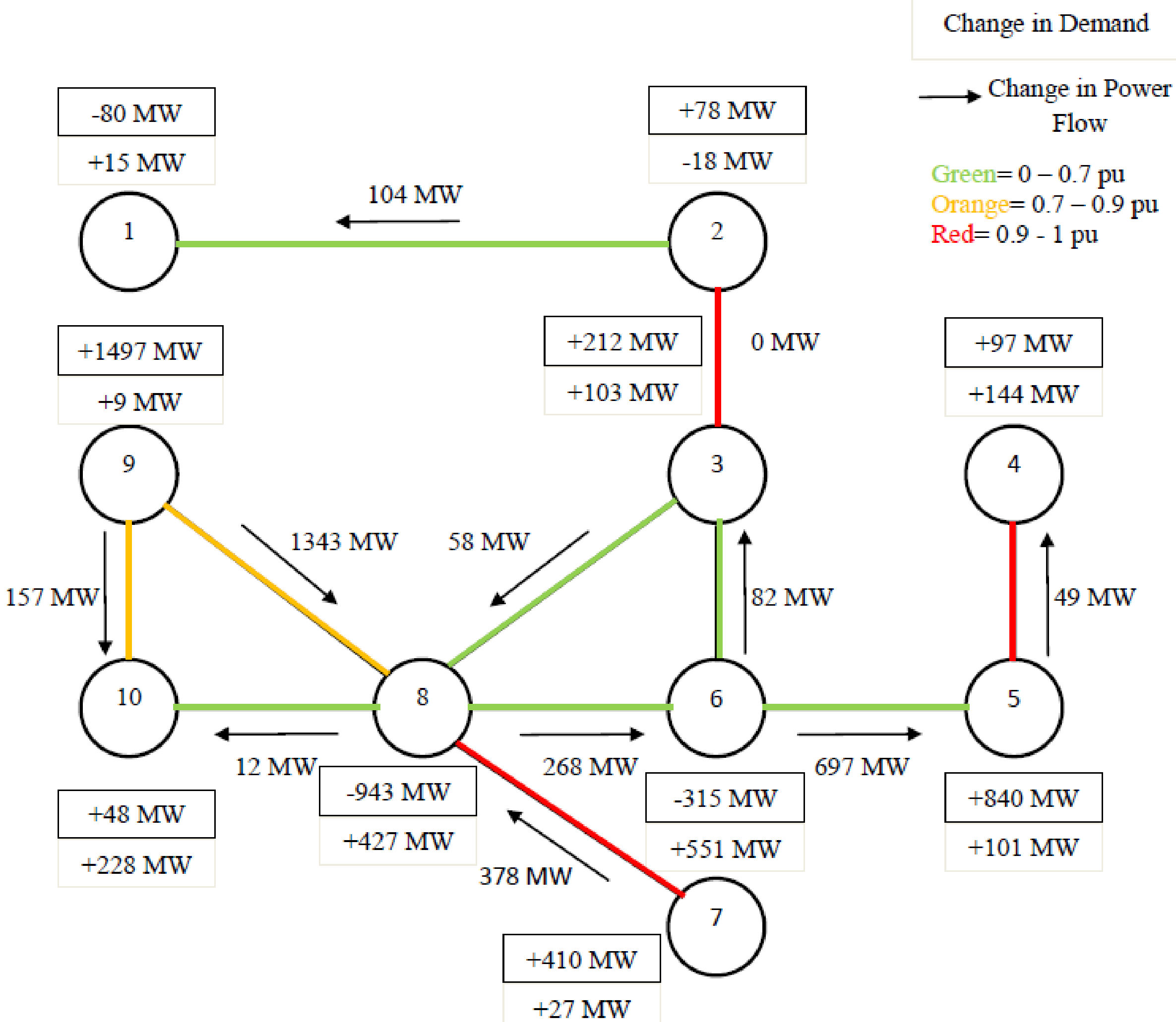


Figure 4-9: Change in Zonal generation, demand and corridor power flows in Ontario (2010-2015).

4.6.3 System Operation in 2025

Figure 4-10 presents the change in the zonal generation, demand and transmission corridor power flows in 2025 as compared to 2015 which is the new base case. The following observations can be made:

- The wind penetration level increases from 4,372 MW to 11,314 MW, with a 1,195 MW of additional wind generation output injected at the zones as determined from the model.
- The wind generation output from the southwestern region (Bruce, Southwest and West zone) is 44% and from the Northern region (NE and NW) is 45% of the total wind generation output.
- Even though the system demand increases by 3,527 MW, the power flowing in the transmission corridors is reduced by 1,452 MW; this can be greatly attributed to the 2,253 MW of wind generation output as determined by the model from the 11,314 MW of installed wind generation capacity in 2025.
- In specific to the southwestern region, even though the system demand increases by 2,755 MW, the power flowing in the transmission corridors is reduced by 686 MW; this can be greatly attributed to the 993 MW of wind generation output as determined by the model from the 2,755 MW of installed wind generation capacity at this region in 2025. Consequently, the transmission corridor between Niagara and SW became less congested where the power flowing through them has reduced from 99% to 97% of its capacity.
- As a result of the 2,067 MW and 4,042 MW installed wind generation capacity at the NW and NE zones respectively, 72% and 56 % of the demand at these zones are being served by wind generation and the rest is being served by hydroelectric plants located at these zones. Given that the primary choice of system operators for spinning reserves are hydroelectric plants, as their output does not require fuel and can be quickly changed, the NW and NE zones are preferable candidates for future wind generation investments for a safe and reliable operation of wind generation. However, further transmission expansions to the transmission corridor connecting these zones to Ontario's demand centre are required to benefit from their wind generation output. Consequently, incentives programs such as the FIT program should be modified to encourage investments in the remote areas of the province; prices for wind generation production should differ based on location rather than a fixed price across the province.

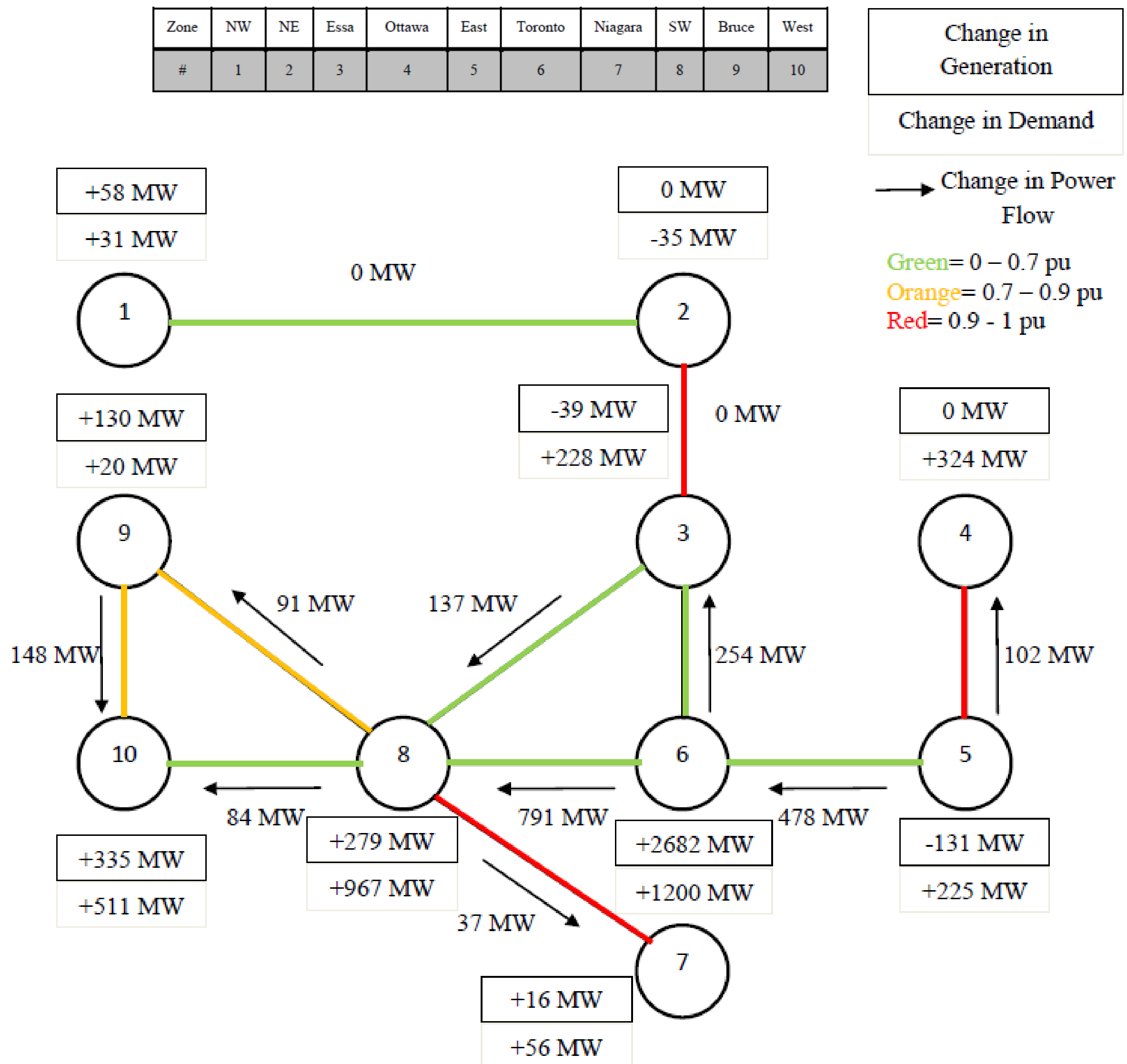


Figure 4-10: Change in Zonal generation, demand and corridor power flows in Ontario (2015-2025).

4.6.4 Operating Reserves

The generation reserve margin (GRM) is calculated from the model for the 3 years under study; 2010, 2015 and 2025. The GRM denotes the capacity reserve available in the system during the peak load occurrence, as a percent of the system peak load demand [20]. The GRM was found to be 15%, 17.3% and 23.2% for 2010, 2015 and 2025 respectively.

4.6.5 Cost of Delivered Energy

The cost of delivered energy during the peak demand hour is calculated to be 13 ₡/kWh, 19.1 ₡/kWh and 18.9 ₡/kWh for 2010, 2015 and 2025 respectively. The increase in the cost of delivered energy in 2015 is attributed to the increase in wind generation and its associated back up reserves, which is accounted for, by Equation (4.15). The cost of delivered energy also increases because of the planned refurbishment of Pickering B nuclear generation station (2,064 MW) in 2014, thus reducing the capacity of nuclear generation in the system. In 2025, with the increase in wind penetration from 4,273 MW to 11,314 MW the cost of delivered energy slightly decreased, because of the increase in cheap generation reserves in the system, with nuclear generation increasing from 10,800 MW to 13,479 MW and hydroelectric generation from 8,755 MW to 10,771 MW.

4.6.6 Green-House-Gas Emissions

Ontario is driven towards a green economy and is incorporating renewable energy technologies in its supply resources mix to address the global warming issue, and reduce green-house-gas (GHG) emissions. The main factors in fossil fuel-fired generation contribution to GHG emissions are the fuel characteristics such as its carbon content and caloric value, its location (fuel transmission losses) and the plant conversion efficiency. The main factor in the contribution of hydroelectric generation to GHG emissions is from the energy used in construction and its associated emissions. Nuclear generation's contribution to the GHG emissions is from the energy used to extract its fuel (uranium), while that of wind generation is from the energy used in manufacturing of the blade, the tower and the foundation [61].

The GHG emissions rates are expressed in terms of Carbon Dioxide equivalent (CO_2e) which includes carbon dioxide (CO_2), Methane (CH_4), Nitrous Oxide (NO_2), and other contaminants. The GHG intensity is expressed in grams of CO_2e per kWh (gCO_2e/kWh). Using the CO_2e emission rate for different type of generation technologies shown in Table 4-3, the GHG intensity is calculated to be 214.4 gCO_2e/kWh, 162.7 gCO_2e/kWh, and 150 gCO_2e/kWh for 2010, 2015 and 2025 respectively. The phasing-out of coal-fired generation and increase in wind generation penetration levels results in significant decrease in the GHG emissions in Ontario.

4.6.7 Voltage Profiles

Figure 4-11 presents the zonal voltages for the 3 years understudy; 2010, 2015, and 2025. As observed the only change in voltage occurred in the Toronto, West and Essa zones. The voltages in these zones have gradually increased with the exception of the Toronto zone where its voltage hit its lower limit in 2015.

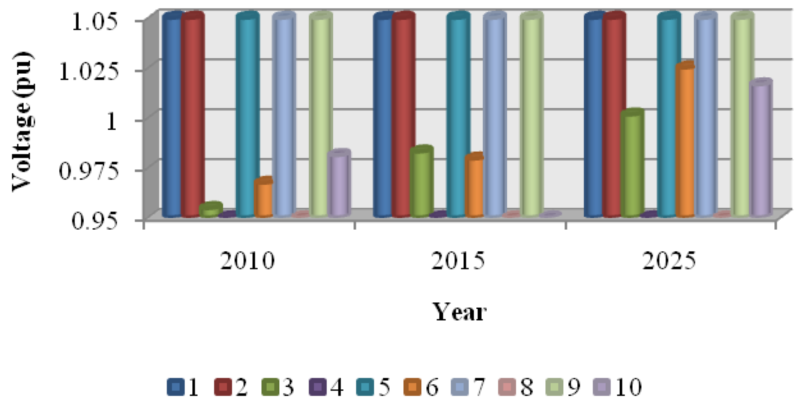


Figure 4-11: Zonal Voltage Profile in Ontario (2010-2025).

4.7 Probabilistic Case study

Monte Carlo Simulation is a decision-making tool that incorporates the uncertainty of its determinant. Depending on the range of the determinant's PDF, Monte Carlo simulations converge in certain number of iterations, producing an estimated outcome that internalizes the determinant uncertainty. For every determinant there is a probability distribution that best describes its uncertainty such as normal, uniform, lognormal and other PDFs.

In this section, a Monte Carlo simulation is used in order to account for the intermittency and variability of wind generation with the inherent uncertainty being the wind generation's CF. Based on the historical data of Ontario's wind generation a lognormal distribution is chosen to represent the wind generation's CF. The study also incorporates the decreasing trend in wind generation CF and its variability, as the penetration level increases over the years. This is evident from the considered PDF of the CFs (Figure 4-12), wherein the mean (μ) of the PDFs used are 27%, 24% and 20% for 2010, 2015, and 2025 respectively, along with a decreasing standard deviation (σ) of 22%, 18%, and 15% for 2010, 2015, and 2025 respectively.

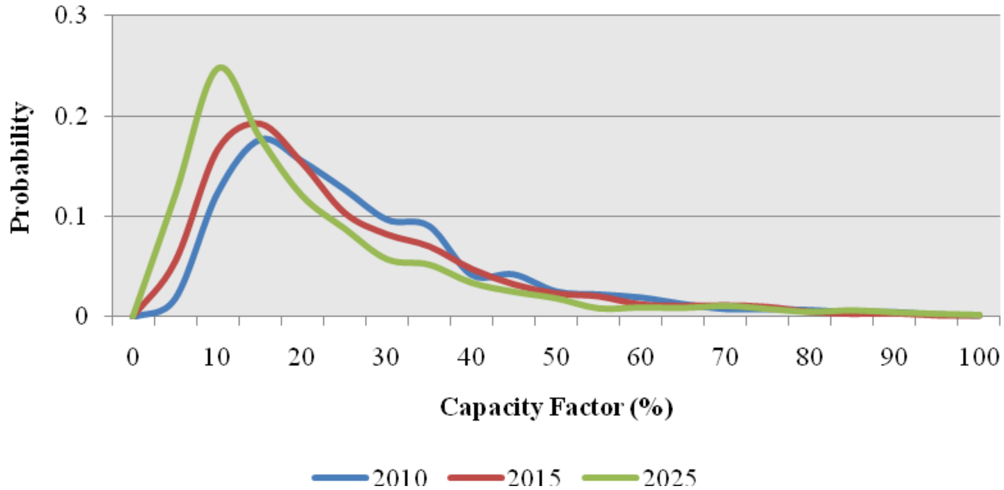


Figure 4-12: PDF of Monte Carlo Simulation's Wind Generation's CF output (2010-2025).

4.7.1 Electricity Production

The expected electricity production in Ontario during the peak demand hour of each year is plotted over 2000 iterations of Monte Carlo simulation in Figure 4-13, when it is observed to converge, and resulting in 25,253 MW, 26,918 MW, and 30,590 MW of generation for 2010, 2015 and 2025 respectively. The expected electricity production for each year is broken down to the contribution of each generation technology by percentage (Figure 4-14).

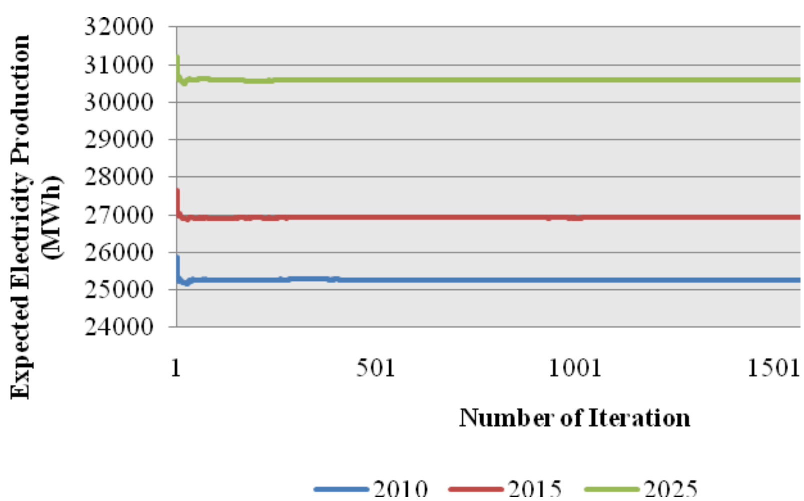


Figure 4-13: Expected Electricity Production in Ontario (2010- 2025).

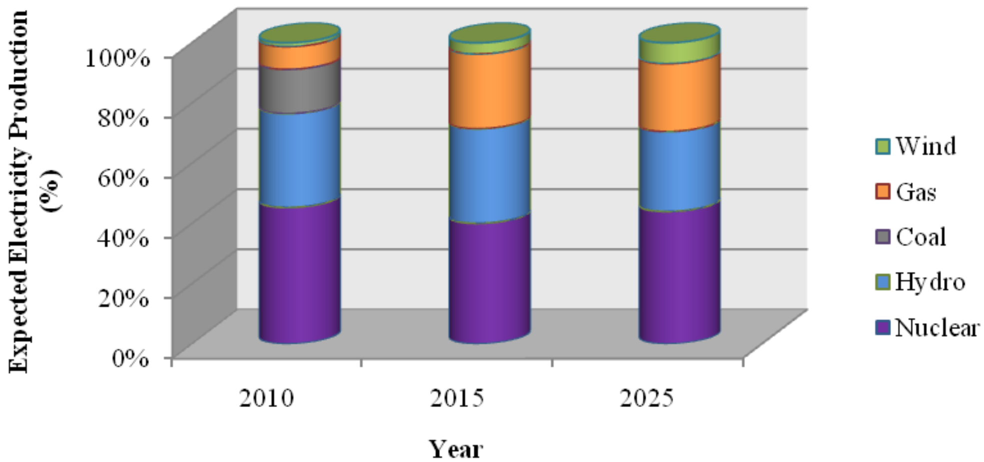


Figure 4-14: Expected Electricity Production in Ontario by Fuel Type (2010- 2025).

4.7.2 Operating Reserves

The expected GRM as identified for each year is plotted over 2000 iterations of Monte Carlo simulation in Figure 4-15 to Figure 4-17, and converges to 11.75%, 15.3% and 21.3% for 2010, 2015 and 2025 respectively. The corresponding reserve margin in MW values is 2,930 MW, 3,963 MW and 6,081MW for 2010, 2015 and 2025 respectively.

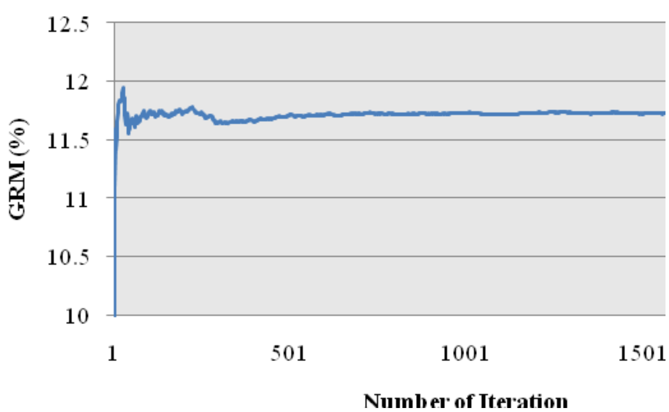


Figure 4-15: Expected GRM in Ontario (2010).

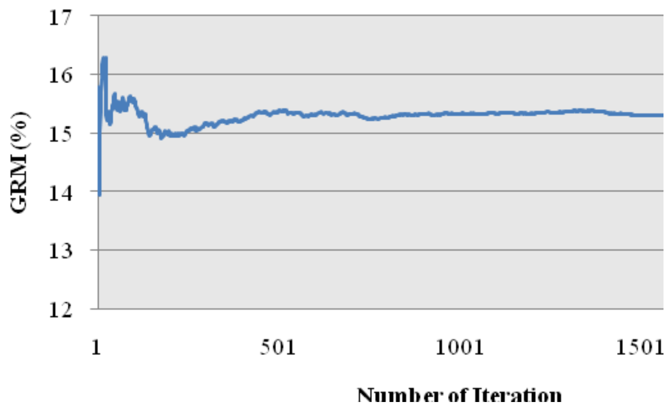


Figure 4-16: Expected GRM in Ontario (2015).

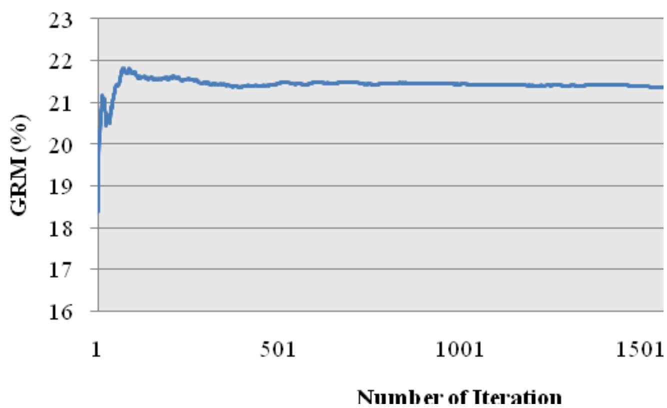


Figure 4-17: Expected GRM in Ontario (2025).

4.7.3 Expected Cost of Delivered Energy

The expected cost of generation during the peak demand hour of each year is plotted over 2000 iterations of Monte Carlo simulation in Figure 4-18 to Figure 4-20, and is seen to converge to 11.4 ₵/kWh, 17.4 ₵/kWh and 16.6 ₵/kWh for 2010, 2015 and 2025 respectively. As discussed previously in the deterministic case study, the reduction in the cost of delivered energy in 2025 from that of 2015 is due to the increased availability of cheap generation, wherein nuclear generation increased from 10,800 MW to 13,479 MW and hydroelectric generation increased from 8,755 MW to 10,771 MW.

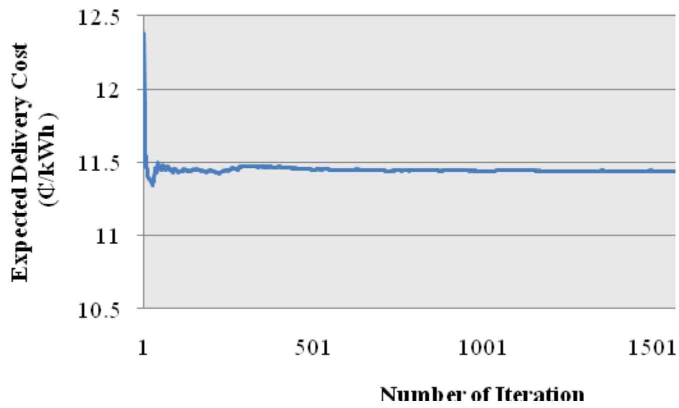


Figure 4-18: Expected Cost of Delivered Energy in Ontario (2010).

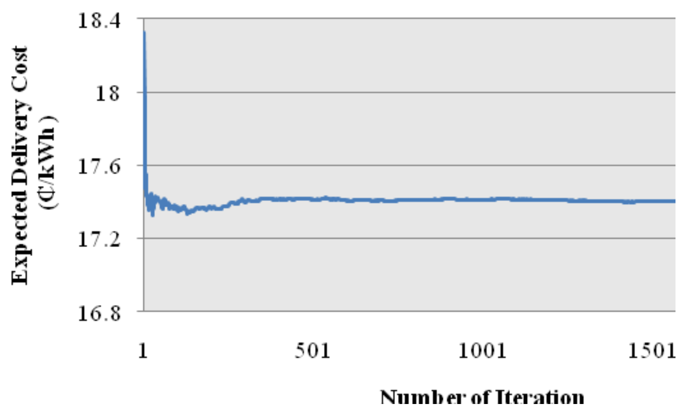


Figure 4-19: Expected Cost of Delivered Energy in Ontario (2015).

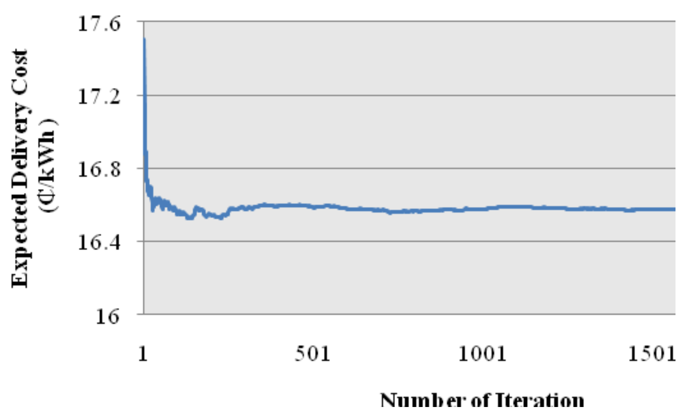


Figure 4-20: Expected Cost of Delivered Energy in Ontario (2025).

4.7.4 Power Losses

The expected network power losses in the transmission system during the peak demand hour of each year is plotted over 2000 iterations of Monte Carlo simulation, and converges to 530 MW, 662 MW, and 723 MW for 2010, 2015 and 2025 respectively, which is 2.2%, 2.5% and 2.4 % for 2010, 2015 and 2025 respectively as presented in Figure 4-21.

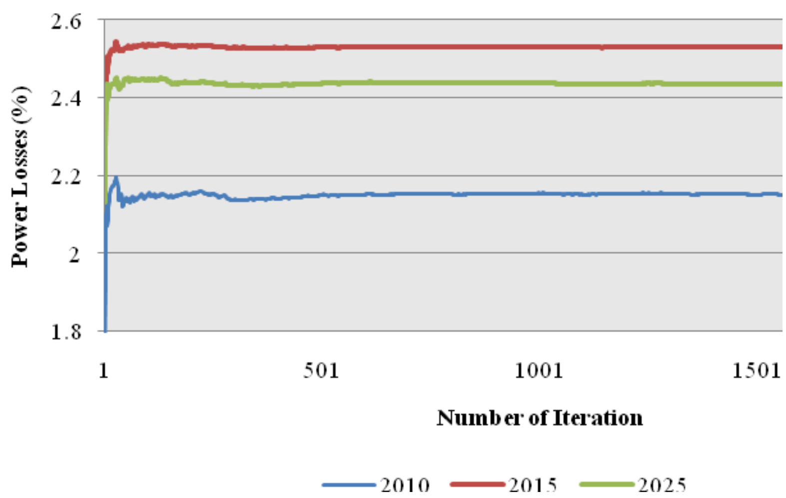


Figure 4-21: Expected Power Losses in Ontario (2010 - 2025).

The increase in the network power losses is mainly attributed to the non-dispatchability of wind generation as most of the wind generation penetration occurs far from the Toronto area which is the demand centre of Ontario and consequently increasing the power flowing on the transmission corridors between the zones thereby increasing the network power losses. However, the power losses have reduced in 2025 from 2015 in spite of a 6942 MW increase in installed wind generation capacity. The reduction is attributed to the increase in generation capacity in Toronto area from refurbishment of Pickering B nuclear generation station (2064 MW). Moreover, the northern zones (NE and NW) undergo high penetration of wind generation in this period 2015 – 2025, and their zonal demand is mostly met by local wind generation as presented in Figure 4-22. The rest of their zonal demand is met by their respective zonal conventional generation. Therefore their zonal conventional generation is reduced and consequently reduces the power flow on the transmission corridors between the zones and the demand centre.

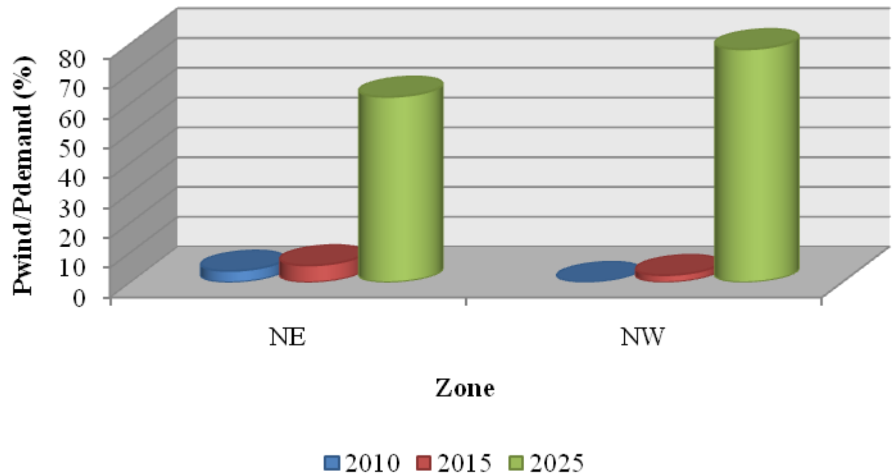


Figure 4-22: Share of Zonal Wind Generation in Meeting Zonal Demand (2010 - 2025).

4.7.5 Green House Gas Emissions

The expected GHG emissions during the peak demand of each year is plotted over 2000 iterations of Monte Carlo simulation in Figure 4-23 to Figure 4-25, and converges to 4,920 tons, 3,795 ton, and 3,984 tons MW for 2010, 2015 and 2025 respectively. Which is expressed in terms of GHG intensity as 200 gCO_2e/kWh, 145 gCO_2e/kWh, and 133 gCO_2e/kWh for 2010, 2015 and 2025 respectively.

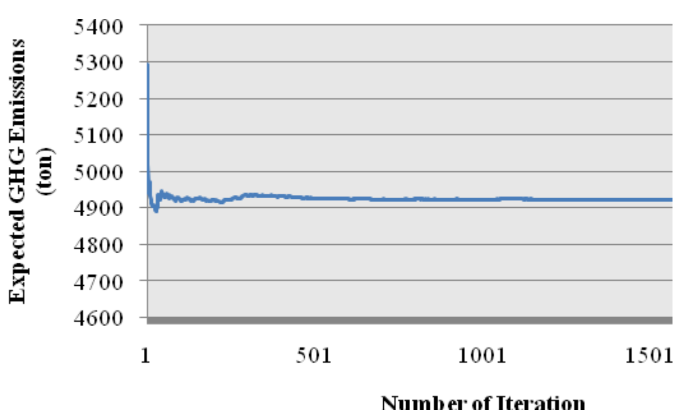


Figure 4-23: Expected GHG Emissions in Ontario (2010).

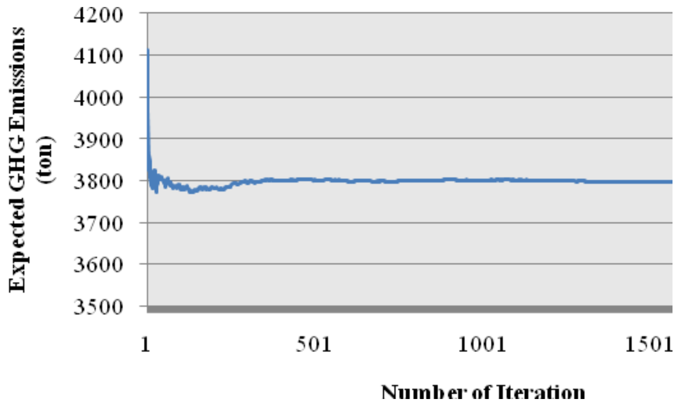


Figure 4-24: Expected GHG Emissions in Ontario (2015).

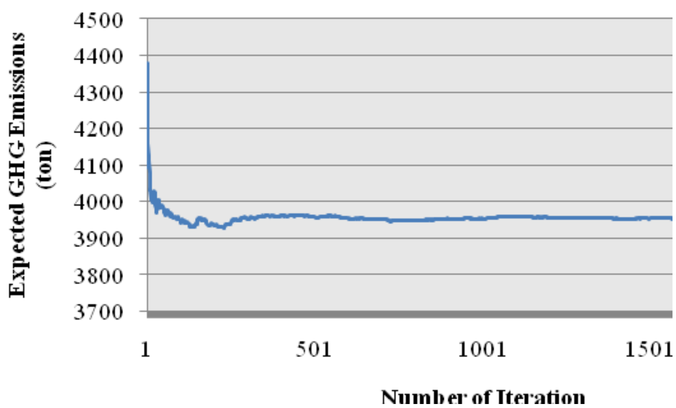


Figure 4-25: Expected GHG Emissions in Ontario (2025).

The social cost of carbon (SCC) is calculated for each year assuming a $35 per ton CO2e, resulting in $172,168, $132,834, and $138,209 for 2010, 2015, and 2025 respectively. Normalizing the yearly SCC by dividing over the demand of each year, results in a cost of GHG emissions per demand. The cost of GHG emissions per unit of demand is 7 $/MWh, 5 $/MWh, and 4.6 $/MWh per MWh for 2010, 2015, and 2025 respectively.

4.8 Concluding Remarks

In this chapter, a transmission network model for Ontario is developed based on the 500 and 230 KV transmission corridors with their planned enhancements for the three years under study - 2010, 2015 and 2025. The zonal supply mix of generation resources includes nuclear, wind, hydro, gas-fired generation and coal-fired generation was developed as well as the zonal peak demand. An optimal power flow model was developed and then used in a deterministic case study. Monte Carlo simulations are then carried out considering the variability and uncertainty of wind generation. Both case studies examine the effect of different wind generation penetration levels on the Ontario electrical grid and analyze long-term wind generation impact analyses.

The model is solved using the COINBOINMIN solver in GAMS. The results quantify the impact of the different wind generation penetration levels - 1,234 MW, 4,273 MW and 11,313 MW for the three years under study - 2010, 2015 and 2025 respectively, on the Ontario electrical grid. It is concluded that the operating reserves requirements during peak demand hours will increase from 11.75% in 2010 to 15.3%, and 21.3% in 2015 and 2025 respectively as wind capacity becomes a larger proportion of the installed generation base in Ontario. The implication for increasing operating reserves requirements is that additional back-up generation, namely gas-fired generation, would be required for optimal system performance. It is also concluded that the cost of delivery of energy would increase because of wind generation penetration from 11.4 ₵/kWh in 2010 to 17.4 ₵/kWh and 16.6 ₵/kWh in 2015 and 2025 respectively. The power losses are expected to increase as well with the penetration of wind generation as most of the wind capacity is located far from the Toronto area which is the demand centre. Finally, the GHG emission intensity is expected to reduce with the penetration of wind generation from 200 gCO_2e / kWh in 2010 to 145 gCO_2e / kWh, and 133 gCO_2e / kWh in 2015 and 2025 respectively.

Chapter 5
Conclusions

5.1 Thesis Summary

In this thesis, first, a long-term statistical analysis of wind generation data of wind farms in Ontario is presented. Thereafter, an operational planning model for Ontario is developed and used to assess the system operational impacts of wind generation penetration on the Ontario power system for three specific years; 2010, 2015 and 2025, using the key findings from the long-term statistical analysis.

- Chapter-2 presents an overview of wind energy generation. The major technologies utilized in harnessing wind energy are discussed; different types of wind turbines and wind generators. Wind modeling is also discussed, wherein turbine power and wind speed-power relationship is presented in detail. A brief literature review of wind integration studies, assessing the impact of wind generation penetration on power systems is presented, with the different methodologies used.

- Chapter-3 presents a long-term statistical trend analysis of wind generation patterns in Ontario. Using various wind generation data sets of Ontario wind farms during 2007 – 2010, on hourly, monthly, seasonal and yearly time-scales, some important insight is presented. The analysis carried out, includes, long-term total wind generation CF trends on yearly, seasonal, and monthly scales. To arrive at a better understanding of the wind generation intermittency and variability in Ontario, long term wind generation variability trends are presented. The correlation between the CFs of Ontario's WFs is determined using the Pearson Product-Moment Correlation Coefficient and examined against their distances from one another to understand the effect of geographic diversity for WFs on total wind generation. The electricity system demand for on- and off-peak periods is analyzed to examine the contribution of wind generation during these periods.

- Chapter-4 presents a transmission network model for Ontario based on the 500 kV and 230 KV transmission corridors with their planned enhancements for the three years under study- 2010, 2015 and 2025. The zonal supply mix of generation resources included are, nuclear, wind, hydro, gas-fired and coal-fired generation. An optimal power flow model is developed and used in a deterministic case study. Monte Carlo simulations are then carried out considering the variability and uncertainty of wind generation. Both case studies examine the effect of different wind generation penetration levels on the Ontario electrical grid and analyze long-term wind generation impacts. The model is solved using the COINBOINMIN solver in GAMS. The results quantify the impact of the different wind generation penetration levels.

5.2 Contribution of the Thesis

The main contributions of the research presented in this thesis are as follows:

a. From the analysis presented it is observed that geographical dispersion of wind farm investments is recommended in order to reduce the variability and fluctuations in wind generation output. It has been found that in order to smooth-out the variability in total wind generation output, low correlation between WFs' outputs is required, which in case of Ontario can be achieved by separating WFs or groups of WFs by 320 km or more.

b. It is also concluded that the information on long-term total wind generation CF are not sufficient for investment or operational planning decisions because the intermittency and variability of the energy output in the short-term do not provide a solid basis. From the analysis presented it is observed that wind generation in Ontario can only be relied upon if there is an adequate back-up operating reserve to account for its shortfalls.

c. The NW and NE zones are preferable candidates for future wind generation investments for a safe and reliable operation of wind generation. However, further transmission expansions to the transmission corridor connecting these zones to Ontario's demand centre will be required to benefit from their wind generation output. Consequently, incentives programs such as the FIT program should be modified to encourage investments in the remote areas of the province; prices for wind generation production should differ based on location rather than a fixed price across the province.

d. The results quantify the impact of the different wind generation penetration levels - 1,234 MW, 4,273 MW and 11,313 MW for the three years under study - 2010, 2015 and 2025 respectively, on the Ontario electrical grid. It is concluded that the operating reserves requirements during peak demand hours will increase from 11.75% in 2010 to 15.3%, and 21.3% in 2015 and 2025 respectively as wind capacity becomes a larger proportion of the installed generation base in Ontario. The implication for increasing operating reserves requirements is that additional back-up generation, namely gas-fired generation, would be required for optimal system performance. It is also concluded that the cost of delivery of energy would increase because of wind generation penetration from 11.4 ₵/kWh in 2010 to 17.4 ₵/kWh and 16.6 ₵/kWh in 2015 and 2025 respectively. The power losses are expected to increase as well with the penetration of wind generation as most of the wind capacity is located far from the Toronto area which is the demand centre. Finally, the GHG emission intensity is expected to reduce with the penetration of wind generation from 200 gCO_2e/kWh in 2010 to 145 gCO_2e/kWh, and 133 gCO_2e/kWh in 2015 and 2025 respectively.

5.3 Future Work

Based on the research presented in this thesis, some ideas and directions for further research can be identified, as follows:

a. The present work concentrates on the impacts of wind generation on the Ontario power system. It would be important to extend the analysis to other power systems around the world, for example, some European countries such as Denmark and Spain, or certain U.S. states, which would provide perspective and vision on this issues and to make conclusive, comparative, performance measures of these systems, and increase confidence in estimates and the role that wind generation can play in meeting demand.

b. It would be pertinent to examine the impact of other intermittent energy generation sources such as solar photovoltaic generation, and their penetration in the Ontario grid, in conjunction with the wind generation sources.

c. The present work dwells upon wind generation impacts on system operating reserves, i.e., spinning reserves only. This maybe further extended to examine other related aspects such as primary and secondary frequency control, non-spinning reserve requirements and system operational risk indices.

Appendix

Data sets used in this thesis are publicly available on the IESO website.

- Ontario's hourly wind farms generation output:

  http://ieso.com/imoweb/pubs/marketReports/download/HourlyWindFarmGen_20110826.csv

- Ontario's hourly electricity demand:

  http://ieso.com/imoweb/pubs/marketReports/download/HourlyDemands_20110826.csv

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