METHODS FOR REDUCING VEHICULAR GREENHOUSE GAS EMISSIONS USING ELECTRIC VEHICLES AND WIND-ELECTRICITY

by

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DEDICATION

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

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ABSTRACT

Recently, electric vehicles (EVs) have been gaining attention in passenger transportation due to their greater fuel economy and reduced greenhouse gas (GHG) emissions compared to conventional vehicles (CVs). The amount of GHG emissions reduction from EVs depends on the energy sources used to generate electricity. Wind is a clean, renewable energy source and EVs charged from wind-generated electricity do not produce any emissions. However, wind is variable in nature.

This thesis examines the potential impact of EVs on reducing a jurisdiction's vehicular GHG emissions using locally available wind-electricity. Four methods of charging EVs using wind-electricity are considered, with grid-electricity as a backup, and the overall well-to-wheels GHG emission reductions are discussed. The thesis includes a case study of Summerside. The results show that up to 68% of the EVs' demands were met with wind-electricity, and Summerside's vehicular GHG emissions were reduced by between 56% and 73% when compared to CVs.

LIST OF ABBREVIATIONS USED

AC	Alternating Current
AER	All Electric Range
AGL	Above Ground Level
BC	Battery Capacity
BES	Battery Energy Storage
BEV	Battery Electric Vehicle
CAES	Compressed Air Energy Storage
CD	Commuting Distance
CH_4	Methane
CO_2e	Carbon Dioxide Equivalent
CV	Conventional Vehicle
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
ETS	Electric Thermal Storage
EV	Electric Vehicle
g	Gram
GHG	Greenhouse Gases
GtB	Generation-To-Battery
GW	Gigawatt
GWh	Gigawatt-hour
HEV	Hybrid Electric Vehicle

Hfcs	Hydro Fluorocarbons
IC	Internal Combustion
IEA	International Energy Outlook
IPCC	Intergovernmental Panel On Climate Change
kg	Kilogram
km	Kilometre
km/L	Kilometer Per Litre
kW	Kilowatt
kWh	Kilowatt-Hour
LCA	Lifecycle Assessment
MW	Megawatt
MWh	Megawatt-hour
mpg	Miles Per Gallon
Mt	Million Metric Tons
N_2O	Nitrous Oxide
NB Power	New Brunswick Power
NRCan	Natural Resources Canada
NRDC	Natural Resources Defense Council
NSP	Nova Scotia Power
OECD	Organization for Economic Co-operation and Development
P.E.I	Prince Edward Island
PEV	Plug-In Electric Vehicle
PHES	Pumped Hydro Energy Storage
PHEV	Plug-In Hybrid-Electric Vehicle

SOC	State Of Charge
$SOC_{CurrtimeQuantum}$	Current Time Quantum State Of Charge
$SOC_{PrevtimeQuantum}$	Previous Time Quantum State Of Charge
SUVs	Sport Utility Vehicles
t	Metric Tonne
TtW	Tank-To-Wheels
UF	Utility Factor
V2G	Vehicle-To-Grid
VBA	Visual Basic For Applications
WEO	World Energy Outlook
WtB	Well-To-Battery
WtG	Well-To-Generation
WtT	Well-To-Tank
WtW	Well-To-Wheels
WWEA	World Wind Energy Association

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CHAPTER 1 INTRODUCTION

Today, energy security and global climate change are two major problems affecting people and the environment worldwide [1]. These problems are highly integrated with each other and mitigating global climate change without affecting energy security is becoming a significant challenge for many governments and policy makers in the twenty-first century [2].

Energy security has become a significant concern in many jurisdictions with increasing energy demand, rising energy costs, and energy production and supply issues [3]. The International Energy Agency (IEA) defines energy security as, "the uninterrupted physical availability [of energy] at a price which is affordable, while respecting environment concerns" [4]. From the IEA's definition, the energy security of a jurisdiction can be described using three energy indicators: availability ("the uninterrupted physical availability"), affordability ("a price which is affordable"), and acceptability ("respecting environment concerns") [5]. In the past two decades, global primary energy consumption has increased by 45%, and is expected to continue to increase by 39% over the next two decades [6].

In recent years, fossil fuels—notably coal, oil, and gas—have been the world's major sources of primary energy supply [3]; for example, in 2009, fossil fuels accounted for the greatest share of global primary energy supply and the rest was met through hydro energy, nuclear energy, biofuels, and others energy sources such as geothermal, solar, and wind energy (see Figure 1-1) [7].

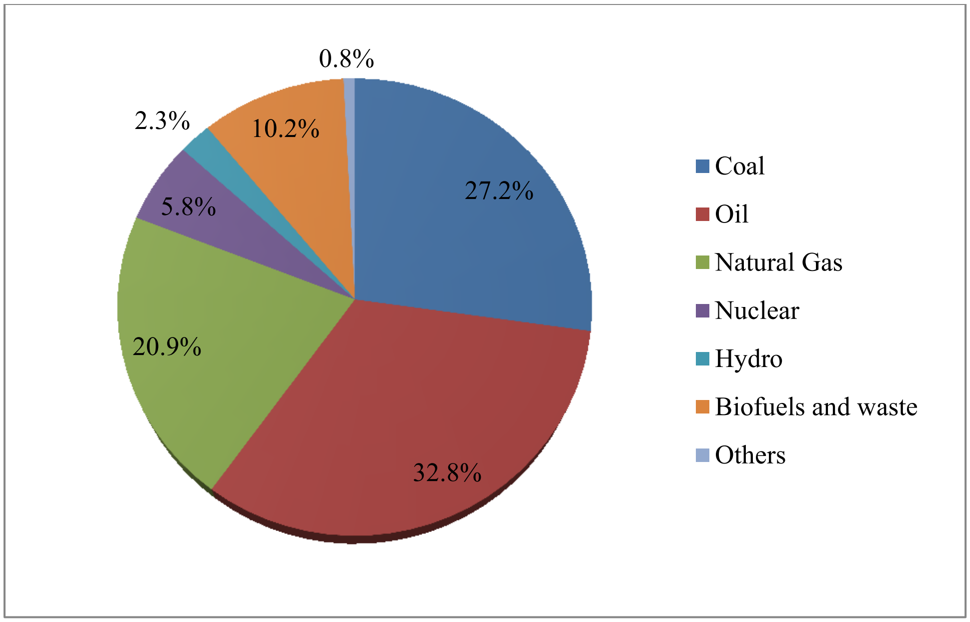

Figure 1-1: World total primary energy supply-2009 [7]

According to the IEA's World Energy Outlook (WEO) 2011 report, fossil fuel supplies are anticipated to continue to be the dominant energy source and account for more than half of the increase of primary energy demand by 2035 [3]. Most of the growth in global primary energy demand is expected to be from the non-OECD countries, particularly from India and China.

Worldwide, fossil fuel supplies are mainly used to meet three basic energy services: heating and cooling, electricity generation, and transportation [3]. The growing demand for energy and the increased use of fossil fuels to meet these energy services are contributing to atmospheric greenhouse gas (GHG) emissions—notably carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [8]. Fossil fuel sources have serious impacts and effects on the environment, and are highly subject to price volatility. In 2005, the global greenhouse gas emissions were estimated to be approximately 44,153 Mt of CO_2e from various sectors [9].[1] Of this total, the transportation sector accounted for

[1] CO_2e (CO_2 equivalents) are based on 100-year global warming potential estimates produced by the IPCC [9].

about 14% of global greenhouse gas emissions and has become one of the significant drivers of global climatic change [9].[2]

The transportation sector consists of the movement of people and goods from one place to another by road, rail, sea and air [10]. Road transportation accounts for about three-quarters of the global transport-related greenhouse gas emissions and the rest was from air, rail and shipping [9]. The total oil demand for road transport—primarily from light duty passenger vehicles, and freight transport—is expected to continue to dominate the transportation sector, and to be accountable for about 75% of global transport oil demand by 2035 [3].

Light-duty vehicles (also referred to as passenger light duty vehicles) include passenger cars, mini-vans, sport utility vehicles (SUVs), and personal-use pick-up trucks [10]. Passenger transportation (also referred to as vehicular transportation) is one of the fastest growing end-use jurisdiction's energy sectors [11], and relies heavily on carbon-intensive fossil fuel sources for more than 95% of its worldwide energy [10]. Based on the IEA's estimates, passenger transportation will remain the major consumer of oil, primarily gasoline, in 2035 [3].

Oil reserves are only available in finite (limited) quantities and are concentrated in a few regions of the world [12], as opposed to renewable energy sources, such as wind and solar energy, which are available infinitely. The rest of the world is increasingly reliant on these oil exporting regions. This puts the regions that do not have access to oil reserves in a position of being less energy secure, allowing themselves to become vulnerable to energy availability issues.

The oil production in a number of the oil reserves, however, has begun to reach its peak and is now starting to decline. One way to still continue meeting the growing oil demand for passenger transportation is to increase the production of oil from unconventional fossil fuels, such as shale oil or tar sands. On the other hand, the extraction of oil from the unconventional energy sources is becoming increasingly more expensive, making many jurisdictions exposed to energy affordability issues [12].

[2] The terms "greenhouse gas emissions" and "CO_2e emissions" are used interchangeably throughout the remainder of the thesis.

Oil is one of the more carbon intensive fossil fuel energy sources [13]. The combustion of oil for vehicle propulsion emits CO_2, a significant contributor to global greenhouse gas emissions. This increases the environmental concerns surrounding the continued use of oil for passenger transportation (i.e. acceptability issues) [10].

According to the IEA's Blue Map Energy Scenario, the overall reduction of global energy-related CO_2 emissions could be achieved by cutting down the transport related CO_2 emissions to 30% below 2005 levels by 2050 [14]. However, the energy usage for transportation and its associated greenhouse gas emissions are growing rapidly, due to the increased growth of transportation activity. It is necessary to employ new methods to reduce energy consumption and greenhouse gas emissions from the transportation sector [15]; for example, increasing the fuel efficiency of existing vehicles with advanced vehicle technologies, and replacing existing carbon-intensive energy sources with renewable energy sources, such as wind and solar energy [16].

This thesis will focus on the acceptability aspect of the energy security indicators, providing a way to reduce greenhouse gas emissions from passenger transportation to improve a jurisdiction's energy security.

Recently, there has been a great deal of enthusiasm about the worldwide development and increased production of electric vehicles (EVs) in passenger transportation. This is mainly due to their greater fuel efficiency and reduced greenhouse gas emissions when compared to conventional vehicles (CVs)[14]. An electric vehicle is equipped with an electric motor and operates exclusively on electricity to provide all auxiliary and motive power for vehicle propulsion [17]. The electricity it uses is stored in a battery which is charged from a generation source. Today, there are different methods for charging EVs available, such as simple charging [18], uncontrolled charging [19], delayed charging [19] and fast charging [20]. Typically, EVs do not have direct emissions during vehicle's operation (i.e. no tail pipe emissions) [17].

According to the Electric Power Research Institute (EPRI), the EVs have the potential to reduce greenhouse gas emissions in the transportation sector compared to CVs in the near future [21]. Nevertheless, the ultimate greenhouse gas emissions impact of EVs depends primarily on the emission-intensity of the energy sources used for electricity generation.

However, electricity generation is local and the energy sources used in the generation of electricity range widely from fossil fuels (such as coal, oil, and natural gas) to renewables (wind, solar, and tidal). For example, EVs charged with carbon intensive coal-fired electricity have similar or higher greenhouse gas emissions compared to CVs. Alternatively, EVs that are charged from renewable energy sources, such as wind-generated electricity, could provide a significant reduction of greenhouse gas emissions when compared to CVs [21].

Wind is a clean, renewable energy source and inexhaustible [22]. Recently, many jurisdictions have been adopting policies and standards to address global climate change and energy security by increasing the share of renewable wind energy into their electricity generation mix. Wind is a domestic energy source which cannot be depleted like fossil fuels. It does not burn any fuel to generate electricity and hence does not pollute the air like other forms of electricity generation. However, the strength of wind is not constant (i.e. variable in nature). When wind is available, wind turbines are able to generate electricity, but there will be times when they produce no electricity at all due to the lack of wind. Therefore, it is necessary to exploit the available wind effectively by integrating it into services which do not require a continuous supply of electricity. EVs have the capability to store electricity in their battery that can be used for the propulsion of vehicle. For a jurisdiction with a good wind regime, the use of EVs powered by available wind-generated electricity could provide much of their passenger transportation services, and this would have a negligible carbon footprint when compared to the use of fossil fuel generated electricity.

1.1 Thesis objective

Electric vehicles, like conventional vehicles, require an energy source to supply them with motive energy. While CVs allow the drive to resupply the vehicle with energy in a matter of minutes at a service station, EVs require access to electricity and, depending upon their battery's demand, may take several hours to recharge. The challenge facing most electricity suppliers is in the development of methods to charge EVs with minimum impact on the existing electricity supply. Despite various methods already exist to support the charging of an EV, the approach of this thesis is to ensure the full charging of an EV's battery using available wind-electricity during overnight hours (in this case, 23:00hrs to 07:00hrs, inclusive) to reduce greenhouse gas emissions. Overnight hours are usually the most common time to charge the vehicles, as the vehicles are usually not being driven and are available for charging at home, and to utilize off-peak grid-electricity as a backup.

The objective of this thesis is to develop methods to examine the potential impact of EVs on reducing a jurisdiction's vehicular greenhouse gas emissions using locally available wind-generated electricity.

The objective of each method proposed in this thesis is to ensure that at the end of the charging cycle, each EV is charged to its maximum battery capacity. The following assumptions are made regarding the charging of EVs:

- The time available for the entire charging period is divided into one or more time-quantum.
- Each EV's battery has a maximum capacity (expressed in kWh).
- Each EV is associated with a maximum charging rate (expressed in kWh per time-quantum). While there is no minimum charging rate, there will be a minimum level of charging required to ensure that the battery is at full capacity at the end of the period (i.e. current battery demand divided by the remaining time-quantum).
- If there is insufficient wind-electricity to meet the minimum charge requirements of an EV battery during a time-quantum, the minimum charge requirements of the battery is topped-up with grid-electricity. The greenhouse gas emissions associated with charging the EVs depend upon the greenhouse gas emissions intensity of the grid-electricity.

Four wind allocation methods are proposed:

1. **Equal wind allocation method:** The first method is considered to allocate the available wind-electricity equally to all EVs regardless of their demands. The level of charging each EV is constrained by the battery's maximum charging rate and its demand.

2. **EV demand allocation method:** The second method is considered to determine the wind allocation using each EV's demand for a current time quantum: those with high demand receive more of the available wind-electricity that those with less demand. The technique used to evaluate demand is further explained in the thesis. The aim of this method is to examine the effects of priority allocation.

3. **EV maximum-demand allocation method:** In the methods mentioned above, each EV is able to charge to its maximum allowable level within a time-quantum only if there is sufficient wind-electricity to do so. The third method is considered to charge each EV to its maximum level with the available wind-electricity or grid-electricity, or both. The objective of this method is to complete the EV charging as rapidly as possible, regardless of the source of electricity.

4. **EV minimum-demand allocation method:** The fourth method is an alternative to charging at the maximum rate, and considered to charge each EV with the minimum amount of electricity required in each time-quantum, regardless of its source.

This research includes well-to-wheels (WtW) analysis to determine the amount of greenhouse gas emissions of the EVs and CVs for a given distance travelled. The well-to-wheels analysis accounts for the emissions from the extraction of source fuel from the wells (referred to as well-to-tank (WtT) emissions) and to the distribution of the fuel to the wheels (referred to as tank-to-wheels (TtW) emissions).

This research also considers a case study by introducing EVs for weekday commuting purposes into passenger transportation and discusses the overall greenhouse gas emission impact of commuting; the results are extrapolated for various commuting distance patterns. This research uses data from the City of Summerside, Prince Edward Island (P.E.I), for its case study, but the general approach can be applied to other cities, provinces, and regions.

1.2 Thesis organization

The remaining chapters of the thesis are organized as follows.

Chapter 2 presents an outline of renewable energy and reviews wind as an energy source in the electricity generation and its variable nature. It also presents an overview of EVs and discusses existing research related to the emission impact of integration of EVs and wind-electricity.

Chapter 3 presents the methods to analyse the potential impact of EVs on reducing a jurisdiction's greenhouse gas emissions with locally available wind, and some form of back up from grid-electricity. Also, the implementation of the simulation model with the necessary software tools is discussed.

Chapter 4 presents a case study to examine the proposed methods. The selection of case study locale, input data needed to perform the simulation, and its results are then presented.

Chapter 5 discusses the simulation results based on the assumptions presented in this thesis.

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

CHAPTER 2 LITERATURE REVIEW

This chapter presents the background work related to EVs and wind-electricity generation on reducing greenhouse gas emissions. The chapter begins with an outline of renewable energy, and reviews wind as an energy source in electricity generation, and its variable nature. An overview of EVs and their emission impact are then presented. The chapter concludes by discussing the impact of integration of EVs and locally available wind-generated electricity.

2.1 Renewable energy

In the recent past, fossil fuels—notably coal, oil, and gas—have been accountable for the majority of primary energy supply to meet global energy demand [3]. However, IEA estimates that the share of fossil fuel sources in the global primary energy mix is expected to decline to 75% by 2035 compared to 81% in 2009. On the other hand, the share of renewables in global primary energy mix is to be expected to increase from 13% to 18% for the same period [3].

According to the Energy Information Administration (EIA), renewable energy can be defined as "energy resources that are naturally replenished in a relatively short period of time" [23]. Renewable energy sources include solar, wind, biomass, hydro, geothermal, and wave and tidal energy. They are clean energy sources, inexhaustible, and environmentally friendly compared to conventional fossil fuel energy sources [24]. Today, renewable energy—notably wind energy—is considered to be the solution to the growing global energy challenges while still reducing global greenhouse gas emissions [25].

2.1.1 Wind energy

The Earth is heated unevenly by the Sun, mainly due to the irregularities of the Earth's surface (i.e. land and water). The uneven heating of the atmosphere by the Sun and the rotation of the Earth cause the movement of air, resulting in what we call the wind [26]. Wind is a renewable energy and one of the primary energy sources which is available freely and abundantly in nature [27]. However, the wind is variable in nature; it is necessary to utilize the available wind efficiently, and use the energy when needed [28].

In recent years, wind energy has been of interest to many governments and utilities for one particular use—in the generation of electricity [29]. The wind is rich in kinetic energy, which can be harnessed into mechanical power using wind turbines, and it can be further converted into electricity using generators. Wind is a clean energy source and does not pollute the air like most other forms of electricity generation [30]. Wind energy is also a domestic energy source which cannot be depleted like fossil fuels, and it could helps to increase a jurisdiction's energy security by reducing the dependency on insecure fossil fuels supplies [31].

Worldwide, wind-electricity generation has reached a total nameplate capacity of 196.6 GW and about 37.6 GW was added in 2010 [22]. The top five countries (China, USA, Germany, Spain and India) accounted for about 74% of the global wind capacity in 2010. From Figure 2-1, it is clear the global share of wind-generated electricity is increasing significantly and showed a growth of 32% in 2009, the highest rate since 2001 [22].

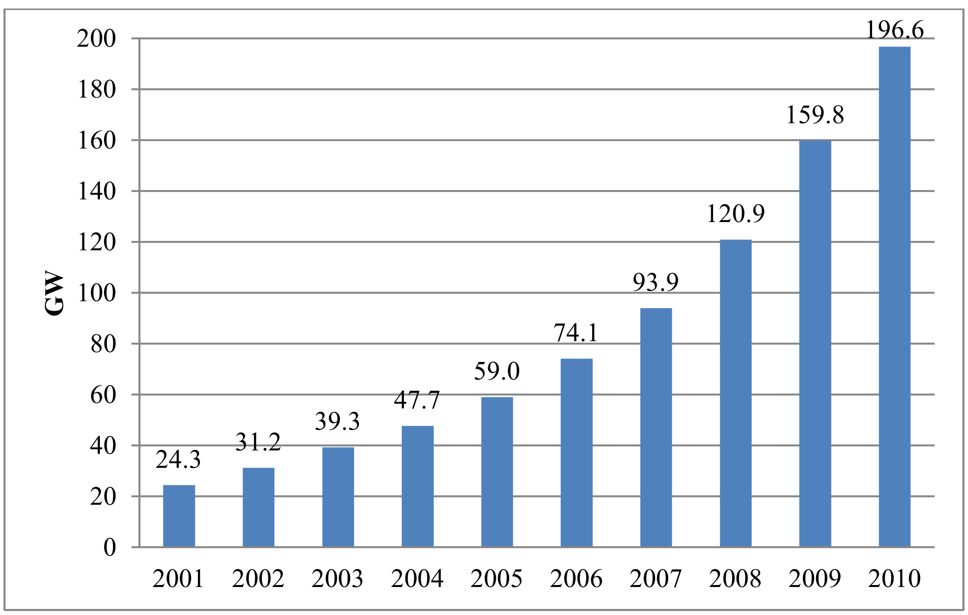

Figure 2-1: Total installed wind capacity for 2001-2010 [22]

In 2010, China became the leader in global total installed wind-electricity generation capacity and accounted for about 44 GW, of which new wind turbines added for 18.9 GW [22]. Also, many countries in the European Union (for example Denmark, Germany, Spain, and Portugal) utilized wind energy to meet about 9% to 21% of their domestic electricity demand [32]. World Wind Energy Association (WWEA) projects that the global wind-electricity generating capacity will increase to 600 GW by the year 2015 and 1,500 GW by the end of 2020 [22]. Furthermore, the cost of electricity generated from wind energy is rapidly decreasing compared to cost of electricity generated from fossil fuel sources due to the increasing installed capacity of wind-turbines [22].

2.1.2 Wind variability

Wind energy is an indirect form of solar energy, and it will be available as long as the Sun shines and the Earth rotates [31]. However, wind energy is variable in nature [33]. Wind is not a constantly available source of energy and the wind speed varies the electricity output. When wind is available, wind turbines are able to generate electricity; otherwise the wind-turbines will be idle (i.e. no electricity generation) [34]. Many governments have taken steps towards the integration of available wind in to their energy mix for a significant reduction of greenhouse gas emissions. However, the incorporation of wind-generated electricity into the electric grid is a great challenge for utilities and electricity suppliers due to its variability [33]. For example, on-demand electricity services (such as to power lights, appliances and equipment in homes and office buildings) requires continuous, uninterrupted supplies of electricity from utilities to meet the demand throughout the day.

2.1.3 Addressing wind variability

Wind variability can be addressed in a number of ways; one of the most common ways to address this issue is to provide backup power, which can be called upon at very short notice to meet the energy demand [35]. When wind-electricity generation is low or insufficient, the back-up sources (such as hydroelectricity or gas turbines) can respond rapidly to substitute the wind to meet the electricity demand, and can go idle when there is sufficient or excessive wind [36]. However, for a large-scale installed wind-electricity generating capacity, it can be difficult for utilities to provide backup power at very short notice. The provision of backup power from high carbon-intensive fossil fuel energy sources (such as from oil or gas turbines) could also impose additional system costs and emissions to the electric grid [33].

As an alternative to backup power, energy storage is one of the innovative methods for addressing wind's variability [37], and it has been previously used for various types of renewable energy sources [38]. During the periods of low system demand or high wind availability, utilities store the excess wind-generated electricity using energy storage devices. When the wind is unavailable or insufficient to meet the system demand, energy storage provides power back to the electrical grid to balance supply and demand [36]. Energy storage techniques can help utilities in increasing the utilization of wind energy in their electricity generation mix. Some of the major energy storage technologies available in the market are pumped hydro energy storage (PHES), compressed air energy storage (CAES), electric thermal storage (ETS) and battery energy storage (BES) [39].

2.2 An overview of electric vehicles

Worldwide, growing environmental concerns and energy challenges have prompted many governments and automakers to develop efficient and sustainable vehicles for transportation [40]. As an alternative to CVs, EVs are provided with high efficiency electric motors and controllers with an on-board rechargeable battery for vehicle propulsion [14]. EVs have the potential to shift the use of high carbon-intensive fossil fuels—notably gasoline—to less carbon-intensive fuels (such as biofuels, or renewables) for propulsion, and to reduce vehicular greenhouse gas emissions [14].

As a point of comparison, the fundamentals of hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and electric vehicles are discussed below.

2.2.1 Hybrid electric vehicles

A hybrid electric vehicle is similar to a conventional vehicle, it operates exclusively on gasoline. HEVs have an internal combustion (IC) engine and an electric motor for vehicle propulsion [41]. Electricity required for the on-board vehicle battery to power the electric motor is generated from the gasoline IC engine and from regenerative braking (typically, the electric motor runs in reverse as a generator during coasting and braking) [41]. In general, HEVs use the electric drive for start-stop city driving, having an advantage over CVs in that when idling, the electric motor is turned off, whereas a conventional vehicle remains running when idling. Broadly speaking, there are two classes of HEV, parallel hybrid and series hybrid.

2.2.1.1 Parallel hybrid

As shown in Figure 2-2, a parallel hybrid (also referred to as a partial hybrid) runs on both the IC engine and an electric motor to provide all motive power to propel the vehicle [42]. In a parallel hybrid, the gasoline IC engine is used mostly for propulsion, although the electric motor is used for rapid acceleration; for example, when passing another vehicle or climbing a hill [41].

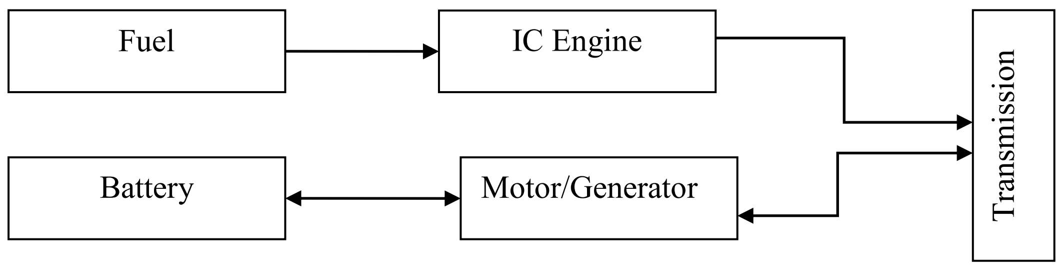

Figure 2-2: Schematic of a parallel hybrid [43]

2.2.1.2 Series hybrid

A series hybrid (also referred to as a "full hybrid") uses a gasoline IC engine solely to generate electricity, which is stored and used by an electric motor that provides all the motive power for vehicle propulsion [42]. Due to the combination of an IC engine with an electric motor, the overall fuel efficiency of the vehicle is improved and hence has lower emissions than conventional vehicles or partial hybrid vehicles [41].

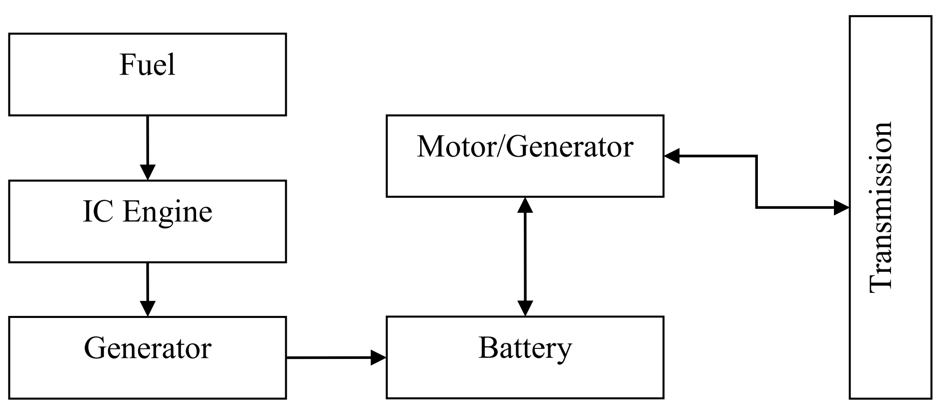

Figure 2-3: Schematic of a series hybrid [43]

2.2.2 Plug-in hybrid electric vehicles

Plug-in hybrid electric vehicles are powered by an IC engine, an electric motor and a relatively large battery pack system [44]. The PHEV batteries can be charged on-board using an IC engine, from regenerative braking, and from a conventional electrical power source. PHEVs are similar to hybrid electric vehicles; however they can operate in an "All-Electric Range (AER)" for longer periods due to their large battery-pack, and can be powered from the electric grid [44]. The AER range is expressed as the total distance that a fully charged vehicle can travel using stored electricity from the battery before needing a full recharge.

A PHEV has two operating modes: Charge Depleting and Charge Sustaining (modes [45]. Typically, the charge depleting mode is designed for the pure electric mode of operation. The charge sustaining mode is similar to hybrid electric vehicles operation. This mode of operation solely relies on gasoline for vehicle propulsion and is suitable for long distance driving. When driven, the PHEV operates exclusively on charge depleting mode before exhausting its battery and then switching it to charge sustaining mode (i.e., like an HEV) [45]. For example, a "PHEV 40" uses electricity for the first 40 miles of travel after each recharge, while the remainder of the travel relies on gasoline [21].[3]

2.2.3 Electric vehicles

An electric vehicle is equipped with an electric motor and operates exclusively on electricity to provide all auxiliary and motive power for the vehicle propulsion [17]. The electricity it uses is stored in a battery and charged from the electrical grid and from regenerative braking. It is also commonly referred to as a battery electric vehicle (BEV) or a plug-in electric vehicle (PEV). Typically, EVs do not have direct exhaust emissions during the vehicle's operation (i.e. no tail pipe emissions) [17]. However, there could be emissions associated with the generation of electricity used to charge EVs for the vehicle propulsion.

[3] The AER is written as a number after the vehicle type. As with all vehicles, regardless of energy source, the actual distance travelled will depend on a number of factors, including driving conditions, driving habits, road conditions, and weather conditions, including temperature.

Electricity generation is local and the energy sources used in the generation of electricity comes from various energy sources, such as from high carbon-intensive fossil fuels (coal, oil, natural gas) to less carbon-intensive energy sources (nuclear, biomass) or renewables [46]. Today, fossil fuel—notably coal—is the main source of energy used in the generation of electricity in many jurisdictions [7]. When an EV is charged with the coal-fired electricity, it emits higher greenhouse gas emissions than a conventional vehicle. However, when EVs are charged using the electricity obtained from clean, renewable energy sources—notably wind—the vehicle produces no emissions at all.

In the recent past, the majority of EVs have used lead-acid batteries or nickel-metal-hydride batteries for on-board electricity storage [47]. Today, the performance and reliability of EVs are comparable to that of CVs; however, EVs are limited to a short distance driving range per charge due to their limited battery capacity [17]. There have been developments in recent years to improve the energy density and the efficiency of battery technology to increase the vehicles' driving range [14]. For example, lithium-ion batteries have a higher energy density three times that of nickel-metal-hydride batteries of the same physical size, and weigh substantially less. In the near future, lithium-ion batteries could become an efficient energy choice to power EVs [48]. Due to the advancement of battery technology and high energy efficiency electric motors, the introduction of EVs could further reduce greenhouse gas emissions in the vehicular transportation.

2.3 Emission impact of EVs

EVs have the potential to be more fuel-efficient and less polluting than CVs in the future. However, it is essential to perform a well-to-wheels analysis in order to evaluate the emission impact of an electric vehicle compared to a conventional vehicle. This analysis accounts for the total greenhouse gas emissions associated with the extraction of source fuel from the wells and to the distribution of the fuel to the wheels for vehicle propulsion. For example, in CVs, the well-to-wheels analysis accounts for the greenhouse gas emissions from the extraction of crude oil from oil wells to the refined gasoline in the fuel tank for the vehicle propulsion. Similarly for EVs, the well-to-wheels analysis accounts for the greenhouse gas emissions from the extraction of energy sources, such as coal, oil, or natural gas, from mines to the generation of electricity at power plants, to charge the EV batteries.

In 2007, the EPRI and the Natural Resources Defense Council (NRDC) published study on environmental assessment of plug-in hybrid electric vehicles on reducing greenhouse gas emissions in the United States [21]. The EPRI study compared the well-to-wheels greenhouse gas emissions-per-mile for three distinct vehicle types: CVs, HEVs, and PHEVs between 2010 and 2050 [21]. The report determines the greenhouse gas emissions for PHEVs based on the vehicle's Utility Factor (UF), the distance driven electrically and non-electrically (i.e., with gasoline). In the EPRI report, a variety of UFs were presented for different plug-in hybrid-electric vehicles, notably 0.12 (PHEV 10), 0.49 (PHEV 20), and 0.66 (PHEV 40)[4].

The analysis in the EPRI study used a total of nine modeling scenarios, were created at the combinations of high CO_2, medium CO_2 and low CO_2 intensity electric sectors and low, medium, and high fleet penetrations of PHEVs, to analyze the potential greenhouse gas emissions impact of PHEVs over the period of 2010 to 2050. Each of the nine scenarios showed significant reductions of greenhouse gas emissions (38% to 65%) from PHEVs compared to CVs and HEVs, respectively.

The results showed that greenhouse gas emissions from PHEVs depend on the type of energy sources used in electricity generation (e.g. conventional coal, advanced coal, nuclear or renewables). With an assumption of advanced electricity generation technologies and renewables, the emission intensity (i.e. gCO_2e/kWh) used in their analysis was 33-84% less carbon intensive compared to the average CO_2 intensity of the electric sector in 2005 (612 g CO_2e/kWh). Furthermore, the study evaluated the well-to-wheels emissions for PHEVs from the generation of electricity only. Nevertheless, there are emissions associated with the extraction and, transportation of the source fuels to the electricity generation plant [21].

As with the EPRI study, Sullivan and Stephen [49] analyzed the environmental and energy impact of PHEVs in the United States, using well-to-wheels emissions analysis

[4] In the EPRI report, a PHEV 10, 20 and 40 indicates that the vehicle has an all-electric range of 10, 20 and 40 miles, respectively.

for the three distinct vehicle types (CVs, HEVs, and PHEVs). Based on the current U.S. electricity emission intensity, the study found that PHEVs could reduce CO_2 emissions by 25% in the short term and up to 50% in the long term, relative to conventional hybrid vehicles. The CO_2 emissions per distance travelled (i.e., gCO_2/km) are examined based on the emission intensity from gasoline and electricity, respectively. The results showed that PHEVs travelled per km using electricity generated from coal and natural gas can reduce CO_2 emissions by 37% and 57% respectively when compared to conventional gasoline vehicles. However, this study assumed that the gasoline vehicles are relatively less efficient and so found greater well-to-wheels emissions reduction for PHEVs.

In a recent study, Samaras and Meisterling [50] conducted a lifecycle assessment (LCA) of greenhouse gas emissions from PHEVs in the United States. The LCA model in their study quantifies the environmental impacts from vehicle production, battery production and the use phase. Of these, emissions associated with vehicle and battery production is not significant compared to the emissions from the vehicle's usage. Three different greenhouse gas emission intensity scenarios were examined under the various sources of electricity production: base-case, carbon-intensive, and low-carbon intensive scenario. In the base-case scenario, the greenhouse gas emission intensity is assumed to be 670 gCO_2e per kWh, which is similar to the average intensity of the current U.S. electricity generation mix portfolio. In the carbon-intensive scenario, it is assumed that coal (the most carbon-intensive fuel) is predominantly used for electricity generation and its emission intensity is about 950 gCO_2e per kWh. The low-carbon intensive scenario represents a case where electricity is generated from the mix of renewables, nuclear, or coal (with carbon capture and storage technology) and its emission intensity is about 200 gCO_2e per kWh.

The results showed that PHEVs could reduce greenhouse gas emissions by 32% compared to relative CVs, but have small reductions compared to HEVs in base-case scenario. Similarly, in the low-carbon scenario the PHEVs could reduce greenhouse gas emissions by up to 63% and 47%, compared to the CVs and HEVs, respectively. However, PHEVs have up to 18% higher emissions than HEVs under the carbon-intensive scenario due to the higher CO_2e emission intensity from coal-generated electricity.

Previous studies investigating greenhouse gas impacts focus on HEVs, or PHEVs, or both. A recent study by Hughes has analyzed the electric drive vehicles (HEVs, PHEVs, and EVs) and their potential impact of greenhouse gas emissions reduction on passenger transportation [51]. The analysis in the report has considered four different passenger vehicles: conventional vehicles (Hyundai Elantra), hybrid-electric vehicles (Toyota Prius), plug-in hybrid electric vehicles (Chevy Volt), and electric vehicles (Nissan Leaf). The well-to-wheels emission analysis was conducted for the period of 2010, 2015, and 2020 for various driving conditions (such as city driving, highway driving, and combined city-highway driving). The report suggests that EVs in general and PHEVs in particular, provide significant greenhouse gas emissions reduction in passenger transportation when compared to existing conventional gasoline vehicles.

2.4 Electric vehicles and wind-electricity

An electric vehicle has the potential to displace the use of carbon-intensive fossil fuels—notably gasoline—in CVs with the electricity obtained from the grid [14]. However, when EVs are charged using the electricity generated from high carbon-intensive fuels (such as coal), they could have similar or increased greenhouse gas emissions compared to CVs. Wind is a renewable energy source and the electricity generated from wind is clean and carbon-free [22], and integrating EVs with wind-generated electricity could be a significant factor in the reduction of greenhouse gas emissions from vehicular transportation ([52] & [53]).

In a recent study by Ekman [18], the synergy between the high penetration of wind energy and large fleet of EVs was analyzed for the Danish electric power system. This power system has planned to increase the wind power generation beyond its current level to meet the jurisdiction's energy demand. However, wind is a variable energy source, and poses significant challenges for energy management and system stability in the Danish electric grid. For this reason, four different EV charging strategies were considered:

- **Simple charging:** In this approach, EVs are assumed to be connected to grid for charging after work hours at home.

- **Night charging:** EVs are assumed to be charged only during the night hours; however for unusual driving pattern vehicles, a small fraction of the charging is allowed during the day time.
- **Smart charging:** EVs are assumed to be charged during periods of low system demand or during excess wind power production.
- **Smart Vehicle-to-Grid (V2G):** The grid-connected EVs charge their batteries during periods of low system demand or excess wind power production, similar to smart charging, and additionally discharge to the domestic electric grid during periods of high system demand to meet end-user electricity demand.

The study examined two scenarios for wind power production and EV penetration in Denmark: *Scenario 2025* and *Scenario 2050*. In *Scenario 2025*, it is assumed that the Danish power system could have an installed wind power capacity of 8 GW with a fleet of 500,000 EVs. The average power consumption and storage capacity of EVs were assumed to be 200W and 15kWh, respectively. In *Scenario 2050*, installed wind power capacity is assumed to increase to 12 GW and the majority of motor vehicles are electrified. The average power consumption and storage capacity of EVs were assumed to be 300W and 35kWh, respectively.

In both scenarios, results indicate that the simple charging strategy increases the imbalances between the EV's power consumption and wind production. The nightly charging strategy provides a slight improvement of balance between wind production and power consumption. It also helps to reduce the excess wind power production; however there is an additional need for electricity from fossil fuel generation to charge the EVs. The smart charging strategy significantly reduces the excess wind production and provides an overall balance between wind production and power consumption. Smart charging using the V2G mode reduces excess power production and satisfies the majority share of an EV's power consumption using wind. This study showed that EVs charged using wind in an intelligent manner has the potential to provide a balance between wind power production and consumption in a future Danish power system.

Similarly, Lund and Kempton [53] studied the integration of wind energy into the transportation and electricity sector using EVs through Vehicle-to-Grid technology. The V2G technology is used to store electricity into grid-connected EVs during the periods of low system demand, which can be sold to the domestic electric grid when EVs are not in use for transportation or during the periods of high system demand.

Four types of vehicle fleets were considered and given as:

- REF : Reference combustion vehicle fleet
- BEV : Battery Electric Vehicles
- InBEV : Intelligent Battery Electric Vehicles
- V2G : Vehicle to Grid cars

This study compares combustion cars in the reference case with battery EVs using night charging, and intelligent charging with V2G. The night charging is assumed to start after 4 pm and it will likely have excess wind power due to low system demand. For the Intelligent Charging and the V2G cases, the grid-connected EVs are charged during the period of excess generation of wind-electricity. However, when there is not excess wind-electricity generation, the EVs are charged from other backup sources to make sure that the EVs are fully charged prior to driving periods.

The results from the study showed that BEV with scheduled off-peak nightly charging significantly reduces both excess wind-electricity generation and CO_2 emissions. Besides, the addition of intelligent BEV fleets to nightly charging substantially reduces excess electricity generation from wind and CO_2 emissions compared to the BEV fleets with the nightly charging scenario. For the V2G case, the ability for BEVs to discharge the stored electricity from the vehicle’s battery to the grid provides small benefits on top of the intelligent BEV charging scenario.

The Vehicle-to-Grid technology is a new and emerging electric storage technology [36]. However, the overall impacts of V2G technology using EVs will depend on a number of factors, including battery size, charging method, maximum charging or discharging rate, battery charging efficiency and its transmission losses. For example, the capital costs of lithium-ion batteries used in the EVs are expensive and have a limited life cycle of charging and discharging [54]. Hence, the increased usage of EVs to charge and discharge for Vehicle-to-Grid could affect the performance of the battery and vehicle's fuel economy. Moreover, the V2G technology is more feasible for vehicles with large battery storage capacity (for example, school busses, and commercial fleets).

Overall, previous studies showed that charging of EVs using the available wind-generated electricity have the potential to incorporate large portions of wind energy into a jurisdiction's energy systems and to reduce vehicular emissions.

2.5 Summary

In this chapter, previous works related to EVs and wind-electricity on reducing greenhouse gas emissions was reviewed. The role of renewable energy sources—notably wind—as an energy source in the generation of electricity, and its variability has been studied. Further, the overview of EVs and its emission impact was presented. The existing work related to the integration of EVs and wind-generated electricity was presented. This review has highlighted that EVs have the ability to maximize the utilization of the locally available wind-electricity in to a jurisdiction's energy systems and to reduce vehicular greenhouse gas emissions.

CHAPTER 3 METHOD AND IMPLEMENTATION

This chapter outlines the methods required to analyze the potential for EVs using wind-generated electricity to reduce a jurisdiction's vehicular greenhouse gas emissions. Along with the design of the methods, it also discusses a sample application of the methods, and the software tools for the implementation of the simulation model.

3.1 Methods

This section explains the methods to perform the well-to-wheels greenhouse gas emissions analysis for conventional and electric vehicles. It also presents the design of four different wind allocation methods to charge EVs using available wind-electricity, with some form of back up from grid-electricity.

3.1.1 Well-to-Wheels GHG emission analysis

The formulas to derive the well-to-wheels greenhouse gas emissions for both CVs and EVs are presented [51].[5]

3.1.1.1 Conventional vehicles

A conventional vehicle has an internal combustion engine and operates on either gasoline or diesel. For the purpose of this analysis, it is assumed that the CVs operate exclusively on gasoline.

3.1.1.1.1 Estimating Well-to-Wheels GHG emissions

The well-to-wheels analysis accounts for the total greenhouse gas emissions associated with the extraction, production, conversion, and distribution of the source fuel (i.e. well-to-tank emissions) and the consumption of fuel while driving (i.e. tank-to-wheels emissions) [51]. The well-to-wheels emissions per km can be calculated using the following equation (1),

$$GHG_{WtW/km} = GHG_{WtT/km} + GHG_{TtW/km} \quad (1)$$

[5] Some of the equations used in this thesis for "well-to-wheels" GHG analysis were extracted and modified from a report previously published by the author and Dr. Larry Hughes for Nova Scotia Power titled "An analysis of electric vehicles and their potential impact on Nova Scotia's passenger vehicle emissions" [51].

With the GHG emissions per km known from equation (1), the total GHG emissions over a given distance travelled can be calculated as shown in equation (2).

$$GHG_{Total} = \text{Distance Travelled} \times GHG_{WtW/km} \quad (2)$$

The GHG emissions per km and the total GHG emissions can be obtained using equations (1) and (2) with respect to the vehicle's fuel economies for various driving conditions—notably city-driving, highway-driving, and combined city-highway driving.

3.1.1.1.2 Well-to-Tank emissions

For CVs, the well-to-tank greenhouse gas emissions are associated with the extraction, production, and distribution of the gasoline. In order to obtain the well-to-tank emissions, it is necessary to know the sources of the crude oil, its quality, the method of transport, the refining process, the method of distribution, and the source of electricity to operate the filling-station's fuel pumps [51].

For this analysis, based on the EPRI report [21], it is estimated that in the United States, a conventional vehicle with a fuel economy of 24.6 miles/gallon (10.5 km/litre) emits 100g CO_2e/mile (62.1g CO_2e/km) for the year 2010. It is assumed that the emissions associated with other vehicles depend upon their fuel economy and the ratio shown in equation (3) [51].

$$GHG_{WtT/km} = \left(\frac{10.5}{\text{Fuel Economy}} \right) \times 62.1 \quad (3)$$

Well-to-tank emissions are determined from a vehicle's fuel economy and can be calculated for various driving conditions, such as city-driving, highway-driving, and combined city-highway driving.

3.1.1.1.3 Tank-to-Wheels emissions

The tank-to-wheels greenhouse gas emissions for CVs are associated with the emissions from the combustion of gasoline to propel the vehicle. When one U.S. gallon of gasoline is combusted, it yields approximately 9260g of CO_2e, of which about 95% are attributable to carbon dioxide. The remainder is a mixture of methane, nitrous oxide, and hydro fluorocarbons (HFCs) [8].[6] The metric equivalent is 2446g CO_2e/litre.[7]

As with well-to-tank emissions, tank-to-wheels emissions are determined from the fuel economy and can be calculated for various driving conditions; the method to obtain the estimated tank-to-wheels emissions is shown in equation (4) [51].

$$GHG_{TtW/km} = \left(\frac{2446}{\text{Fuel Economy}} \right) \tag{4}$$

3.1.1.2 Electric vehicles

An electric vehicle is equipped with one or more electric motors and a rechargeable battery for the vehicle's propulsion [17]. Typically, EV batteries are charged from the electrical grid and from regenerative braking.

3.1.1.2.1 Estimating Well-to Battery GHG emissions

EVs do not have direct emissions during vehicle's operation (i.e. no tail pipe emissions). Therefore, there are no well-to-wheels emissions; any greenhouse gas emissions associated with an electric vehicle are assumed to come from the supplier of the electricity and are referred to as the well-to-battery emissions (equivalent to the well-to-tank emissions in a CV).

The well-to-battery emissions per km depend upon:

- The emissions associated with the upstream production (such as extraction and production) and transportation of energy sources from the well (e.g., mine) to the place of generation; these emissions can include fugitive emissions of, for example, methane from coal mines or natural gas pipelines.

---

[6] Carbon dioxide is the principal greenhouse gas resulting from the combustion of fossil fuels. Methane is from upstream processes related to the production and transportation of the fuel source. Nitrous oxide is emitted during agricultural and industrial activities. Hydro fluorocarbons are from a variety of industrial processes.

[7] One U.S. gallon is converted to litres using the conversion factor of 3.7854 (i.e. 1 US. Gallon = 3.7854 litre).

- The vehicle's charging efficiency, expressed in terms of the AC kWh consumed per kilometer in the charging process and the efficiency of the charging process (the conversion efficiency).
- The electricity supplier's emissions intensity, expressed in grams of CO_2e emitted per kWh.

For this analysis, the well-to-battery emissions per km for an EV is first estimated from the total emissions associated with the supply chain of every fuel source used by the electricity supplier (referred to as well-to-generation (WtG)) and the total emissions from the electricity supplier's generating facilities (referred to as generation-to-battery (GtB)) [51]; from this, the emissions intensity (gCO_2e per kWh) can be calculated as shown in equation (5).

$$\text{Emissions intensity}_{\text{WtB}} = \left(\frac{\sum \text{Emissions}_{\text{WtG}} + \sum \text{Emissions}_{\text{GtB}}}{\text{Total electricity generated}} \right) \tag{5}$$

With equation (5), the well-to-battery emissions per km can be determined from the product of the emissions intensity and the vehicle's electricity consumption per km as shown in equation (6) [51].

$$\text{GHG}_{\text{WtB/km}} = \left(\frac{\text{Electricity consumed per km}}{\text{Conversion Efficiency}} \right) \times \text{Emissions intensity}_{\text{WtB}} \tag{6}$$

Overall, there are a number of possible emissions associated with different supply chains, and well-to-generation emissions are often omitted from calculations of well-to-battery emissions. However, some effort has been made in this thesis to address this issue (for example, see [55] and [50]). Furthermore, the U.S. EPA is presently developing a method of determining well-to-generation emissions [56].

With the GHG emissions per km known from equation (6), the total GHG emissions over a given distance travelled can be calculated as shown in equation (7).

$$\text{GHG}_{\text{Total}} = \text{Distance Travelled} \times \text{GHG}_{\text{WtB/km}} \tag{7}$$

The GHG emissions per km and the total GHG emissions can be obtained using equations (6) and (7) for city-driving, highway-driving, and combined city-highway driving conditions.

3.1.2 EV wind allocation

This section presents the design of four different wind allocation methods for supplying available wind-electricity, with some form of backup from grid-electricity, to charge EVs.

3.1.2.1 EV variables

The variables used in the different wind allocation methods are as follows:

Time Quantum represents the time interval and the resolution of the time quantum which depends on the processing speed of the system used for the simulation.

EV Battery Capacity (BC) represents the maximum or total energy capacity of the EV battery.

Maximum Input Charging Rate (MICR) is defined as the maximum rate at which EVs are able to charge the battery for per time quantum.

State of Charge (SOC) is defined as the available capacity of the battery after charging or discharging over a period of time quantum.

Current time quantum State of Charge ($SOC_{CurrtimeQuantum}$) is the available capacity of the battery after charging or discharging for the current time quantum.

Previous time quantum State of Charge ($SOC_{PrevtimeQuantum}$) is the available capacity of the battery after charging or discharging for the previous time quantum.

Available wind is defined as the aggregated wind-electricity generation output for the current time quantum.

3.1.2.1.1 EV demand calculation

An EV's demand is defined as the amount of electricity required to charge it over a period of time quantum to reach the maximum capacity of its battery, and can be calculated as shown in equation (8).

$$\text{EV Demand} = \left(\text{BC} - \text{SOC}_{\text{PrevtimeQuantum}}\right) \tag{8}$$

EV $\text{Demand}_{\text{Total}}$ for a given time quantum is the sum of demand from all EVs and it is calculated as shown in equation (9),

$$\text{EV Demand}_{\text{Total}} = \sum \text{EV Demand} \tag{9}$$

3.1.2.1.2 EV maximum demand calculation

An EV's maximum demand is defined as the amount of electricity required to charge an EV for the current time quantum with respect to its maximum input charging rate. It is referred to as EV $\text{Demand}_{\text{MAX}}$ and can be calculated using the following algorithm,

$$\begin{aligned}
&\text{IF EV Demand} > \text{EV Maximum Input Charging Rate THEN} \\
&\quad \text{EV Demand}_{\text{MAX}} = \text{EV Maximum Input Charging Rate} \\
&\text{ELSE} \\
&\quad \text{EV Demand}_{\text{MAX}} = \text{EV Demand} \\
&\text{END}
\end{aligned} \tag{10}$$

EV $\text{Demand}_{\text{MAX\_Total}}$ for a given time quantum is the sum of the maximum demand from all EVs and can be calculated as shown in equation (11).

$$\text{EV Demand}_{\text{MAX\_Total}} = \sum \text{EV Demand}_{\text{MAX}} \tag{11}$$

3.1.2.1.3 EV minimum demand calculation

For a system with an EV charging period of 'N' time quantum, the minimum demand is defined as the least volume of electricity that is required in each time quantum to charge the EV's battery to attain its respective demand at the end of the charging period. It can be calculated as shown in equation (12).

$$\text{EV Demand}_{\text{Min}} = \left(\frac{\text{BC} - \text{SOC}_{\text{PrevtimeQuantum}}}{\text{Hours remaining}}\right) \tag{12}$$

The EV's minimum demand is limited to its maximum input charging rate of the current time quantum as shown below,

$$\text{IF EV Demand}_{\text{Min}} > \text{EV Maximum Input Charging Rate THEN}$$
$$\text{EV Demand}_{\text{Min}} = \text{EV Maximum Input Charging Rate}$$
$$\text{END} \tag{13}$$

EV Demand$_{\text{Min_Total}}$ for a given time quantum is the sum of the minimum demand from all EVs and can be determined as shown in equation (14).

$$\text{EV Demand}_{\text{Min\_Total}} = \sum \text{EV Demand}_{\text{Min}} \tag{14}$$

3.1.2.2 Equal wind allocation

In the equal wind allocation method, the available wind-generated electricity is allocated equally to all the EVs regardless of their individual demands.

To determine the allocation of wind-electricity to charge EVs, it is necessary to know the total number of EVs connected to the system that need to charge their battery for the current time quantum; these are referred to as active EV units. With this, the allocation of wind to charge each EV for the current time quantum can be calculated as shown in equation (15).

$$\text{EV Wind Allocation} = \left(\frac{\text{Available Wind}}{\text{Active EV Units}} \right) \tag{15}$$

The allocated wind-electricity is always limited to the maximum EV demand for the current time quantum,

$$\text{IF EV Wind Allocation} = \text{EV Demand}_{\text{MAX}} \quad \text{THEN}$$
$$\text{EV Wind Allocation} = \text{EV Demand}_{\text{MAX}}$$
$$\text{END} \tag{16}$$

In this method, all EVs are charged with about the same amount of electricity but no one vehicle gets significantly more than any of the others since they are all treated equally in the system.

In order to minimize the chance of getting peak demand at the end of the charging period, this method attempts to charge each individual EV at least its minimum demand for each time quantum from the available wind-electricity, or from a combination of wind and grid-electricity. When allocated wind-electricity meets or exceeds the EV’s minimum demand, it does not require any such grid-electricity. However, when the allocated wind-electricity is insufficient to meet the EV's minimum demand, it is charged from grid-electricity in following algorithm,

$$
\begin{aligned}
&\text{IF EV Wind Allocation} < \text{EV Demand}_{\text{Min}} \quad \text{THEN} \\
&\quad \text{EV Grid Allocation} = \text{EV Demand}_{\text{Min}} - \text{EV Wind Allocation} \\
&\text{ELSE} \\
&\quad \text{EV Grid Allocation} = 0 \\
&\text{END}
\end{aligned}
\tag{17}
$$

3.1.2.3 EV demand allocation

In the EV demand allocation method, the allocation of wind to charge EVs is determined by each EV's current demand: those with high demand receive more of the available wind-electricity that those with less demand.

To calculate the wind allocation, it is necessary to determine the ratio of each EV's demand to the total demand from all EV units in the system for the current time quantum, and this is termed as the percentage of demand. From equations (8) and (9), the percentage of demand for each individual EV can be calculated using equation (18).

$$\text{EV Percentage of Demand} = \left(\frac{\text{EV Demand}}{\text{EV Demand}_{\text{Total}}} \right) \times 100 \tag{18}$$

With the above calculated percentage of demand and the available wind, the allocation of wind to charge each EV for the current time quantum can be determined as shown in equation (19).

$$\text{EV Wind Allocation} = (\text{EV Percentage of Demand} \times \text{Available Wind}) \tag{19}$$

For each EV, the allocation of wind is directly proportional to its percentage of demand and limited to the maximum EV demand for current time quantum (see equation (16)). As with the equal wind allocation, this method also assures that each EV is charged to at least its minimum demand for every time quantum from the available wind-electricity, or from a combination of wind and grid-electricity as shown in equation (17).

3.1.2.4 EV maximum-demand allocation

In this method, the maximum demand of each EV for the current time quantum is met with the available wind-electricity, grid-electricity, or both. This method attempts to complete the EV charging as rapidly as possible, regardless of the source of electricity.

In order to determine the wind allocation for the EVs, it is necessary to obtain the ratio of the available wind-electricity to the maximum demand from all EVs (i.e. EV $\text{Demand}_{\text{MAX\_Total}}$) for the current time quantum as shown in equation (20).

$$\text{Wind factor}_{\text{MAX}} = \text{minimum}\left(\frac{\text{Available Wind}}{\text{EV Demand}_{\text{MAX\_Total}}}, 1\right) \tag{20}$$

With this, the allocation to charge each individual EV is determined by its maximum demand for the current time quantum using,

$$\text{EV Wind Allocation} = \text{Wind factor}_{\text{MAX}} \times \text{EV Demand}_{\text{MAX}} \tag{21}$$

$$\text{EV Grid Allocation} = (1 - \text{Wind factor}_{\text{MAX}}) \times \text{EV Demand}_{\text{MAX}} \tag{22}$$

When the available wind-electricity meets or exceeds the EVs' maximum demand total (i.e. the wind $\text{factor}_{\text{MAX}}$ is 1), each individual EV is charged to its maximum demand from the available wind-electricity using equation (21). Therefore, there is no need for the utilization of grid electricity. However, when the available wind-electricity is less than the EVs' maximum demand total (i.e. wind $\text{factor}_{\text{MAX}} < 1$), each individual EV is charged to its maximum demand from the combination of wind and grid-electricity as shown in equations (21) and (22).

3.1.2.5 EV minimum-demand allocation

In this method, each EV is charged with the minimum amount of electricity required in each time-quantum with wind-electricity or through some combination of wind and grid-electricity. If the level of wind-electricity in a future time-quantum is unknown, this method is to attempt to reduce the consumption of grid-electricity by minimizing its consumption during each time-quantum.

To calculate the allocation of wind to charge EVs, it is necessary to obtain the ratio of the available wind to the minimum demand from all EVs (i.e. EV $\text{Demand}_{\text{Min\_Total}}$) as shown in equation (23).

$$\text{Wind factor}_{\text{Min}} = \text{minimum}\left(\frac{\text{Available Wind}}{\text{EV Demand}_{\text{Min\_Total}}},1\right) \tag{23}$$

With this, the allocation to charge each individual EV for the current time quantum can be determined using,

$$\text{EV Wind Allocation} = \text{Wind factor}_{\text{Min}} \times \text{EV Demand}_{\text{Min}} \tag{24}$$

$$\text{EV Grid Allocation} = (1 - \text{Wind factor}_{\text{Min}}) \times \text{EV Demand}_{\text{Min}} \tag{25}$$

When there is sufficient wind-electricity (i.e., Wind $\text{factor}_{\text{Min}}$ is 1), each individual EV is charged up to its minimum demand from the available wind-electricity using equation (24); however, when there is insufficient wind-electricity (i.e., Wind $\text{factor}_{\text{Min}} <1$), each individual EV must be charged with available wind and grid-electricity using equations (24) and (25) to meet the minimum demand for the current time quantum.

It should be noted that an EV connected to the system becomes fully charged to its demand for the current time quantum and cannot accept any more additional units of wind or grid-electricity for the remaining time quantum of the EV charging period in any of the above mentioned wind allocation methods. Also, any wind-electricity still remaining from the wind allocation is considered surplus and will be made available to other electricity services.

3.2 Sample application of the methods

This section demonstrates the sample application of the four different EV wind allocation methods for a one-hour EV charging period.

3.2.1 Data

The following data was used for the demonstration of the methods:

Available wind data: the aggregated wind-electricity generation data from wind farm for each time quantum, in electricity (kWh).

EV units: the number of EVs employed in the simulation.

EV Battery Capacity: the maximum capacity of the EV battery, in terms of electricity (kW).

EV maximum input charging rate: the maximum charging rate an EV's battery for the current time quantum, in electricity (kW per time-quantum).

EV demand profile data: a distance traveled data, in kms.

Electric emission intensity data: the greenhouse gas emission intensity from the electricity supplier, and expressed in grams of CO_2e emitted per kWh.

Fuel economy data: the distance traveled by a vehicle per unit of fuel consumed, expressed as miles per gallon (mpg) or kilometer per litre (km/L) for CVs, and AC kWh/miles or AC kWh/km for EVs.

In the examples given, each time quantum is assumed to be one hour; in each case, there is an eight-hour EV charging period. Table 3-1 shows the data for the first hour of the eight-hour EV charging period (hereafter referred to as the "current hour"). Seven EVs are chosen for this example and are numbered sequentially from 1 to 7. Similarly, the available wind-electricity data for this current hour is assumed to be 7kWh.

Table 3-1: EV data

EV unit number	**EV1**	**EV2**	**EV3**	**EV4**	**EV5**	**EV6**	**EV7**
EV Battery Capacity (kW)	24	24	24	24	24	24	24
Maximum input charging rate (kWh)	3.3	3.3	3.3	3.3	3.3	3.3	3.3
$SOC_{Prev\ hour}$ (kWh)	22	20	18	16	14	12	10
EV Demand (kWh)	2	4	6	8	10	12	14
EV $Demand_{MAX}$ (kWh)	2	3.3	3.3	3.3	3.3	3.3	3.3
EV $Demand_{Min}$ (kWh)	0.25	0.50	0.75	1.00	1.25	1.50	1.75

For the purpose of this analysis, it is assumed that each individual EV has a battery capacity of 24kW and a maximum input charging rate of 3.3 kWh. Based on the previous hour's state of charge ($SOC_{Prevhour}$) value, the EV demand for the current hour is calculated for each individual EV using equation (8) and shown in Table 3-1.

The total demand from EV1 to EV7 is calculated as follows,

$$\text{EV Demand}_{\text{Total}} = \sum \text{EV Demand} = 56kWh$$

The maximum demand of each EV for the current hour is calculated using equation (10) and shown in Table 3-1 (see EV $\text{Demand}_{\text{MAX}}$). The total maximum demand from all EVs for the current hour is calculated and given as follows,

$$\text{EV Demand}_{\text{MAX\_Total}} = \sum \text{EV Demand}_{\text{MAX}} = 21.80kWh$$

The minimum demand is calculated using equation (12) for the current hour and shown in Table 3-1 (see EV $\text{Demand}_{\text{Min}}$). For example, the minimum demand of EV1 for the current hour is calculated as follows,

$$\text{EV Demand}_{\text{Min}} = \left(\frac{\text{BC - SOC}_{\text{Prevhour}}}{\text{Hours remaining}} \right)$$

$$= \left(\frac{24-22}{8} \right) = 0.25kWh$$

From the above calculation, EV1 requires a charge of at least 0.25kWh for the current hour in order to attain its demand at the end of the eight-hour charging period. The total minimum demand from all EVs for the current hour is calculated using equation (14) and given as,

$$\text{EV Demand}_{\text{Min\_Total}} = \sum \text{EV Demand}_{\text{Min}} = 7kW$$

3.2.2 Equal wind allocation

In the equal wind-allocation method, the available wind-electricity of 7 kWh is allocated equally to all EVs regardless of their individual demand requirements. Table 3-2 shows the allocation of wind and grid-electricity for the seven EVs.

Table 3-2: Equal wind allocation

EV Units	EV1	EV2	EV3	EV4	EV5	EV6	EV7
Wind Allocation (kWh)	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Grid Allocation (kWh)	0	0	0	0	0.25	0.50	0.75

For the current hour, there are seven active EV units that are connected to system requiring a charge. The allocation of wind-electricity for the EVs for the current hour is calculated using equation (15),

$$\text{EV Wind Allocation} = \left(\frac{\text{Available Wind}}{\text{Active EV Units}}\right) = \frac{7kWh}{7} = 1kWh$$

The allocated wind-electricity is limited to the EV's maximum demand for the current hour as shown in equation (16). With this, each individual EV is allocated with an equal share of 1 kWh of the available wind-electricity for the current hour. Table 3-1 and Table 3-2 show that for EVs 1 to 4, the allocated wind-electricity is sufficient to meet their minimum demand and there is no need for grid-electricity. However, in the case of EVs 5 to 7, the allocated wind-electricity is less than their minimum demand. Hence, those EVs are charged through a combination of wind and grid-electricity to meet their minimum demand for the current hour as shown in equation (17).

3.2.3 EV demand allocation

In the EV demand allocation method, the allocation of wind to charge the EVs is determined by each EV's current demand requirements. Table 3-3 shows the percentage of demand, and wind and grid allocation of the seven EVs.

Table 3-3: EV demand allocation

EV Units	**EV1**	**EV2**	**EV3**	**EV4**	**EV5**	**EV6**	**EV7**
Percentage of Demand	3.6%	7.1%	10.7%	14.3%	17.9%	21.4%	25.0%
Wind Allocation (kWh)	0.25	0.50	0.75	1.00	1.25	1.50	1.75
Grid Allocation (kWh)	0	0	0	0	0	0	0

The percentage of demand of EVs is determined from the ratio of each individual EV current demand to the total demand from all EV units in the system using equation (18). For example, the percentage of EV1's demand is calculated as follows,

$$\text{EV Percentage of Demand} = \left(\frac{\text{EV1 Demand}}{\text{EV Demand}_{\text{Total}}}\right) = \left(\frac{2}{56}\right) = 3.6\%$$

With the above calculated percentage of demand and the available wind, the allocation of wind to charge the EV for the current hour is calculated as follows,

$$\text{EV Wind Allocation} = (\text{EV Percentage of Demand} \times \text{Available Wind})$$

$$= (3.6\% \times 7\,\text{kWh}) = 0.25\,\text{kWh}$$

Similarly, the percentage of demand and the wind allocation is calculated for the rest of the EVs and shown in Table 3-3. In this method, the allocation of wind to charge the EVs is directly proportional to their individual percentages of demand. That is, EV1 has a lower percentage of demand and is provided with 0.25 kWh of available wind, whereas EV7 has a higher percentage of demand and is provided with 1.75 kWh of wind-electricity. Table 3-1 and Table 3-3 show that the minimum demand for the current hour for the seven EVs is completely met with wind-electricity; therefore, there is no need of grid-electricity.

3.2.4 EV maximum-demand allocation

In this method, the maximum demand of the EVs (1-7) for the current hour is to be met with the available wind-electricity or grid-electricity, or both. Table 3-4 shows the allocation of wind and grid-electricity for the current hour.

Table 3-4: EV maximum-demand allocation

EV Units	**EV1**	**EV2**	**EV3**	**EV4**	**EV5**	**EV6**	**EV7**
Wind Allocation (kWh)	0.64	1.06	1.06	1.06	1.06	1.06	1.06
Grid Allocation (kWh)	1.36	2.24	2.24	2.24	2.24	2.24	2.24

The allocation of wind to charge the EVs is based on the ratio of the available wind-electricity (7kWH) to the total maximum demand for electricity (21.80kWh) from all EVs for the current hour.

$$\text{Wind factor}_{MAX} = \text{minimum}\left(\frac{\text{Available Wind}}{\text{EV Demand}_{MAX\_Total}}, 1\right)$$

$$= \text{minimum}\left(\frac{7}{21.80}, 1\right) = 0.32$$

The calculated value above shows that the available wind-electricity is less than the EVs' maximum demand total (i.e. wind $factor_{MAX}$ <1). Therefore, each individual EV is charged using a combination of available wind and grid-electricity as shown in equations (21) and (22). An example of allocation of wind and grid-electricity to charge EV1 is given as follows,

$$\text{EV1 Wind Allocation} = \text{Wind factor}_{MAX} \times \text{EV Demand}_{MAX}$$

$$= (0.32 \times 2\,\text{kWh}) = 0.64\,\text{kWh}$$

$$\text{EV1 Grid Allocation} = (1 - \text{Wind factor}_{MAX}) \times \text{EV Demand}_{MAX}$$

$$= ((1 - 0.32) \times 2\text{kWh}) = 1.36\,\text{kWh}$$

Similarly, the allocation of wind and grid-electricity is calculated for the remaining EVs and is shown in Table 3-4.

3.2.5 EV minimum-demand allocation

In this method, the minimum hourly demand of each EV is met with available wind-electricity or some combination of wind and grid-electricity. Table 3-5 shows the allocation of wind and grid-electricity for the EVs for the current hour.

Table 3-5: EV minimum-demand allocation

EV Units	**EV1**	**EV2**	**EV3**	**EV4**	**EV5**	**EV6**	**EV7**
Wind Allocation (kWh)	0.25	0.50	0.75	1.00	1.25	1.50	1.75
Grid Allocation (kWh)	0	0	0	0	0	0	0

The allocation of the wind to charge the EVs is determined from the ratio of the available wind to the total minimum demand from all EVs for the current hour.

$$\text{Wind factor}_{Min} = \text{minimum}\left(\frac{\text{Available Wind}}{\text{EV Demand}_{Min\_Total}}, 1\right)$$

$$= \text{minimum}\left(\frac{7\text{kWh}}{7\text{kWh}}, 1\right) = 1$$

As shown in the calculated value above, the available wind is equal to the EVs' minimum demand total (i.e. wind $\text{factor}_{\text{Min}} = 1$). Therefore, each individual EV is charged to its minimum demand for the current hour from the available wind-electricity using equation (24).

3.3 Implementation

The application of the methods in the previous section shows how a small, tabular dataset could represent the data available for the research. In light of this, it was decided that spreadsheet and its associated tools will be used for the implementation of the methods.

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

Visual Basic for Applications (VBA) is a programming language that can be used within Excel 2007 to perform complex computations that involve repetitive operations. With this application, macros or complex programs can be developed to automate operations and perform analyses with more consistency than that which is manually in Excel spreadsheets. Also, long, iterative, and time-consuming tasks can be computed more quickly than in the default Excel spreadsheets.

Using these software tools, the simulation of well-to-wheels greenhouse gas emission analysis and the four different wind allocation methods is implemented.

3.4 Summary

This chapter presented a set of methods for calculating well-to-wheels greenhouse gas emissions for conventional and electric vehicles. It also presented the design of four different wind allocation methods, along with the variables required to represent the charging of EVs with available wind-electricity. In some cases backup from grid-electricity was necessary. An example of the application of the methods was given with the required data. The software tools used to implement the proposed methods were also discussed.

In the next chapter, the implementation of the proposed methods is presented through a case study simulation, along with its results.

CHAPTER 4 CASE STUDY AND RESULTS

This chapter presents a case study to examine the proposed methods to analyze the impact of EVs on reducing vehicular greenhouse gas emissions in the City of Summerside, P.E.I. It also presents the rationale for selection of Summerside, along with the input data required to perform the simulation. The case study is implemented using the software tools, Microsoft Office Excel 2007 and VBA, and the results of the simulations are presented.

4.1 Background

Summerside is P.E.I.'s second largest city [57], with abundant wind resource due to its geographic location and its city-operated wind farm. In Summerside, passenger vehicles are the most common mode of transportation [58]. They are a major consumer of refined oil products—notably gasoline—and one of the significant greenhouse gas emitters [58]. This makes Summerside an ideal location for the electrification of passenger vehicles, since much of the city's passenger transportation services could be met with locally available wind-generated electricity, which will have a negligible carbon footprint when compared to conventional gasoline vehicles. Furthermore, an average hourly wind data along with driving distance travelled data are available for Summerside.

4.2 Electricity supply

In 2010, Summerside imported about 53.7% and 22.3%, respectively of its electricity from NB Power's generation facilities in New Brunswick (grid-electricity) and West Cape Energy in P.E.I. (wind-electricity), with the remainder coming from Summerside's own wind farm which accounted for almost one-quarter of the city's total electricity supply [59]. Figure 4-1 shows the electricity suppliers for Summerside for 2010.

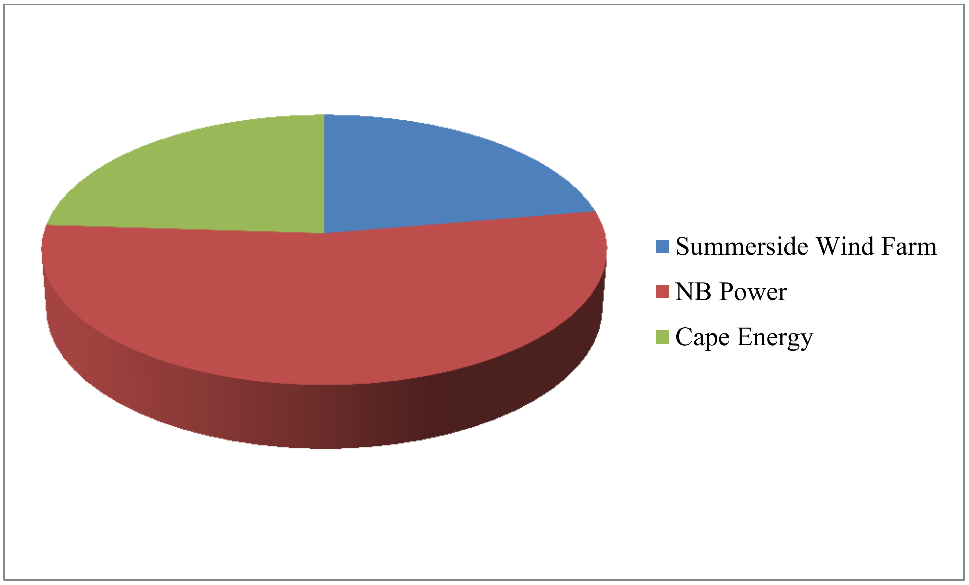

Figure 4-1: Electricity suppliers for Summerside [59]

For the purpose of this research, the wind-electricity from the Summerside wind farm and the grid-electricity from NB Power were considered (excluding electricity from West Cape energy) and these are discussed in detail below.

4.3 Summerside's wind resource

Summerside has a good wind resource and experiences average wind speeds of 6-6.5m/s at 30m above ground level (AGL), 7-7.5m/s at 50m AGL, and 7.5-8m/s at 80m AGL [60]. Figure 4-2 shows the color-coded Wind Atlas for P.E.I. at 80m above ground level. Summerside is one of the high-wind regions of Prince Edward Island and is indicated on the Figure 4-2.

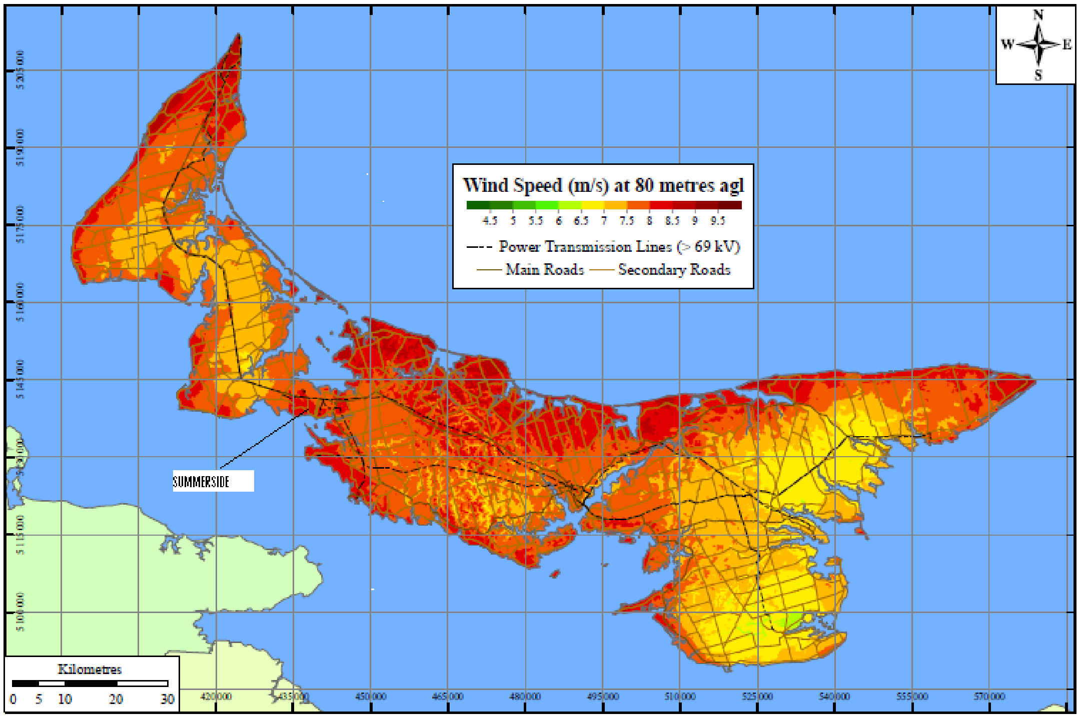

Figure 4-2: Wind atlas for P.E.I. [61]

In 2009, Summerside developed a wind farm with a total installed wind-electricity generating capacity of 12 MW consisting of four Vestas V-90 wind turbines, each capable of producing 3 MW of electricity. The expected capacity factor of the wind farm was 29%.[8] At the end of 2009, the wind farm became fully operational [60].

For this study, the average hourly wind-electricity generation data was obtained from the 12 MW wind farm; the data covers the period of 1 January 2010 to 31 December 2010; the total annual wind-generated electricity for this period was 30.28 GWh giving an annual capacity factor of 28.8%. The average monthly output (from hourly data) for 2010 is shown in Figure 4-3.

[8] The capacity factor is defined as the ratio of actual power produced to the theoretical maximum power for the given period.

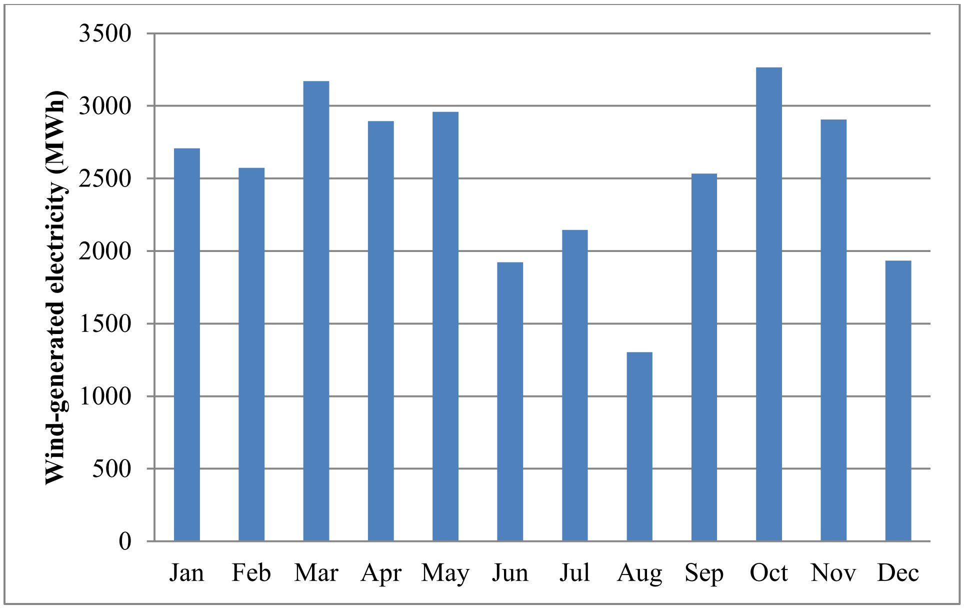

Figure 4-3: Monthly output from Summerside wind farm for 2010

The wind-electricity generation from the wind farm exceeded 2,500 MWh each month for January to May and September to November. During the months of March and October, the wind-electricity generation reached the maximum of 3,170 MWh and 3,266 MWh, respectively. Overall, wind-electricity generation values exceed 1,000 MWh per month.

4.4 Grid-electricity: NB Power

As a wind farm's output is variable, Summerside has an agreement with New Brunswick (NB), where NB Power acts as Summerside's on-demand grid electricity source, depending on the wind supply, to ensure that Summerside's electricity requirements are met [59]. For the case study simulation, it is assumed that backup grid-electricity for the EV wind allocation is supplied by NB Power.

In 2010, NB Power's generation mix was estimated as 40% (hydroelectric) and 60% (conventional steam) and greenhouse gas emissions intensity from net electrical generation of 519.60g of CO_2e per kWh [62]. Since well-to-generation emissions were not publicly available for NB Power, the supply-chain emissions intensity was estimated to be 10% of the generation-to-battery's emissions intensity [50]. The choice of 10% reflects well-to-generation research that suggested that these emissions are within this range [50]. Overall, NB Power's electricity GHG emission intensity is estimated to be 571.56g of CO_2e per kWh for 2010.

4.5 Vehicles data

This section discusses the vehicles that will be examined in the case study simulation, along with their respective fuel economy data for the well-to-wheels analysis. In addition, the vehicles' driving distance travelled data for Summerside are also discussed.

4.5.1 Hyundai Elantra

The Hyundai Elantra with manual transmission is one of the various fuel-efficient mid-sized CVs in Canada [63]. For the purposes of this study, the Hyundai Elantra represents a conventional vehicle to be used in the simulation. The fuel consumption data for the Elantra was obtained from Natural Resources Canada (NRCan) Fuel Consumption Guide for the year 2011 and shown in Table 4-1.

Table 4-1: Hyundai Elantra fuel economy and emissions [63]

Driving characteristics	Fuel consumption (L/100km)	Fuel economy (km/L)	Well-to-tank emissions (gCO_2e/km)	Tank-to-Wheels emissions (gCO_2e/km)	Well-to-wheels emissions (gCO_2e/km)
City	6.8	14.7	44.2	166.3	210.5
Highway	4.9	20.4	31.8	119.9	151.7
Combined	5.9	16.8	38.6	145.4	184.1

From Table 4-1, it is clear that the Elantra has better highway than city fuel economy (km/litre). NRCan assumes that the distance an average Canadian vehicle travels has a city-highway ratio of 55:45; the case study uses this ratio in determining the combined city-highway driving fuel economy [63].

For the purpose of the well-to-wheels analysis, the reciprocal of fuel consumption (i.e., litre/100 kilometre) is used as the fuel economy for the Elantra (i.e., kilometres/litre). The well-to-tank and tank-to-wheels emission for the Elantra were calculated for city, highway, and combined city-highway driving conditions using the fuel economy data (see equations (3) and (4)).

Similarly, the well-to-wheels emissions were calculated using equation (1) and shown in Table 4-1. It is observed that the Elantra has lower well-to-wheels greenhouse gas emissions for highway driving (151.7g $CO_2e/km_{Highway}$) than for city driving (210.5g CO_2e/km_{City}) due to higher fuel economy.

4.5.2 Nissan Leaf

The Nissan Leaf is the most fuel-efficient mid-sized electric vehicle in Canada, with 24 kWh lithium-ion batteries and a 3.3kW onboard charger [64]. For the purpose of this study, the Leaf's fuel economy data for Canada was estimated from the EPA fuel economy guide for the year 2011.[9]

The Leaf's Canadian electric range is expected to be 100 miles or 160 km on a single electric charge [65].[10] The Leaf's estimated city, highway, and combined fuel consumptions are shown in Table 4-2.

Table 4-2: Nissan Leaf fuel economy [66]

Driving characteristics	Fuel economy		
	kWh/100mile	kWh/100km	kWh/km
City	32	19.9	0.199
Highway	37	23.0	0.230
Combined	34.3	21.3	0.213

The Leaf has three charging modes: Level 1, Level 2, and Level 3 [67]. Level 1 charging is a slow charging process and includes a 110/120V "trickle charge" cable that works with the onboard charging system. Based on the amperage of the connected electrical outlet, it takes about 20 hours to charge the battery starting from depletion. Level 2 charging uses a home charging dock that is connected to a dedicated electrical outlet of 208-240V, 40A. It takes approximately 7-8 hours to charge the battery starting from depletion. Level 3 charging included a 480V quick charger, and takes about 26 mins to charge the battery to 80% of capacity starting from depletion.

[9] At the time of writing, the Leaf's fuel economy data for Canada was not available from the NRCan Fuel Consumption guide.

[10] Nissan Canada basis this number on the EPA LA4 city driving fuel economy test.

The well-to-battery greenhouse gas emissions per km for the Nissan Leaf are specific to the electricity supplier's emission intensity. Assuming that the Leaf's electrical consumption includes the conversion efficiency (none is specified), the well-to-battery emissions are simply the product of electricity consumption (kWh/km) and the electricity supplier's emissions intensity (g CO_2e per kWh) (see equation (6)). Since this can vary by supplier, Figure 4-4 shows the expected emissions per kilometre for electricity suppliers with well-to-battery emissions intensities ranging from a low of 100g CO_2e per kWh to 1,000g CO_2e per kWh.

"Highway" refers to a Leaf being driven under highway conditions, while "City" refers to driving a Leaf in city conditions.

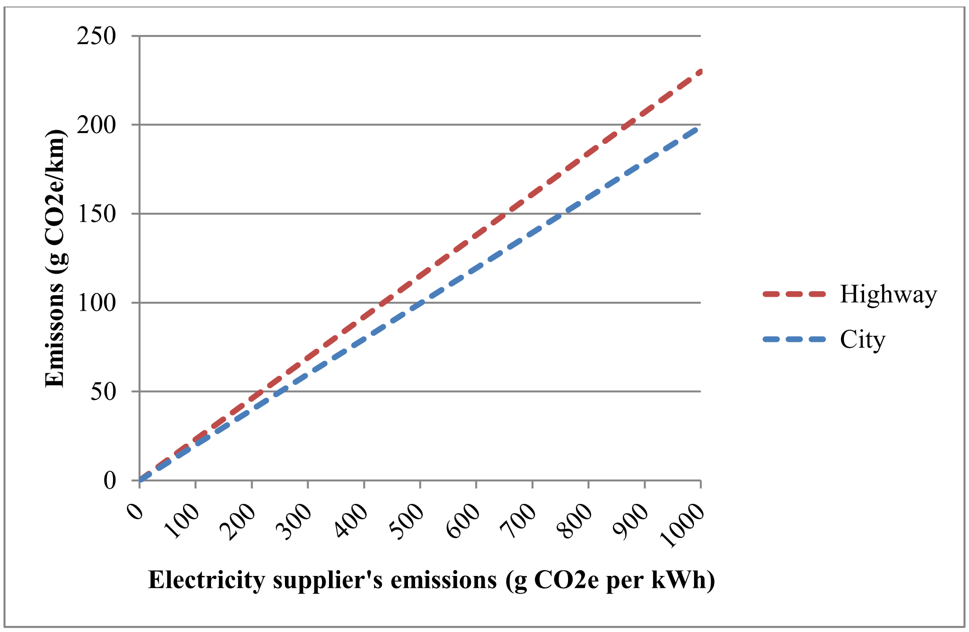

Figure 4-4: Nissan Leaf–emissions Vs supplier's emissions intensity

In the case of the Nissan Leaf, the CO_2e emissions per kilometre range from 19.9g CO_2e/km_{City} or 23g $CO_2e/km_{Highway}$ for an electricity supplier with an emissions intensity of 100g CO_2e per kWh to 199g CO_2e/km_{City} or 230g $CO_2e/km_{Highway}$ for a supplier with an intensity of 1,000g CO_2e per kWh.

4.6 Driving distance data

The vehicles' driving distance data for the case study was obtained from the commuting distance data for Summerside.

According to 2006 Census of Population by Statistics Canada, there were about 7,570 people in Summerside who were considered employed, including those who worked at home, worked outside Canada, had no fixed workplace address, or had a usual place of work [68]. Of these, there were about 7,220 people who worked outside of the home at some location in Summerside, over 90% of whom used a passenger vehicle to travel to and from work. Figure 4-5 shows an estimate of the mode of transportation and number of commuters per mode in Summerside.

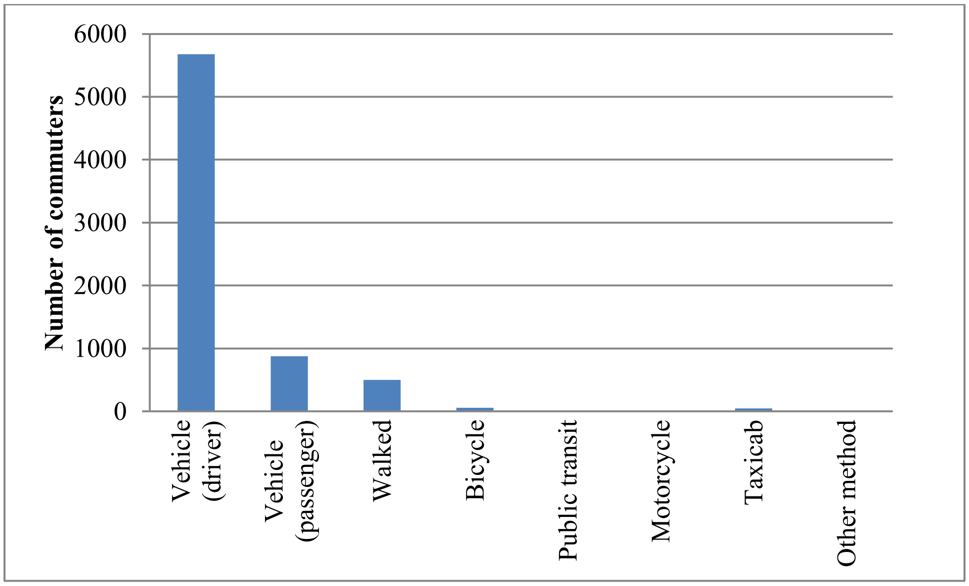

Figure 4-5: Estimated transportation mode and number of commuters [69]

From Figure 4-5, it is observed that the overwhelming mode of choice for travelling to work in Summerside is the passenger vehicle, followed by walking. Of the approximately 5,675 passenger vehicles driven in Summerside, there is no easy way of determining the vehicle type (i.e., car, truck, or van) as vehicles registrations are classified by weight [70].

Figure 4-6 shows the number of commuters and straight-line commuting distances for Summerside. The median, straight-line distance for commuters who commuted to their usual places of work in Summerside is 2.8km [71].

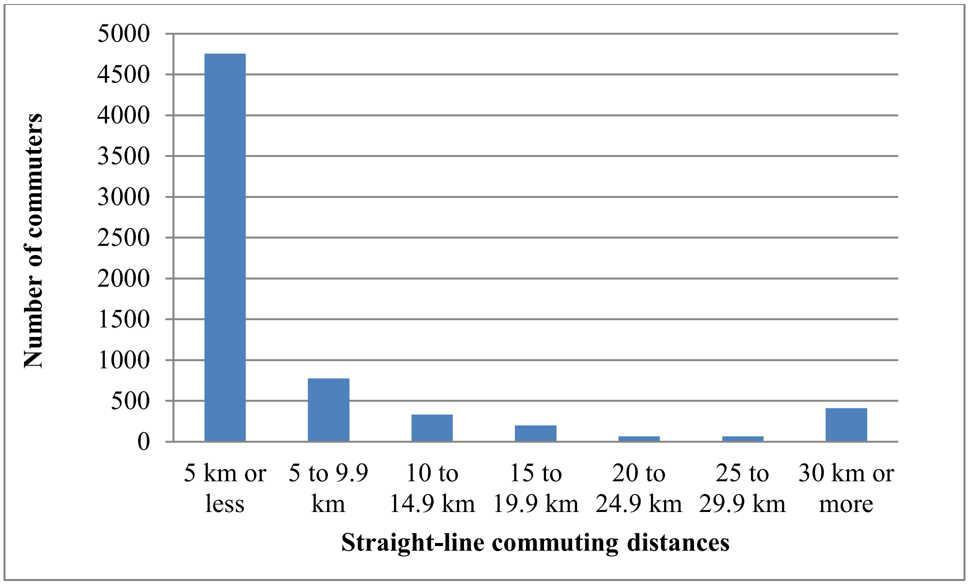

Figure 4-6: Total commuters by straight-line commuter distance [71]

From Figure 4-6 , information on the distance from commuters' homes to their places of work is restricted to those who have a "usual place of work". The distances provided refer to a range of one-way, straight-line distances with no indication of the mode being used. For the purpose of this study, the round-trip commuting distances was obtained by doubling the given straight-line distances as shown in Table 4-3. For simplicity, the upper limit of the round trip commuting distances is rounded to the nearest whole kilometre. It is assumed that the number of commuters who traveled round-trip commuting distances is the same as the numbers travelling straight-line commuting distances for Summerside.

Table 4-3: Round-trip commuting distances

Straight-line commuting distance (km)	Round-trip commuting distance (km)
5 km or less	10 km or less
5 to 9.9 km	10.1 to 20 km
10 to 14.9 km	20.1 to 30 km
15 to 19.9 km	30.1 to 40 km
20 to 24.9 km	40.1 to 50 km
25 to 29.9 km	50.1 to 60km
30 km or more	60.1 km or more

4.7 Case study simulation results

In this section, simulations for a one year period was conducted ,where the Elantras and the Leafs were used for weekday commuting purposes in Summerside and the obtained results are then presented.

4.7.1 Data

For this simulation, the time quantum was considered to be a one-hour time interval. In the case of the Leaf, with a Level 2 charging mode (that is, the 208-240V, 40A home charging dock), it takes about 7-8 hours to charge the battery starting from depletion. Therefore, the Leafs were assumed to be charged during the overnight period (2300hrs-0700hrs) with Level 2 charging mode and a standard 3.3kW onboard charger. The overnight hours are chosen as it is expected to be the most common time when the commuters do not drive and vehicle will be present. Besides, the Summerside's electricity demand tends to be lower during this charging period than during the hours of peak demand; hence, this off-peak electricity could be used as a backup for the EV wind allocation without any need of additional generation capacity from the grid.

The driving distance travelled data for this simulation is extracted from the round-trip commuting distance data for Summerside (see Table 4-3). Using this, seven different commuting distance (CD) patterns are considered for this analysis. Each pattern is referred to by the upper limit of its round-trip commuting distance range (i.e., CD 10 indicates that a vehicle's daily round trip commuting distance is 10 kms); however, for CD 60+, it is assumed that a vehicle's daily round-trip commuting distance is 100 kms, as there is no indication of the upper limit of the distance travelled data from Statistics Canada.

For this simulation, two distinct vehicle fleets (i.e., conventional gasoline vehicles and electric vehicles) were considered, with each fleet consisting of 100 vehicles; the vehicles were allocated into groups representative of the total commuters by round-trip commuting distance data. For example, 72% of commuters travelled a round-trip commuting distance of 10 km or less; therefore, for the CD 10 pattern, 72 vehicles were considered.

Table 4-4 shows seven different commuting distance patterns and their corresponding number of vehicles. The table also includes the annual commuting distances, which assumes that the vehicles are used for weekday commuting only.

Table 4-4: Commuting distance patterns

Commuting patterns	Round-trip distances (kms)	Number of Vehicles	Annual commuting distances[11] (kms)
CD 10	10	72	187,920
CD 20	20	12	62,640
CD 30	30	5	39,150
CD 40	40	3	31,320
CD 50	50	1	13,050
CD 60	60	1	15,660
CD 60+	100	6	156,600

The emissions associated with the Elantras predominantly rely on gasoline as its sole energy source. However, the emissions associated with the Leafs depend on the total amount of electricity supplied from available wind or grid electricity, or both. Hence, the annual total electricity generation needed to power the Leafs' from all the commuting patterns was estimated to be 116.5 MWh. By using EV wind allocation methods, the amount of available wind and grid-electricity used by the Leafs in each of seven different commuting patterns can be obtained. With this, the greenhouse gas emissions associated with the Leafs can be calculated.

The results presented compare the annual total greenhouse gas emissions for the Elantras, and the Leafs (both the grid and the combination of wind and grid) for four different wind allocation methods.

4.7.2 Equal wind allocation

Figure 4-7 shows the total allocation of available wind and grid-electricity for the Leafs with seven different commuting distance patterns.

[11] For a year, there were 261 weekday commuting days.

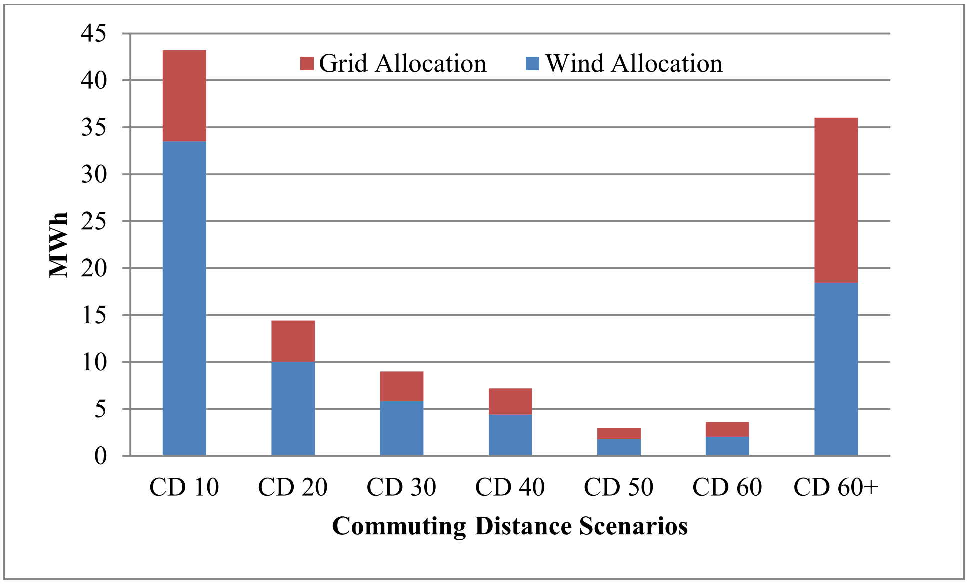

Figure 4-7: Wind and grid-electricity allocation for the Leafs

Of the annual total required demand for electricity of 116.5 MWh from all the Leafs, approximately 76 MWh was provided from the Summerside wind farm and the rest was supplied by grid-electricity using the equal wind allocation method. As the available wind-electricity was allocated equally to all vehicles regardless of their individual demand requirements, pattern CD 10, with the largest number of vehicles, procured the maximum amount of wind-electricity.

The annual total greenhouse gas emissions for the Elantras and the Leafs for the seven different commuting patterns are shown in Figure 4-8. In all the commuting patterns, the vehicles were assumed to operate under highway driving conditions.

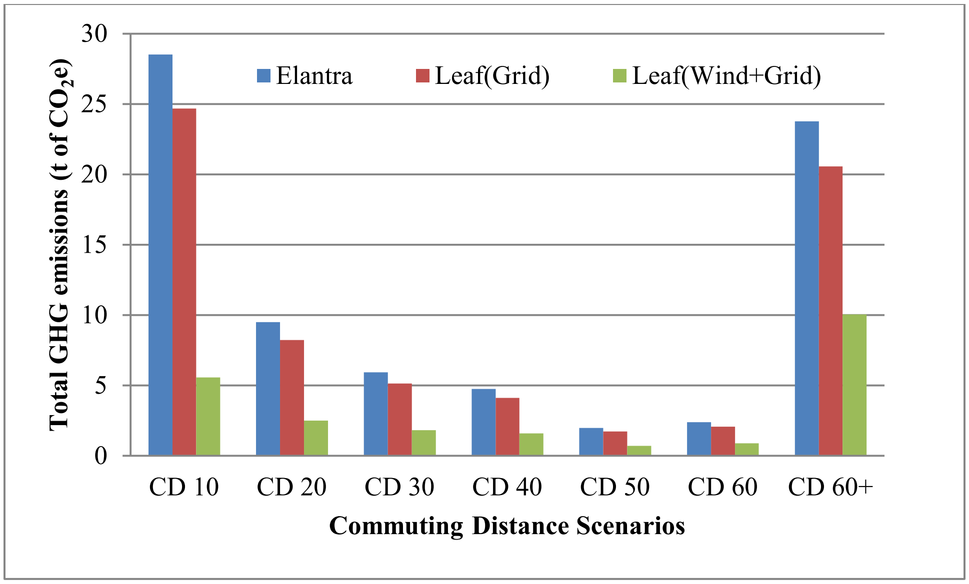

Figure 4-8: Annual total GHG emissions for the Elantras and the Leafs

When the Leafs were charged using the wind and grid-electricity, the annual total greenhouse gas emissions were reduced significantly across all the seven different commuting distance patterns. However, without the available wind-generated electricity, the Leafs emissions were markedly higher, but still better than the Elantras emissions. In the case of the CD 10 pattern, the amount of greenhouse gas emissions reduction for the Leafs using the available wind was more significant (23 t of CO_2e, lower) compared to the Elantra because of their greater utilization of wind-generated electricity (5.56 t of CO_2e for the Leaf (Wind+Grid) ; 28.51 t of CO_2e for the Elantra).

4.7.3 EV demand allocation

The following Figure 4-9 shows the total amount of electricity supplied by both the available wind and grid-electricity using the demand allocation method for the Leafs seven different commuting distance patterns.

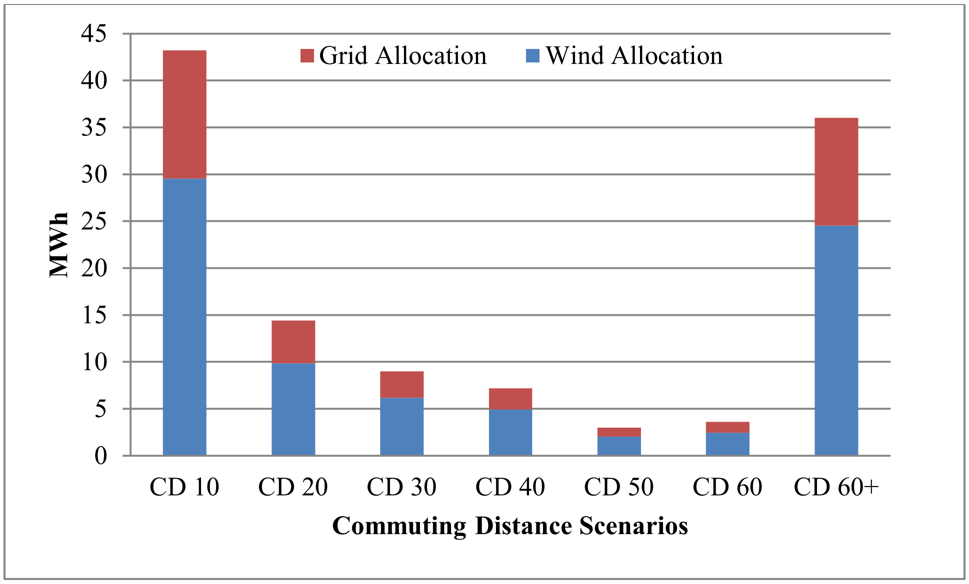

Figure 4-9: Wind and grid-electricity allocation for the Leafs

In all the commuting distance patterns, using the EV demand allocation method, the available wind-generated electricity met about 68% of the Leafs total required demand for electricity, and grid-electricity was used to supply the rest of the demand. As the allocation of wind to charge Leafs was based on their individual demand requirements; for example, in commuting pattern CD 60+, the vehicles with higher demand requirements obtained a markedly significant amount of the wind-generated electricity, when compared to the equal wind allocation method.

Figure 4-10 shows the annual total greenhouse gas emissions for the Elantras and the Leafs under highway driving conditions for the seven different commuting patterns.

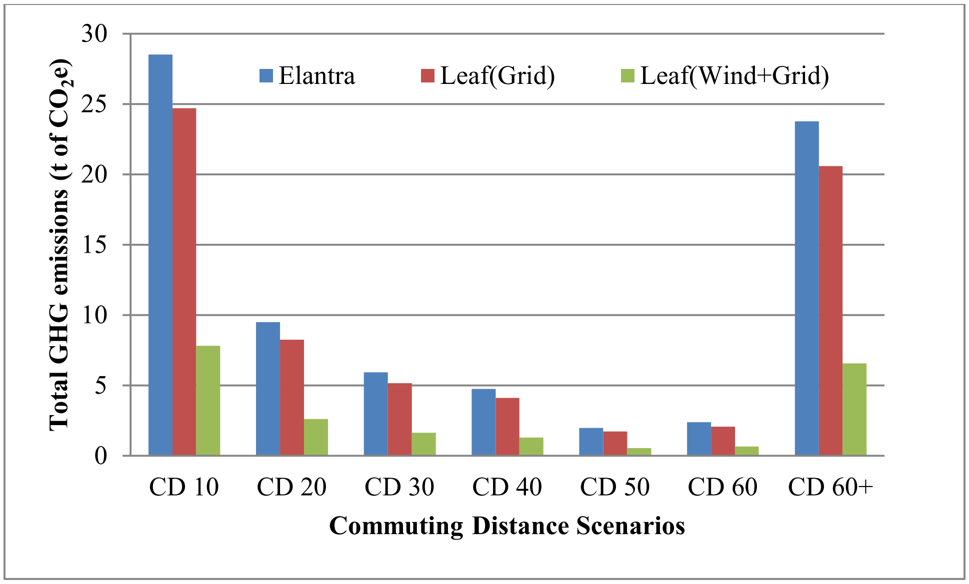

Figure 4-10: Annual total GHG emissions for the Elantras and the Leafs

In all the commuting patterns, the Elantras had the highest emissions due to their greater well-to-wheels greenhouse gas emissions. The emissions associated with the Leafs using the grid-electricity were lower than the Elantras. However, the addition of wind combined with grid-electricity results in a significant reduction of annual total greenhouse gas emissions from the Leafs for all the commuting distance patterns. For example, in the case of the CD 10, the Leafs using available wind and grid-electricity achieved a significant greenhouse gas emissions reduction of about 21 of CO_2e compared to the emissions associated with the Elantras (7.8 t of CO_2e for the Leaf (Wind+Grid); 28.5 t of CO_2e for the Elantra).

4.7.4 EV maximum-demand allocation

The annual total amount of electricity allocated from both wind and grid-electricity for the Leafs is shown in Figure 4-11.

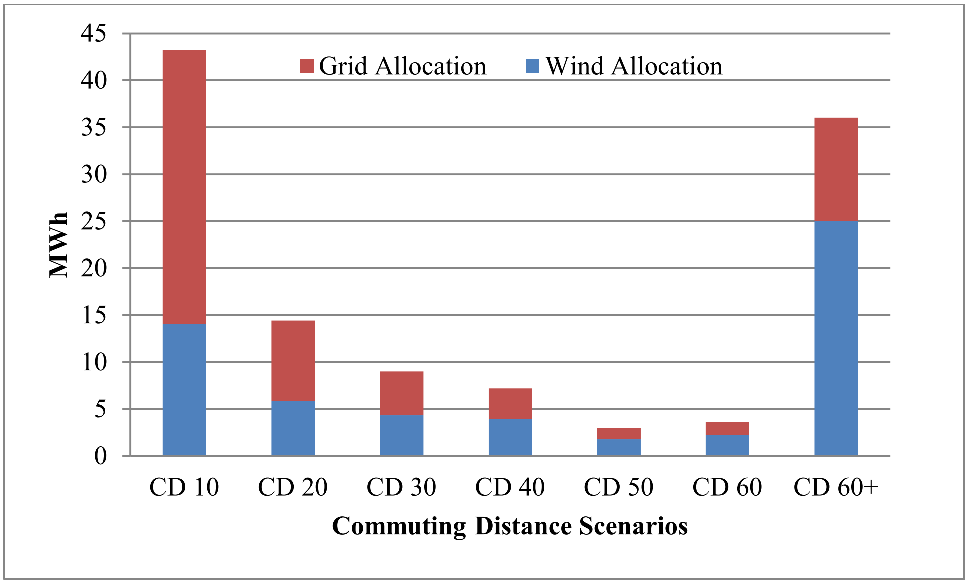

Figure 4-11: Wind and grid-electricity allocation for the Leafs

For the EV maximum-demand allocation method, the available wind-generated electricity consumed by the Leafs from all the commuting patterns was marginally less than one-half of the Leafs' annual total required demand for electricity (i.e. 57 MWh of 116.5 MWh). As the allocation for each Leaf was based on its maximum demand for the charging hour, the CD 60+ pattern had the majority share of wind-electricity due to the vehicle's maximum demand requirement.

Figure 4-12 shows the annual total greenhouse gas emissions for the Elantras and the Leafs for seven different commuting distance patterns under highway driving conditions.

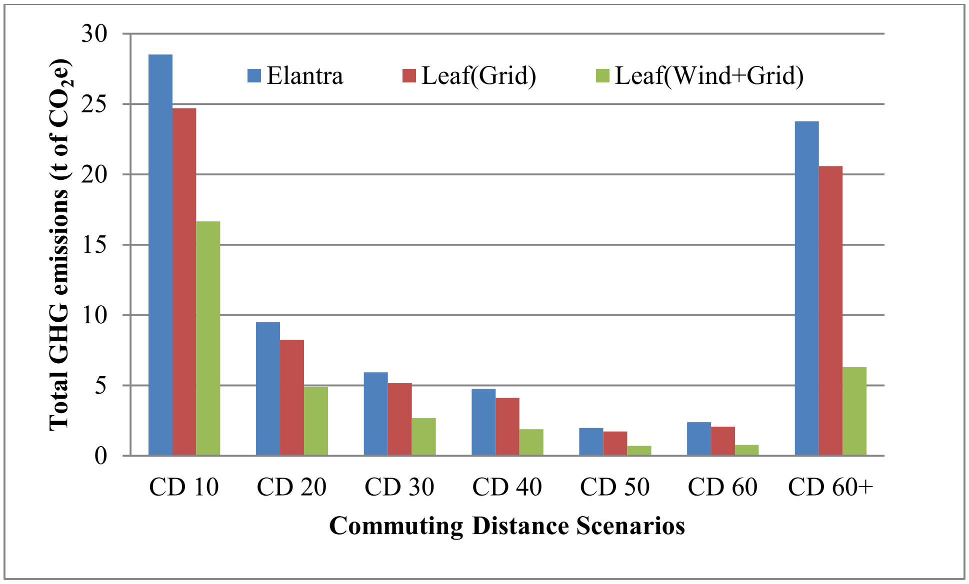

Figure 4-12: Annual total GHG emissions for the Elantras and the Leafs

In all these patterns, there is a marked decline in annual total greenhouse gas emissions for the Leafs using the available wind and grid-electricity compared to the Elantras. Since more wind-generated electricity was used by the Leafs for the CD 60+ patterns, the total amount of greenhouse gas emissions from the Leafs was about one-fifth of the total emissions from the Elantras. Also, the Leafs in the CD 60+ pattern had the most significant emissions reduction (about 18 t of CO_2e, lower) when compared to all other commuting distance patterns.

4.7.5 EV minimum-demand allocation

Figure 4-13 shows the allocation of wind and grid-electricity for the Leafs for the seven different commuting distance patterns.

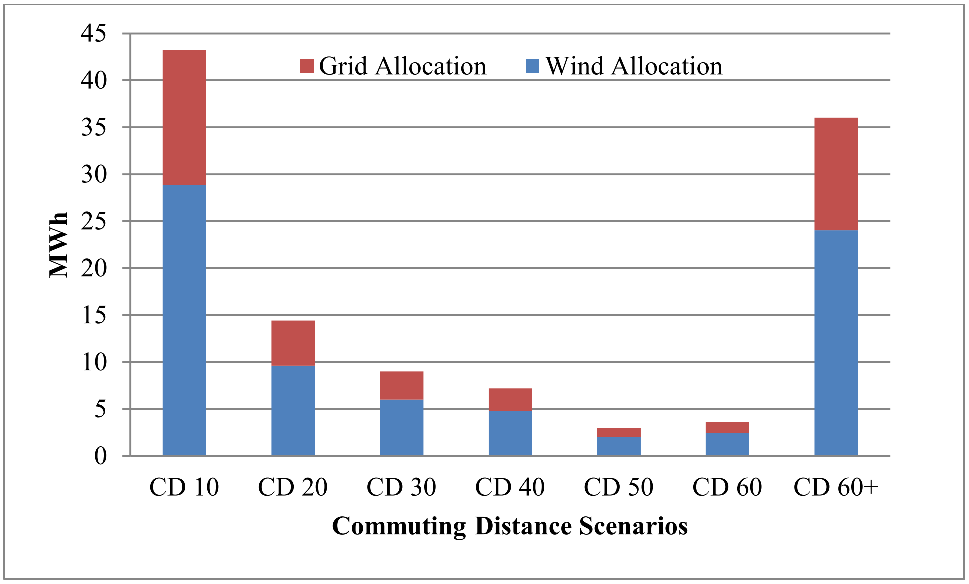

Figure 4-13: Wind and grid-electricity allocation for the Leafs

Using this method, the available wind was utilized to meet about two-thirds of the annual total required demand for electricity for the Leafs from all the commuting patterns. Any shortfall was met from off-peak grid electricity. Figure 4-14 shows the annual total greenhouse gas emissions for the Elantras and the Leafs for the seven different commuting patterns under highway driving conditions.

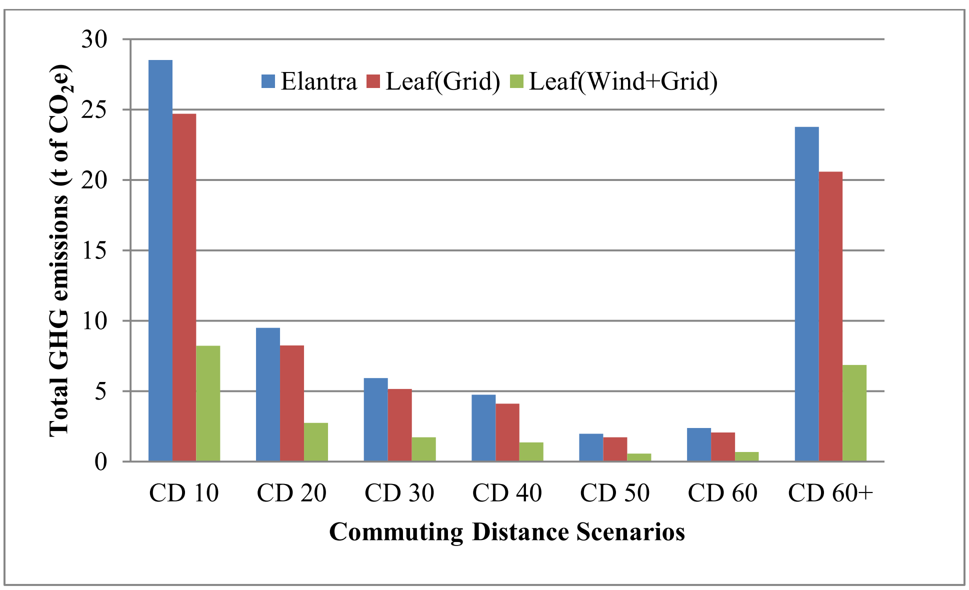

Figure 4-14: Annual total GHG emissions for the Elantras and the Leafs

As with the previous wind allocation methods, the Elantras had higher emissions than the Leaf for all the commuting patterns. In the case of charging the Leafs with the available wind and grid-electricity, they exhibited a markedly lower amount of greenhouse gas emissions than when they were charged with grid electricity only. For example, in the CD 10 pattern, when the Leafs were charged with a combination of available wind and grid-electricity, their annual total greenhouse gas emissions were less than about one-third and one-quarter of the total emissions from the Leafs using the grid-electricity and the Elantras, respectively (8.2 t of CO_2e for the Leaf (Wind+Grid), and 24.7 t of CO_2e for the Leaf (Grid); 28.5 t of CO_2e for the Elantra).

4.8 Summary

This chapter presented the rationale for the selection of Summerside as a case study and an overview of the city's electricity supply and its available wind resource. The vehicles, including both the conventional and electric vehicles, to be examined in the case study were discussed with the driving distance travelled data for Summerside. The simulations were performed for the case study for seven different commuting patterns under combined city-highway driving conditions. The results of the simulation were presented, showing the degree to which electricity generated from Summerside's wind farm was able to meet the EVs demand requirements and to reduce greenhouse gas emissions, when compared to the conventional gasoline vehicles.

CHAPTER 5 DISCUSSION

This chapter presents discussion on the results analysis for the case study simulation performed. The results of the thesis have shown that the Leafs charged using the available wind with grid-electricity as a backup has the potential to reduce a jurisdiction's vehicular greenhouse gas emissions compared to the Elantras. These results were predicated on a number of assumptions, some of which are discussed in this section.

5.1 Case study results analysis

This thesis has developed four methods to allocate available wind-electricity to charge EVs, with grid-electricity as a backup. A case study was considered to examine the proposed methods and to determine the impact of EVs on reducing greenhouse gas emissions, when compared to CVs. Figure 5-1 shows the annual total greenhouse gas emissions of the different vehicles (i.e., Elantras and Leafs) used in the case study simulation.

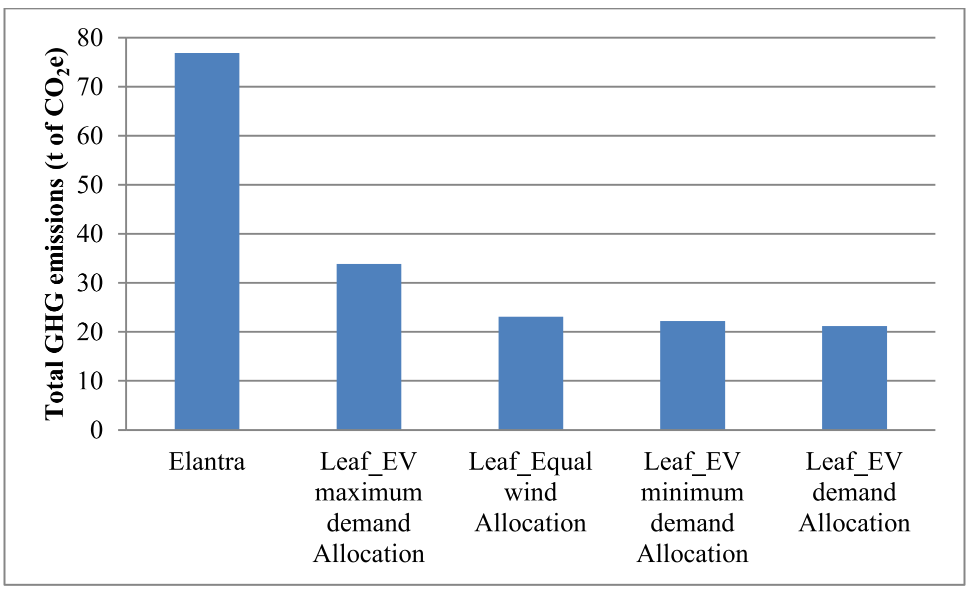

Figure 5-1: Total GHG emissions for the Elantras and the Leafs for 2010

Figure 5-1 shows that the Elantras emit more greenhouse gas than the Leafs under any of the wind allocation methods, due to their higher well-to-wheels emissions. The annual total greenhouse gas emissions associated with the Leafs using the EV maximum-demand allocation method are lower than those of the Elantras, but their emissions are considerably higher than that of the Leafs charged using other wind allocation methods.

As this method tries to charge each EV to its maximum demand for each hour regardless of its source of electricity, the utilization of wind-electricity is lower in all the commuting patterns. Despite that, the Leafs using the EV maximum-demand allocation method was able to reduce Summerside's vehicular greenhouse gas emissions by at least 43t of CO_2e, when compared to emissions associated with the Elantras.

In the case of charging the Leafs using the equal wind allocation method, the results have shown that the Leafs procured about 65% of their demand for electricity from locally available wind. As this method allocates the available wind to all vehicles in equal amounts, the CD 10 pattern with the largest number of vehicles, obtained the maximum share of wind-electricity. With this, the Leafs using equal wind allocation method reduced Summerside's vehicular greenhouse gas emissions by about 54t of CO_2e, when compared to the Elantras.

Since the level of wind-electricity in a future time-quantum is unknown, the EV minimum-demand allocation method always attempts to reduce the consumption of grid-electricity by minimizing its consumption during each time-quantum. With this, the amount of wind-electricity utilization for the Leafs using EV minimum-demand allocation method was marginally better than the Leafs using the equal wind allocation method, and reduced Summerside vehicular greenhouse gas emissions by about 55t of CO_2e, when compared to the Elantras.

Of the four wind-allocation methods considered in the simulation, the results indicate that the Leafs using the EV demand-allocation method utilized the maximum share of available wind-electricity (about 80 MWh of electricity). As this method allocates the available wind based on the EV's demand, the CD 60+ pattern, which consists of vehicles with high demand, procured a higher amount of wind-electricity compared to all other commuting patterns. Hence, the Leafs using EV demand allocation method achieved a total annual greenhouse gas emissions reduction of about 56t of CO_2e (the most significant reduction), when compared to the emissions associated with the Elantras.

Using the available wind data provided for the one-year period, 1 January 2010 to 31 December 2010, the case study results showed that the Leafs have the potential to reduce vehicular greenhouse gas emissions between 56% (from EV maximum-demand allocation method) to about 73% (from EV demand allocation method) when compared to total emissions associated with the Elantra, as shown in Table 5-1.

Since wind is a variable energy source and a jurisdiction's wind availability can change over time, the case study simulation was recalculated for another one-year period using the wind data from 1 January 2011 to 31 December 2011, to estimate how the four wind allocation methods would have performed in reducing the annual total greenhouse gas emissions. For the year 2011, the amount of wind availability for the overnight charging period was about 9% greater than that of year 2010. The following Table 5-1 shows the annual total greenhouse gas emissions for the Elantras and Leafs, when they were used for weekday commuting purposes in Summerside for 2010 and 2011.

Table 5-1: Leafs GHG emissions reductions for 2010 and 2011

		Leafs (2010)		**Leafs (2011)**	
	Elantra (t of CO_2e)	**Wind Allocation (MWh)**	**GHG emissions (t of CO_2e)**	**Wind Allocation (MWh)**	**GHG emissions (t of CO_2e)**
Equal wind Allocation	76.8	76.0	23.1	83.6	18.5
EV demand Allocation	76.8	79.5	21.1	87.0	16.6
EV max-demand Allocation	76.8	57.2	33.9	63.7	29.9
EV min-demand Allocation	76.8	77.7	22.2	84.4	18.1

In both years, the Leafs using the EV demand allocation method had the most significant annual total greenhouse gas emissions reductions (about 56t of CO_2e for 2010 and 60t of CO_2e for 2011), due to their maximum amount of wind utilization when compared to the other wind allocation methods. Similarly, the Leafs charged using the EV minimum-demand allocation method is the next best alternative in terms of both the wind utilization and annual total greenhouse gas emissions reduction (a decline in emissions by about 55t of CO_2e and 58t of CO_2e for 2010 and 2011, when compared to the Elantras).

Next, the Leafs using the equal wind allocation method exhibit marginally lower wind utilization and annual total greenhouse gas emissions reductions when compared to the Leafs using EV minimum-demand allocation method. The Leafs charged using the EV maximum-demand allocation method had the lowest greenhouse gas emissions reductions, due to the maximum utilization of grid-electricity to meet vehicles hourly maximum demand, when compared to the Leafs using other wind allocation methods. As shown in Table 5-1, the Summerside's 2011 vehicular greenhouse gas emissions were reduced by at least 47t of CO_2e (or 61%) from EV maximum-demand allocation to 60t of CO_2e (or 78%) from EV demand allocation by using Leafs with available wind-electricity. For the year 2011, the amount of annual total greenhouse emissions from the Leafs were lower in all the wind allocation methods, when compared to 2010, because of the increased wind availability.

Further to this, the four wind allocation methods can be applied and the results can be simulated for any arbitrary numbers or for forecasted wind data for any jurisdiction. For instance, in a jurisdiction that does not exhibit an above average wind regime, these methods can be used in a controlled comparison to test certain wind conditions (e.g. no wind, four hours of wind and four hours of no wind; eight hours of wind) and to determine which would be the best method to be proceed with their forecasted numbers rather than relying on results obtained from the locale which was chosen for the case study.

5.2 Grid-electricity emission intensity

The results of the case study simulation show that a significant proportion of Summerside's electric vehicles could be charged with the available wind-electricity. However, when there is no wind or during the periods of low wind availability, the vehicles are to be charged from the off-peak grid electricity. Therefore, the greenhouse gas emission intensity of the grid-electricity must be taken into consideration.

In the case of Summerside, grid-electricity was obtained from the NB Power generation facilities, where electricity generation sources included coal, natural gas, oil, hydro and renewables. The greenhouse gas emissions intensity from fossil fuel generated electricity for NB Power was estimated to be 866g of CO2e per kWh [62]. For the purpose of this study, NB Power's greenhouse gas emissions intensity from net electrical generation for the year 2010 was used. Its emissions intensity (571g of CO_2e per kWh) was moderate because of the significant contribution of hydro-electricity [62].

Since the source of energy used in the electricity generation for the overnight charging period is not readily available, this thesis has calculated the emissions associated with the EVs using the emission intensity from the net and fossil fuel electricity generation to determine the impact of the annual total greenhouse gas emissions reductions for the Leafs. Table 5-2 shows the annual total greenhouse gas emissions reductions for the Leafs using four wind allocation methods for the net and fossil fuel electricity emission intensity for the year 2010.

Table 5-2 : Leafs GHG emissions reductions

Wind Allocation Methods	Leafs GHG emissions reductions (t of CO_2e)	
	Using net emission intensity	**Using fossil fuel emission intensity**
Equal wind Allocation	54	58
EV demand Allocation	56	60
EV maximum-demand Allocation	43	47
EV minimum-demand Allocation	55	59

When measuring the Leafs' emission intensity from net electricity generation, it exhibits a considerable amount of reduction in the annual total greenhouse gas using all the wind allocation methods (about 43t of CO_2e to 56t of CO_2e, lower). When the Leafs were charged using fossil fuel generated electricity, their annual total greenhouse emissions reductions were lower than that of the Leafs using net electricity generation, because of their higher electricity emission intensity, but it still reduces the emissions from the vehicles when compared to the Elantra (about 47t of CO_2e to 60t of CO_2e, lower).

Since the greenhouse gas emissions from EVs also depend on the emissions intensity from different grid-electricity generation sources, charging the EV using grid-electricity generated from low carbon-intensive energy sources or renewables could further decrease the vehicular greenhouse gas emissions compared to CVs

5.3 Energy Security

In Summerside, passenger transportation is the most common mode of transportation. Summerside has no indigenous oil reserves or refineries [72]. It imports the majority of its refined oil products from other Canadian refineries to meet its transportation demand

[73]. This makes Summerside vulnerable to energy availability issues. Between 2006 and 2012, changing conditions in the world energy markets has caused an increase in the cost of refined oil products by over 30% in Summerside, exposing it to energy affordability issues [74]. In addition, the combustion of refined oil products for passenger transportation emits greenhouse gases, which has a detrimental effect on the environment and increases acceptability issues. Based on all this, the use of oil for passenger transportation is causing increased concerns for Summerside's energy security.

EVs are gaining attention in passenger transportation due to their increased fuel efficiency and reduced greenhouse gas emissions, when compared to CVs [14]. EVs have the capability to replace the use of refined oil products with locally generated grid-electricity. The introduction of passenger electric vehicles in Summerside could help displace the use of imported refined oil products with the electricity obtained from its domestic electric grid.

The energy sources used for the generation of grid-electricity plays a key role in determining a jurisdiction's energy security. For instance, when EVs are charged using the electricity generated from insecure carbon-intensive fossil fuels supplies, it makes a jurisdiction as vulnerable to availability and acceptability issues as it would be if it used refined oil products. Summerside has good wind resources and has a locally owned 12 MW wind farm. When EVs are charged from this locally available wind, they have the ability to displace the use of insecure fossil fuel energy sources and reduce greenhouse gas emissions.

This thesis has developed four methods to charge EVs using locally available wind-electricity to reduce a jurisdiction's vehicular greenhouse gas emission. The results of the Summerside case study simulation for the year 2010 have shown that EVs charged using available wind-electricity reduced vehicular greenhouse gas emissions by between 56% and 73%, when compared to conventional gasoline vehicles.

Each method attempts to maximize the use of the available wind at each hour for charging EVs, with a minimum amount of back-up grid electricity consumed. It was found that between 49% and 68% of the total electricity demand for the EVs could be met with the locally available wind-electricity from the Summerside wind farm, which could increases its energy security in terms of energy availability for the passenger transportation (i.e. no longer reliant on imported oil).

The increasing cost of gasoline for conventional vehicles is beginning to make electricity a more affordable source of energy for the passenger transportation, as electricity is cheaper in cost that gasoline (in most cases). In Summerside, the average cost of gasoline per litre for the year 2012 is estimated to be $1.20 [75].[12] Summerside Electric, the electricity supplier of the jurisdiction, has a declining block rate structure for its residential customers, where the first 2,000 kWh of each two-month billing period is charged at $0.12/kWh and demand exceeding that is charged at $0.09/kWh [76].

Figure 5-2 shows the annual fuel costs associated with the use of gasoline for Elantra and electricity for the Leaf for various annual commuting distances. Given that the costs of gasoline and electricity for Summerside are likely to rise based on previous years' values [75], this study has assumed a base cost of $1.20/L for gasoline and $0.12/kWh for electricity and possible increases to a maximum cost of $2.10/L for gasoline and $0.30/kWh for electricity, as shown in Figure 5-2.[13] In order to distinguish the vehicle and its fuel cost, the vehicle's name is given followed by the fuel cost; for example, Elantra $1.20 refers to the annual fuel costs for an Elantra if the price of gasoline is $1.20/L.

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[12] All monetary values are expressed in Canadian dollars.

[13] Based on the increasing trend in the cost of gasoline over past few decades, the author has assumed an increase of 25%, 50% and 75% from the base cost [75]. The same assumption is used for projecting the costs of electricity.

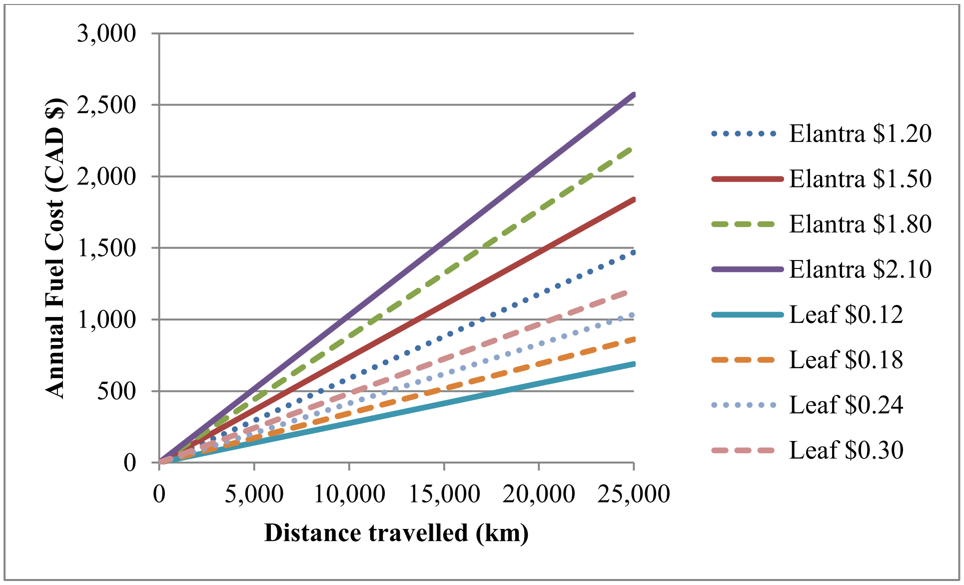

Figure 5-2 : Annual fuel costs for the Elantra and the Leaf

For all the commuting distances, the annual fuel costs associated with the Leaf are considerably lower than the annual fuel costs associated with the Elantra. This difference in the Elantra and the Leaf's annual fuel costs are more pronounced at longer annual commuting distances. For example, a Leaf $0.12 kWh driven for 5,000km and 25,000km a year would have a $156 and $781 reduction in annual fuel costs respectively when compared to an Elantra $1.20.

The thesis focused on a way to reduce greenhouse gas emissions in Summerside (i.e. acceptability). However, it is observed that the introduction of EVs charged using available wind electricity will also improve other aspects of Summerside's energy security (i.e. availability or affordability). Using EVs charged with locally available wind electricity instead of conventional gasoline vehicles could improve Summerside's energy security in terms of availability (49% to 68% of available wind-electricity) for charging EVs), acceptability (annual total emissions reduction of 56% to 73%), and also affordability (an annual fuel cost savings of up to $781).

5.4 Case study vehicles

Today, the vast majorities of passenger vehicles are conventional vehicles and are classified into various types, such as compact cars, mid-sized cars, full size cars, mini-vans and pick-up trucks [63]. While only a limited number of passenger electric vehicles exist, they are growing in number and are becoming more available throughout Canada.

In Summerside, the most common mode of travelling to work is the light duty passenger vehicle. According to the 2006 Census of Population, approximately 5,675 passenger vehicles are driven in Summerside. There is no easy way of determining the vehicle type (i.e., car, truck, or van) as vehicles registrations are classified by weight [70].

For the purpose of the case study simulation, the conventional gasoline vehicle chosen to be used is the Hyundai Elantra. The Hyundai Elantra with manual transmission is one of the most fuel-efficient mid-sized conventional vehicles in Canada [76]. The Nissan Leaf is chosen as the mid-sized electric vehicle to be used in the case study simulation. The Leaf was chosen as it represents the closest pure electricity powered mid-sized vehicle to the conventional Hyundai Elantra.

In order to maintain consistency in the analysis, it was necessary to focus on a single classification of vehicle (i.e. mid-sized vehicles). The analysis of all the types of vehicle would be unwieldy. However, when the actual classification of passenger vehicles data is available for Summerside, it would be advisable to revisit the calculations and results found in this thesis. While this case study used mid-sized vehicles and its data to simulate the results, the general approach of this thesis can be applied to all types of vehicles classification.

5.5 Wind profile

The average hourly wind data for the case study simulation was obtained from Summerside's 12MW wind farm. The wind-electricity generation output profile varies from 0 to 12 MW based upon the wind availability. Figure 5-3 shows an excerpt of the hourly wind data for 21 January 2010 from the Summerside wind farm. On most days during 2010, the wind output was higher during the overnight hours when compared to the rest of the day.

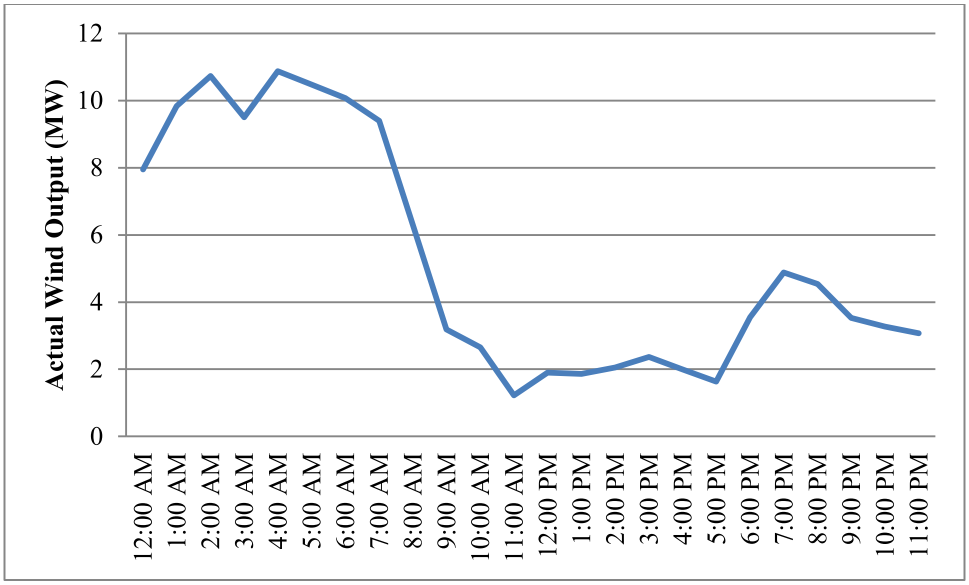

Figure 5-3: An excerpt of actual wind profile data

For the purpose of this research, the actual hourly wind data profile was scaled down to match the level of electricity generation required to meet the maximum hourly demand from all the Leafs. For simplicity, maximum hourly demand from all the Leafs was estimated as 300kWh and the scaled wind-generated electricity values range from 0 to 300kWh, representing zero to full output of the wind farm (i.e. 0 to 12MWh).

In addition, the data used in this analysis was assumed to include any transmission or conversion losses associated with the generation of wind-electricity.

5.6 Well-to-Tank emissions

In this analysis, the well-to-tank greenhouse gas emissions for the Elantra were not publicly available; therefore, the values for the simulation were assumed from the EPRI report for the United States [21]. However, the well-to-tank emissions vary from jurisdiction to jurisdiction and from year to year, and are based upon the sources of the crude oil, the method of transporting them, the quality of the crude, and its refining process. For example, emissions associated with production and refining for conventional light-sweet crude were considerably lower than the emissions associated with heavy crude oil or tar sands. Therefore, when the well-to-tank emissions data is available for any jurisdiction, it would be advisable to use those values in the simulation.

5.7 Time quantum

The available wind data obtained from the Summerside wind farm has a granularity of one hour. Therefore, the time quantum used in this case study simulation was considered to be a one-hour time interval. The four wind allocation methods used in this thesis are not restricted to the hourly wind data obtained from Summerside. When minute by minute and second by second data points are available for wind generation output, it would be advisable to revisit the calculations and results found in this thesis. Overall, a shorter time interval allows the method to re-allocate the available wind-electricity to the remaining EV units more effectively and thereby decrease the amount of surplus wind-electricity.

5.8 Summary

This chapter presented a discussion on the results analysis and assumptions made for the case study simulation. It is observed that the assumptions can vary from jurisdiction to jurisdiction and have a direct influence over the obtained results. The following chapter presents the thesis' concluding remarks, limitations, and suggestions for future work.

CHAPTER 6 CONCLUDING REMARKS

The effects of global climate change and energy security will be two of the most significant challenges affecting people and the environment this century. In order to address these challenges, many jurisdictions are adopting policies and standards to increase the share of locally available renewable energy into their energy mix.

Recently, EVs have been gaining attention due to their increased energy efficiency, and their potential to reduce vehicular greenhouse gas emissions by displacing the use of refined oil products with electricity. Nevertheless, the amount of greenhouse emissions reduction from EVs are determined by the carbon intensity of the energy sources used in the electricity generation, such as coal, oil, natural gas or renewables.

Wind is a renewable energy source and is available freely in nature. The electricity generated from wind is clean and carbon-free. When EVs are charged with wind-generated electricity, the vehicle produces no emissions at all. However, wind is variable in nature and wind-electricity generation is based on the availability of wind. This poses a significant challenge for charging EVs with wind-generated electricity and their potential to reduce vehicular greenhouse gas emissions.

Taking this into consideration, the objective of this thesis was to develop methods to analyze the impact of EVs on reducing a jurisdiction's vehicular greenhouse gas emissions using available wind-electricity. The methods include a well-to-wheels analysis to determine the amount of greenhouse gas emissions of the EVs and CVs for a given distance travelled. As the emissions associated with an EV depend upon the wind utilization, four different wind allocation methods were proposed to charge EVs using available wind, with some form of backup from grid-electricity: equal-wind allocation, EV demand-allocation, EV maximum-demand allocation, and EV minimum-demand allocation. In order to verify the methods, a case study simulation was implemented using Microsoft Office Excel 2007 and VBA.

The City of Summerside, P.E.I. was chosen as the location for the case study because of its abundant wind resource. For this study, the Hyundai Elantra and the Nissan Leaf were chosen as an example of a standard mid-sized passenger conventional gasoline vehicle and an electric vehicle, respectively. The four methods were applied to weekday commuting patterns. For the Leaf, simulation was conducted for overnight charging period, from 23:00hrs to 07:00hrs, inclusive, with a combination of wind and grid-electricity. In this analysis, average hourly wind-data was obtained from Summerside's wind farm along with the driving distance pattern data from Statistics Canada. With this, the well-to-wheels greenhouse gas emissions analysis was conducted for the Elantras and the Leafs for a one-year period.

From the results of the simulation, it is clear that the emissions associated with the Elantras are higher than those of the Leafs under each of the wind allocation methods in all the commuting patterns. Of the four different wind allocation methods considered in the simulation, the results indicate that the EV demand-allocation method utilized the maximum share of available wind-electricity and achieved a considerable reduction in greenhouse gas emissions. The EV minimum-demand allocation method was the next best alternative in both the utilization of available wind and the annual total greenhouse gas emissions reduction. Similarly, the results show that the equal wind allocation method substantially reduces greenhouse emissions, but it is inferior to the EV minimum-demand allocation method. Since the EV maximum-demand allocation method utilized a lower amount of the available wind compared to the other wind allocation methods, its greenhouse gas emissions reduction was less significant. Although the EV maximum-demand allocation was the least desirable method, its greenhouse gas emissions reduction was still better than operating conventional gasoline vehicles.

The simulations showed that between 49% and 68% of the electricity demand from the Leafs could be met with the available wind-electricity from Summerside. Although this reduces vehicular greenhouse gas emissions, the amount of emissions reduction depend on the greenhouse gas emissions-intensity of the grid-electricity. When comparing the Leafs to the Elantras, vehicular greenhouse gas emissions were reduced by at least 56% (from the EV maximum-demand allocation method) to a maximum of 73% (from the EV demand allocation method) in Summerside.

The work presented in this thesis showed that EVs using wind-electricity have the potential to reduce a jurisdiction's vehicular greenhouse gas emissions when compared to conventional gasoline vehicles and to improve a jurisdiction's energy security. As the overall greenhouse gas emissions reduction from EVs also depend upon grid-electricity, the utilization of less-carbon intensive energy sources or renewables in the generation of grid-electricity could further decrease vehicular greenhouse gas emissions.

6.1 Limitations

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

- In this research, the well-to-wheels greenhouse gas emissions comparison was limited to conventional gasoline vehicles and electric vehicles; hybrid gasoline and hybrid gasoline-electric vehicles were not considered.
- The methods in this thesis are limited to Level 1 and Level 2 EV charging only; they do not apply for Level 3 charging (i.e. fast charging).
- The results of the simulation are location specific; which in Summerside's case exhibited a good wind regime.
- Transmission or distribution losses associated with the generation of wind or grid-electricity for EV wind charging was not considered in this case study analysis.

6.2 Future work

This thesis shows that EVs have a potential to reduce a jurisdiction's vehicular greenhouse gas emissions using locally available wind-electricity. It is worthwhile to carry out further research to enhance the existing methods and their results:

- The integration of smart-grid technology with the EVs should be considered since smart grid systems have the capability to match the EVs demand to the real-time condition of the electricity generated from the available wind, or grid.
- Any surplus wind-electricity could be used for other energy services, such as electric thermal storage (ETS) for heating or coupled with grid-electricity to meet the needs of on-demand electricity.

- With more accurate wind-forecasting techniques, the back-up reserves from grid electricity for the EV wind allocation can be better planned (such as generation of grid-electricity from low carbon-intensive energy sources, or from storage) to avoid the peak demand and to reduce grid-related greenhouse gas emissions.
- Ideally, the methods developed in the thesis could be used as part of a pilot study utilizing wind-generated electricity and EVs to verify the validity of the observations.
- The existing methods and their software simulation tools in this thesis could be modified and used with other variable renewable energy sources, such as solar energy to perform the analysis.

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