THE POTENTIAL IMPACTS OF A HIGH PENETRATION OF ELECTRIC VEHICLES ON THE NEWFOUNDLAND TRANSMISSION SYSTEM

By

© Matthew Paul Carter, B.Eng, P.Eng, MBA

A thesis submitted to the School of Graduate

Studies in partial fulfillment of the

Requirements for the degree of

Master of Engineering

Faculty of Engineering and Applied Science

Memorial University of Newfoundland

May 2020

St. John's Newfoundland and Labrador Canada

Abstract

The deployment of electric vehicles is expected to drastically increase throughout the developed world for the foreseeable future. This trend is attributed to the growing acceptance of electric vehicles driven by the emergence of numerous environmental, economic and technical incentives promoting their adoption. This revolutionary change will likely have a monumental impact on most power systems. A large scaled uptake of electric vehicles could also prove beneficial as they have the capability to instantaneously supply active and reactive power back to the grid using Vehicle-2-Grid technology.

This thesis will focus on the Newfoundland Transmission System and investigate the positive and negative impacts associated with a high penetration of electric vehicles. Load flow and power system stability simulations were performed using PSS®E to support this investigation by quantifying the effect of varying levels of electric vehicle penetration in the province. The results of the load flow analysis concluded that, in the absence of any demand-side management strategies, substantial system capacity upgrades would likely be required to avoid jeopardizing system reliability.

The power system stability analysis revealed that a large amount of electric vehicles with Vehicle-2-Grid capability could collectively be utilized to minimize or avoid under frequency load shedding following the sudden loss of the Labrador Island-Link HVdc bipole. A strong correlation was discovered between the net total of HVdc power imports/exports (Net DC) and the total number of connected electric vehicles that would be required to avoid under frequency load shedding on the Island Interconnected System.

This investigation has ultimately demonstrated that without the necessary power system integration or demand-side management strategies, a high penetration of electric vehicles in Newfoundland could lead to needless capital expenditures. Newfoundland and Labrador Hydro would also forgo the benefits of improved frequency response provided through Vehicle-to-Grid technology.

Acknowledgments

First and foremost I'd like to thank my wife, Kara, who has demonstrated incredible patience and selflessness throughout this academic journey in providing the much appreciated support and motivation. I am also extremely grateful to my parents for their constant encouragement, instilling in me a strong work ethic and providing the endless opportunities that have led to my success.

I would like to express my sincere gratitude to my graduate supervisor, Dr. Benjamin Jeyasurya, for providing invaluable guidance and insight. Special thanks go to my former graduate supervisor, the late Dr. Md Azizur Rahman, whose positive attitude and incredible passion in his field provided me with the inspiration to go above and beyond my own expectations.

Finally, I must recognize my colleagues at Newfoundland and Labrador Hydro for their advice and support throughout this process and my employer for providing the necessary resources to perform the analysis compulsory for this thesis.

Matthew P. Carter

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AC:	**Alternating Current**
ACCC:	**AC contingency calculation**
AGC:	**Automatic Generation Control**
BBK:	**Bottom Brook**
BCV:	**Bear Cove**
BCX:	**Barachoix**
BDE:	**Bay d'Espoir**
BEV:	**Battery Electric Vehicle**
BHL:	**Berry Hill**
BUC:	**Buchans**
BWT:	**Bottom Waters**
CARB:	**California Air Resources Board**
CAT:	**Cat Arm**
CBC:	**Come by Chance**
CDM:	**Conservation and Demand Management**
CEA:	**Canadian Electricity Association**
CFLco:	**Churchill Falls Labrador Corporation Limited**
CHD:	**Cow Head**
CO_2:	**Carbon Dioxide**
CPV:	**Cumulative Present Value**
CRV:	**Conne River**
DC:	**Direct Current**
DHR:	**Daniel's Harbour**
DLK:	**Deer Lake**
DMV:	**Department of Motor Vehicles**
DSM:	**Demand Side Management**
EHW:	**English Harbour West**
EMC:	**Electric Mobility Canada**
EV:	**Electric Vehicle**
EVSE:	**Electric Vehicle Supply Equipment**
EVI:	**Electric Vehicles Initiative**
FHD:	**Farewell Head**
G2V:	**Grid-to-Vehicle**
GBK:	**Grandy Brook**
GBY:	**Grand Bay**
GHG:	**Greenhouse Gases**
GLB:	**Glenburnie**
GNP:	**Great Northern Peninsula**
HDV:	**Heavy-Duty Vehicle**
HEV:	**Hybrid Electric Vehicles**
HLY:	**Howley**
HPN:	**Hampden**
HRD:	**Holyrood**
HWD:	**Hardwoods**
HVdc:	**High Voltage Direct Current**
ICEV:	**Internal Combustion Engine Vehicles**
IEA:	**International Energy Agency**
IGBT:	**Insulated-Gate Bipolar Transistor**
IIS:	**Island Interconnected System**
JAM:	**Jackson's Arm**
LAB:	**Labrador**
LCC:	**Line Commutated Converter**

LDV:	**Light-Duty Vehicle**
LIL:	**Labrador-Island Link**
LIS:	**Labrador Interconnection System**
MBK:	**Main Brook**
MDV:	**Medium-Duty Vehicle**
MDR:	**Massey Drive**
ML:	**Maritime-Island Link**
MSRP:	**Manufacturer's Suggested Retail Price**
N-0	**Pre-contingency**
N-1:	**Single Contingency Event**
N-2:	**Double Contingency Event**
NASA:	**National Aeronautics and Space Administration**
NCA:	**Nickel Cobalt Aluminum**
NERC:	**North American Electric Reliability Corporation**
NFLD:	**Newfoundland**
NLSO:	**Newfoundland and Labrador System Operator**
NL:	**Newfoundland and Labrador**
NLH:	**Newfoundland and Labrador Hydro**
NLP:	**Newfoundland Power**
NMC:	**Nickel Manganese Cobalt**
NPCC:	**Northeast Power Coordinating Council**
NRCAN:	**Natural Resources Canada**
NS:	**Nova Scotia**
NUGs:	**Non-Utility Generators**
O&M:	**Operating and Maintenance**
OLTC:	**On-Load Tap Changer**
OPD:	**Oxen Pond**
PBN:	**Peter’s Barron**
PEV:	**Plug-in Electric Vehicle**
pf:	**Power Factor**
PFC:	**Power Factor Correction**
PHEV:	**Plug-in Hybrid Electric Vehicle**
PPD:	**Parson’s Pond**
PPT:	**Plum Point**
P-Q:	**Active – Reactive Power**
PSSs:	**Power System Stabilizers**
PSS®E:	**Power System Simulator for Engineer**
pu (or p.u.)	**Per Unit**
PUB:	**Public Utilities Board**
RHR:	**Rocky Harbour**
ROCOF:	**Rate of Change of Frequency**
RWC:	**Roddickton**
SBK:	**South Brook**
SOP:	**Soldiers Pond**
SPS:	**Special Protection Scheme**
SSD:	**Sunnyside**
STA:	**St. Anthony**
STB:	**Stony Brook**
SUV:	**Sport Utility Vehicles**
SVC:	**Static Var Compensator**
SVL:	**Stephenville**
T:	**Transformer**
TCO:	**Total Cost of Ownership**
TL:	**Transmission Line**
TOD:	**Time of Day**
TOU:	**Time of Use**

UFLS: Under-frequency Load Shedding
V1G: See G2V
V2G: Vehicle-to-Grid
V2H: Vehicle-to-Home
V2V: Vehicle-to-Vehicle
VSC: Voltage Sourced Converter
WAV: Western Avalon
WDL: Wiltondale
ZEV: Zero Emissions Vehicle

List of Symbols/Units

A	Amp
CO_2-eq	Carbon dioxide equivalent
f_0	Nominal Frequency [Hz]
df/dt	Rate of Change of Frequency (ROCOF)
Δ	Change/Delta
Hz	Hertz
J	Moment of Inertia [$kg.m^2$]
km	Kilometer
kW	Kilo-Watt
kWh	Kilo-Watt Hour
kV	Kilo-Volt
kVA	Kilo-Volt Ampere
$P_m(t)$	Mechanical Power [W]
$P_e(t)$	Electrical Power [W]
P_f	Number of Generator Poles
P_{LIL}	LIL Power Flow [MW]
P_{ML}	ML Power Flow [MW]
H_{sys}	System Inertia [MW*s]
H_{gen}	Inertia Constant for a single generator [MW*s]
MVA	Megavolt-Ampere
MVAR	Mega-Var
MW	Mega-Watt
MWh	Mega-Watt Hour
η:	Mechanical speed
TWh	Tera-Watt Hour
V	Volt
Vac	AC Voltage
Vdc	DC Voltage
VA_{base}:	Apparent Power
VAR:	Var
W:	Watt
Wh:	Watt Hour
ω:	Angular velocity [rad/s]

Chapter 1

Introduction

The global requirement for energy has grown substantially in recent history due to the steady increase in the world's population and widespread economic development. This trend has intrinsically presented a common challenge for all power utility companies, like Newfoundland and Labrador Hydro ("NL Hydro"), since their mandate is to supply energy to all residential, commercial and industrial facilities throughout the province. A key function of any utility is to ensure their power system can support forecasted demand and energy requirements for the conceivable future. In the absence of this proactive approach, power system reliability would eventually become jeopardized due to the unaddressed equipment overloads, poor power quality and abnormal voltage conditions.

The automotive and transportation industry is another sector that is energy intensive and makes a significant contribution to the global demand for energy. The predominant source of energy that propels most types of vehicles comes in the form of fossil fuels. Unfortunately the combustion process of fossil fuels releases harmful emissions into the earth's atmosphere, promoting global warming which is consequentially stimulating climate change.

These environmental concerns along with other factors, such as advancements in battery technology and changing government policy, are triggering the escalation of the widespread adoption of Electric Vehicles (EVs). The increased popularity or acceptance of EVs could have a positive or negative impact on a power grid depending on how they are integrated. The increased demand associated with the connection of multiple charging EVs to a power grid will naturally put added stress on equipment and reduce power quality, likely advancing the need for system upgrades. A massive deployment of EVs throughout a power system can also provide technical advantages, since they have the ability to discharge their batteries and supply power back to the grid assuming they have the appropriate charging equipment. More specifically, this capability provides power utilities with the additional means to help improve power quality, regulate system frequency, shave peak demand and better accommodate the integration of renewables.

1.1 Aim of Thesis

The intent of this thesis is to investigate the potential impacts that a high penetration of EVs could have on the Newfoundland transmission system (66 kV and above). Load flow and transient stability analysis will be performed to quantify the positive and negative effects of varying amounts of connected EVs proportionally distributed across the province. The results of this analysis will generate recommendations that could give NL Hydro valuable insight into the possible consequences and opportunities attributed to a massive adoption of EVs in Newfoundland. The power system studies presented in this thesis will exclusively focus on battery electric vehicles (BEV), which are EVs solely powered by batteries.

The scope of this analysis will be purely technical and primarily focus on NL Hydro owned assets within the Island Interconnected System (IIS) and will not study the impacts on the Labrador Interconnected System. Some of the technical information provided in this thesis, as it pertains to the IIS, is not openly available. The author is employed by NL Hydro as a Transmission Planning Engineer and has access to this technical information not in the pubic domain.

1.2 Thesis Outline

Chapter 2 of this thesis gives the reader a sense of the current landscape and anticipated future outlook of the international, national and local EV markets. The future trends discussed in this chapter will help establish the study assumptions that will guide the power system analysis in subsequent chapters of this thesis.

Chapter 3 provides a comprehensive description of the Newfoundland and Labrador power system. The overview of the system being studied is essential for the reader to comprehend the power system analysis which is the focal point of this thesis.

Chapter 4 is a literature review of EVs, emphasizing on power system integration and the use of smart grid technology for the battery charging and discharging process. The cumulative effect of applying this concept to multiple EVs can positively influence the day-to-day operation of a power grid, however if not correctly implemented it could present challenges to the power system operator. This chapter will conclude with a description of various opportunities and challenges faced by utilities with respect to the simultaneous connection of multiple EVs on their grid.

Chapter 5 is a preamble dedicated to the load flow and power system stability analysis conducted in proceeding chapters. It will include the study assumptions, case descriptions and methodology surrounding the power system analysis.

Chapters 6 and 7 will summarize the results of the load flow and power system stability analysis, respectively. The load flow analysis will identify capacity upgrades associated with various EV penetration levels without consideration of demand-side management strategies including Time-of-Day Rates or utility EV coordinated charging. The power system stability analysis will quantify the benefits of Vehicle-to-Grid technology and how it can reduce under frequency load shedding following the sudden loss of an HVdc bipole link at high power flows.

Chapter 8 will provide conclusions and recommendations based on the results of the load flow and power system stability analysis. The chapter will also highlight the key contributions to research and suggest future research topics that could build on the theme of this thesis.

Chapter 2

Electric Vehicle Industry Outlook

2.1 Introduction

The primary objective of this chapter is to provide the reader with a sense of the current landscape and anticipated future outlook of the international, national and local EV markets. The future trends of these EV markets will help establish the study assumptions that will guide the power system analysis performed in Chapters 6 and 7. This discussion will begin with a short summary on the history of the EV, since it is essential for the reader to understand the past before they can appreciate the present state and future projections of the industry. This will be followed by an overview of some of the factors that presently promote and deter the acceptance of the EV.

2.2 The History of the Electric Vehicle

The automobile is without question one of the most influential and practical inventions of our time. Since its inception at the turn of twentieth century, the car has made the world a much smaller place. It has given society the luxury of commuting at faster speeds and has provided the opportunity and incentive for people to travel further and more often.

The traditional internal combustion engine vehicles (ICEV) have historically dominated the industry, even though the EV has been in existence for over 130 years [1]. The Benz Patent-Motorwagen, a vehicle powered by an internal combustion engine, is universally regarded as the first automobile and was invented in the year 1884 [1]. The first practical EV was actually developed two years prior by English inventor Thomas Parker which was shortly after the invention of its two key components, the electric motor and the battery [1].

At the beginning of ninetieth century the EV was much more popular in comparison to the ICEV. This trend was changed by the creation of mass production and the assembly line which caused the gasoline car to prevail as the frontrunner of the automobile industry [1]. These cost effective manufacturing techniques were popularized in the early twentieth century by Ford Motor Company when they manufactured the 1908 Model T [2]. The EV could not compete and the ICEV has dominated the market ever since.

The EV was essentially nonexistent for the next half century until the arrival of small scale EVs in the late 1950s [1]. The performance of these small more compact vehicles was inferior in comparison to its competitors and consequently this evolution only lasted for a couple decades. However, in the 1990s the interest for EVs was reborn due to high gas prices and new government environmental regulations to minimize harmful gas emissions released during the combustion of fossil fuel [1]. The state of California passed the Zero Emission Vehicle (ZEV) mandate in 1990 in an attempt to mitigate their air pollution problem [3]. This new legislation forced automakers operating in California to sell a certain percentage of Zero Emission Vehicles each year [1]. Approximately 20 percent of the states in America would also adopt the ZEV mandate [1].

General Motors decided to comply with the ZEV mandate and developed the high performing EV1, the first mass produced or mainstream EV in the modern era developed by a major automaker company [1]. The EV1 was made available only through lease agreements for a select few locations in the United States, which included the state of California [3]. A total of approximately 1,100 units were produced over a three year period from 1996 to 1999 [3].

By the early 2000s California and the other US states supporting ZEV were forced to drop the mandate due to pressure from automakers who argued the policy was too strict and would adversely affect profits from their core business [3]. There was originally a compromise and EVs were to be developed in accordance with customer demand [3]. Automakers performed minimal EV advertising and even practiced the approach of de-marketing and essentially there was no true concession [3]. The hydrogen fuel cell also started to emerge as viable source of energy that was considered a zero emission vehicle [3].

General Motors seized the production of the EV1 in 1999 and the ZEV Mandate was completely lifted on April 24, 2003 [3]. All the lease agreements for the EV1s were terminated and owners were forced to return their vehicle or there would be legal consequences [3]. A large percentage of the 1,100 EV1s were destroyed by General Motors [3].

The popular and contentious documentary film, "Who Killed the Electric Car?" highlighted the demise of the EV1. This documentary suggests that the death of the EV in the late 1990s was caused by the following suspects [3]:

- **Consumers:** A lack of awareness or knowledge of the EV limited customer demand.
- **Oil Companies:** The massive deployment of EVs would drastically reduce their profits since they held a monopoly over transportation fuel. Oil companies argued that EVs were not as environmentally friendly as advertised and that tax payers would take the burden of paying for charging infrastructure.
- **Car Companies:** There was fear that the marketing of the EV would weaken their traditional business and result in a decline in overall profits. They were also concerned the revenue stream associated with their service departments would see a substantial decrease since EVs require much less maintenance.
- **Government:** There is a tendency for government policy to be strongly influenced by the oil and automobile industries. There was also limited EV support by the general public at the time; certainly not enough to put pressure on politicians.
- **California Air Resources Board (CARB):** They cancelled the ZEV mandate in hopes of better alternatives to replace the EV.

- **Hydrogen Fuel Cell:** In the late 1990s CARB suspected that this form of technology would be a superior substitute to the EV. It was later determined to be inferior in comparison to the EV, due to the limited access of hydrogen and the lack of costly charging infrastructure.

The EV industry remained dormant until the late 2000s, a time when gas prices were soaring and the desire to confront the global warming crisis became more of a priority [1]. Tesla, Inc., an American automaker has led the charge on this second revival of the EV [1]. The following section will provide more insight into why there has been a recent resurgence of the EV and will also discuss some of the barriers still faced by the industry.

2.3 The Modern Acceptance of the Electric Vehicle

There historically has been some reluctance in accepting the EV, as alluded to in the previous section. In recent years EVs have become more popular and are starting to capture more of the market share. This section will discuss some of the incentives and existing barriers influencing the adoption rate of EVs.

2.3.1 Environmental Incentives

The automobile has generally served the greater good, but it has come with its shortcomings, most notably the negative effect they collectively have on the environment. The typical engine of an ICEV uses gasoline or diesel as its fuel that when combusted releases harmful emissions in the form of greenhouse gases (GHG), including carbon dioxide (CO_2). Greenhouse gases form a barrier in the atmosphere which allows the entry of light, but prevents its departure. This phenomenon causes heat to be trapped in the atmosphere creating a greenhouse effect known as global warming.

The majority of the science community hypothesizes that global warming is causing climate change which is posing a serious risk to the well-being of mankind that must be mitigated [4]. Figure 2-1 is a plot provided by the National Aeronautics and Space Administration (NASA) showing the global temperature anomaly from 1880 to 2020 [5]. Temperature anomaly is the deviation from the average temperature and a metric often used to assess the warming of the earth. Figure 2-1 shows an upward trend of temperature anomaly over the pasted 130 years, which is evidence that suggests the existence of global warming. Some studies also suggest that these emitted greenhouse gases are also having a negative impact on human health [3] [6]. Consequently, the evidence has motivated society to execute initiatives to reduce the emission of greenhouse gases.

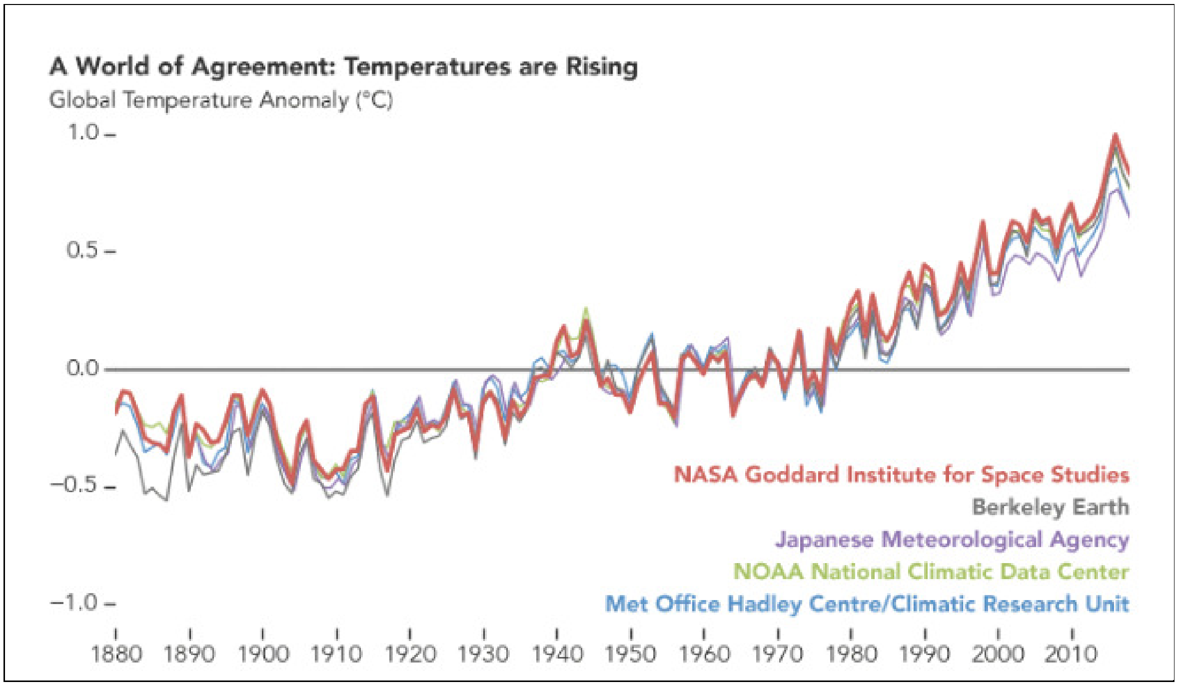


Figure 2-1: Global Temperature Anomaly (°C) (1880-2020)
Source: NASA [5]

The transportation industry has been a large contributor of the release of CO_2 emissions into the earth's atmosphere which is clearly evident from Figure 2-2. This trend has inspired the pursuit of a more cost effective replacement for the ICEV in an attempt to reduce the overall emissions of CO_2. The EV is currently the best substitute from an environmental and technical perspective, as it comparatively has a much smaller carbon footprint and its performance closely matches that of a conventional vehicle. Battery and charging technology is advancing to the point where EVs will soon technically perform at the same level as conventional vehicles [7]. Figure 2-3 illustrates that over its life span, an EV on average emits approximately 10 tonnes of CO_2 (t CO_2-eq) less than an ICE [7].

The idea of human-caused global warming is currently an extremely controversial and divisive subject that is not completely accepted, although there has been extensive amount of scientific evidence to prove its existence. Traditionally the lack of full support has impeded or deterred government policy making in this area. However, in recent years there has been a stronger push by government administrations throughout the world to combat global warming, which will be discussed in further detail in the following section.

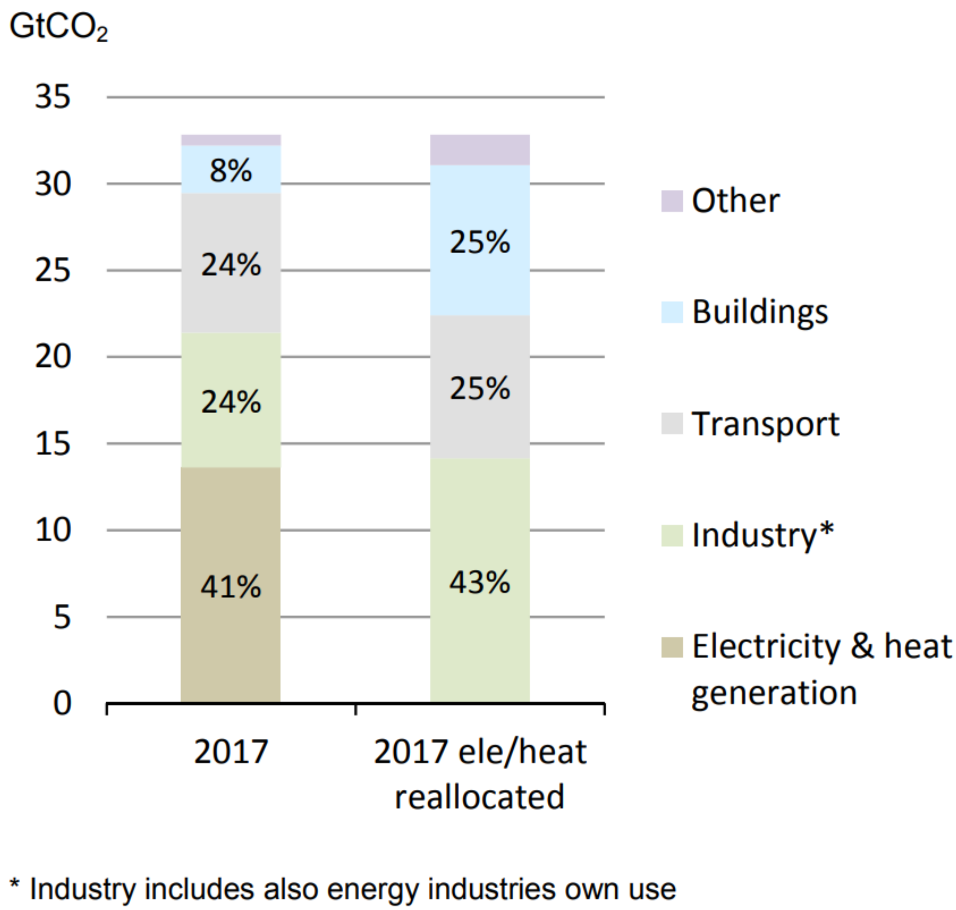


Figure 2-2: Global CO_2 Emissions by Sector, 2017
Source: IEA [8]

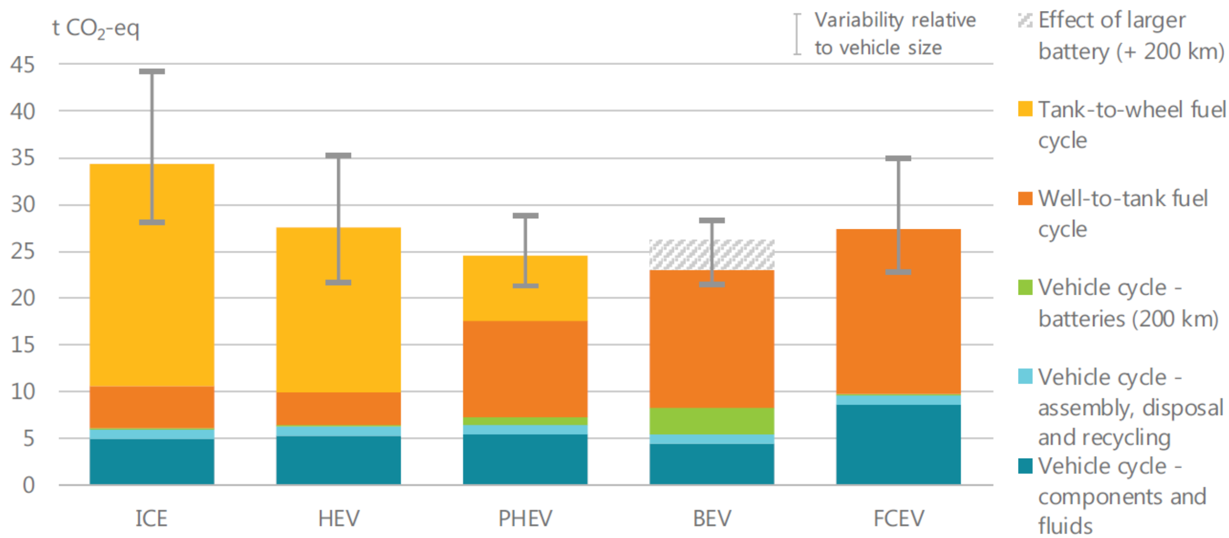


Figure 2-3: Comparative Life-cycle GHG Emissions by Powertrain (Mid-size Vehicles), 2018
Source: IEA [7][1]

2.3.2 Government Policy

The formation of government policy can be an effective mechanism that administrations can use to influence consumer behavior. The threat of global warming and the growing interest in EVs are pressuring governments to create policies to promote the purchase and support the operation of EVs. The countries that are leading the charge in EVs have established targets, regulations, standards and incentives to help accelerate the deployment of EVs. Table 2-1 provides a policy summary for specific regions as it relates to EVs [7]. Some of the more successful or advanced countries in the area of EVs, like Norway, are phasing out some of their policies because they have reached their targets [7]. Section 2.4 will discuss the current landscape and expected future trends of the EV industry from an internationally, nationally and local perspective. This discussion will provide more specifics on some of the current policies established by the specific jurisdictions.

[1] IEA 2019. All rights reserved. Notes: The BEV refers to a vehicle with 200 km range; the addition of the shaded area refers to a vehicle with 400 km range. The ranges suggested by the sensitivity bars represent the case of small cars (lower bound) and of large cars (upper bound) – for BEVs, the lower bound of the sensitivity bar represents a small car with a 200 km range, and the upper bound represents a large car with a 400 km range. The carbon intensity of the electricity mix is assumed equal to the global average (518 g CO2/kWh). FCEVs are assumed to rely entirely on hydrogen produced from steam methane reforming. Other assumptions used to develop this figure are outlined in the Chapter 4 of the Global EV Outlook 2019, focused on life-cycle GHG emissions [7].

Table 2-1: EV-Related Policies/Standards/Incentives in Selected Regions. Source: IEA [7]

Policies/Standards/Incentives		Canada	China	EU	India	Japan	USA
Regulations (vehicles)	ZEV Mandate	✓*	✓				✓*
	Fuel economy standards	✓	✓	✓	✓	✓	✓
Incentives (vehicles)	Fiscal incentives	✓	✓	✓	✓		✓
Targets (vehicles)	-	✓	✓	✓	✓	✓	✓*
Industrial policies	-	✓	✓			✓	
Regulations (chargers)	Hardware standards**	✓	✓	✓	✓	✓	✓
	Building regulations	✓*	✓*	✓	✓		✓*
Incentives (chargers)	Fiscal incentives	✓	✓	✓		✓	✓*
Targets (chargers)	-	✓	✓	✓	✓	✓	✓*

* Indicates that the policy is only implemented at a state/province/local level..
** Standards for chargers are a fundamental prerequisite for the development of EV supply equipment. All regions listed here have developed standards for chargers. Some (China, European Union, India) are mandating specific standards as a minimum requirement; others (Canada, Japan, United States) are not.

Notes: Check mark indicates that the policy is set at national level. Building regulations refer to an obligation to install chargers (or conduits to facilitate their future installation) in new and renovated buildings. Incentives for chargers include direct investment and purchase incentives for both public and private charging.

2.3.3 Economic Incentives

The majority of consumers base their purchasing decisions on the cost and/or quality of a product. Under the assumption that the quality of two products is equivalent, the consumer will generally select the lower cost option. Notable advancements in the area of battery and charger technology have arguably made the performance of the EV analogous to the ICEV. Therefore the cost comparison between both types of vehicles has become one of the most important factors in the decision-making process for consumers to convert from an ICEV to an EV. The higher upfront cost of an EV has been a significant contributor to the delay of EV adoption [9] [10]. Table 2-2 is a list of some of the more popular EVs currently on the market and their manufacturer's suggested retail price (MSRP) [11].

Table 2-2: Popular EVs – MSRP, Electric Range and Electric Efficiency
Source: PLUG'N DRIVE [11]

Model	MSRP	Electric Range	Electric Efficiency (Per 100km)
Audi E-Tron	$90,000	329 km	28.3 kWh
BMW i3	$44,950	246 km	17.8 kWh
Chevrolet BOLT	$44,800	383 km	17.6 kWh
Hyundai IONIQ Electric	$37,899	200 km	15.5 kWh
Hyundai Kona Electric	$44,999	415 km	17.4 kWh
Jaguar I-PACE	$89,800	377 km	27.5 kWh
Kia Niro Electric	$44,995	383 km	18.8 kWh
Kia Soul Electric	$35,895	179 km	19.3 kWh
Nissan LEAF	$41,698	243 km	18.7 kWh
smart fortwo Electric	$29,050	92 km	17.6 kWh
Tesla Model 3 Standard Range	$54,990	386 km	17.1 kWh
Tesla Model S Standard Range	$102,890	460 km	20.6 kWh
Tesla Model X Standard Range	$110,890	410 km	24 kWh
Volkswagen e-Golf	$36,720	201 km	17.4 kWh
Average:	**$57,827**	**307 km**	**20 kWh**

The life-cycle cost or Total Cost of Ownership (TCO) is a more suitable metric to evaluate the economic feasibility between EV and ICEV, since the higher operating costs of the ICEV may offset the more expensive upfront cost of an EV.

A cost benefit analysis was performed to determine which type of vehicle is the lowest cost option over 10 years in Newfoundland. The 2019 Chevrolet TRAX and the 2019 Chevrolet BOLT were compared since they both compare in size and capabilities. The following were the assumptions for the cost benefit analysis:

- Chevrolet TRAX – LS MSRP: $25,700 [12]
- Chevrolet BOLT MSRP: $44,800 [11]
- Electricity Rates: $0.15/kWh[2]
- Price of Gas: $1.30/L

[2] Assumed to be slightly higher than the current rates. TOD Rates not considered

- Chevrolet TRAX Fuel Economy: 8.6 L/100 km[3] [12]
- EV Annual O&M Costs: $100/year [13]
- ICEV Annual O&M Costs: $700/year [14]
- ZEV incentive/rebates: $5000 [15]
- Chevrolet Volt Electric Efficiency per 100 km: 19.5 kWh [11]
- Customer compensation from energy sold to grid (V2G) not considered
- Major repair and insurance costs were assumed to be equal
- No cost of borrowing (0% financing for EV and ICEV)
- Sales tax not included
- Depreciation of each vehicle is 100% after 10 years
- Battery life expected to be greater than 10 years
- Carbon taxes not included
- 2019 dollars
- Discount Rate: 6.5%

The ownership of an EV comes with other perks that are difficult to quantify and were not included in the cost benefit analysis. Many parking lots provide free parking and sometimes free charging for EVs [7]. EV owners are sometimes exempted from paying road tolls, ferry fees and sales tax [7]. An EV can also serve as a back-up supply for the home during an extended power outage, avoiding the need to operate a gas powered generator [16]. Table 2-3 summarizes the results of the cost benefit analysis which concludes that the EV is a marginally more cost effective. The cumulative present value (CPV) is approximately $2,550 more for an ICEV over a 10 year period. The detailed results are provided in Appendix A. Sensitivity analysis was also performed to demonstrate that particular scenarios could result in the ICEV as the lower cost option. The assumptions stated above were also considered for the sensitivity analysis summarized in Table 2-4.

[3] Ranges between 8.1-9.1 L/100km [11]

Table 2-3: EV vs ICEV – Alternative Comparison – CPV (10 Year Study)

Alternatives	Cumulative Net Present Value (CPV)	CPV Difference
EV – Chevrolet BOLT	$41,980	-
ICEV – Chevrolet TRAX	$44,530	$2,550

Table 2-4: EV vs ICEV – Sensitivity Analysis – CPV (10 Year Study)

Alternatives	Cumulative Net Present Value (CPV)	CPV Difference
Scenario 1: No Subsidy for EV		
ICEV – Chevrolet TRAX	$44,530	-
EV – Chevrolet BOLT	$46,390	$1,860
Scenario 2: Fuel Price = $1.07/L		
ICEV – Chevrolet TRAX	$41,850	-
EV – Chevrolet BOLT	$41,980	$130
Scenario 3: Electricity Rates = $0.26/kWh		
ICEV – Chevrolet TRAX	$44,530	-
EV – Chevrolet BOLT	$44,590	$67
Scenario 4: Increase in MSRP of EV by 6.5%		
ICEV – Chevrolet TRAX	$44,530	-
EV – Chevrolet BOLT	$44,710	$180
Scenario 5: Decrease in MSRP of ICEV by 11%		
ICEV – Chevrolet TRAX	$41,870	-
EV – Chevrolet BOLT	$41,980	$110

The results of the cost benefit analysis are consistent with other studies comparing the TCO between EVs and ICEVs [10] [17]. One study suggests that the economic feasibility of an EV could be dependent on driving distance and vehicle class [10].

A high penetration of EVs can be economically detrimental or beneficial to a power utility depending on how EV charging infrastructure is deployed. The application of smart grid technology for EV charging is capable of shifting or reducing the total peak demand on the power system which can thereby defer capital investments for capacity upgrades [16]. The same charging technology can facilitate the capture and storage of cheaper renewable energy created by wind and solar radiation, which can be utilized later rather than relying on more expensive energy sources [18]. The additional revenue generated from charging EVs could be used by government regulated power companies to help reduce electricity rates for its customers.

2.3.4 Technical Advantages for Homeowners and Utilities

A charged plugged-in EV inherently has the ability to supply electrical energy back to the grid. This can be technically beneficial to home owners or power utilities, since EVs can be considered a form of energy that can be dispatched during a power outage or when power system reliability is in jeopardy. A house or building with the necessary electrical and charging infrastructure has the capability of receiving power from a charged EV in the event of an extended power outage [19]. This gives homeowners with EVs the added comfort of knowing they have their own personal back-up power supply. The convenience of having the ability to charge your vehicle in your own driveway is also an appealing feature of an EV. The charging times through a 120/240 V AC supply can be lengthy, but this may not be a concern for the EV owner that does not travel too far from their home.

The aggregated effect of many additional energy sources connected to the grid has the potential to aid power utilities by minimizing customer outages; improving power quality and more cost effectively operate their system. The power system reliability improvements associated with a large scale connection of EVs to the grid will be discussed in much more detail in Chapter 4.

2.3.5 Existing Barriers

There are various environmental, political, economic and technological incentives that are pushing for the widespread adoption of EVs. However, there are still a number of obstacles that are causing people to hesitate from converting from ICEVs to EVs. The following are some of the barriers deferring the acceptance of EVs:

Technical Barriers

- **Range Anxiety:** An ICEV has historically had a longer driving range with a full tank of gasoline in comparison to a fully charged EV. There is a common and often irrational fear of an EV depleting its full battery charge before reaching a charger [20]. Advances in battery/charging technology as well as the installation of more publically accessible chargers will help mitigate anxiety [7].
- **Charging Times:** EV charging times are much slower compared to the fuel-up time for ICEVs. Advances in battery/charging technology are resulting in faster charging times. Technical standards have been developed for faster charging with demands up to 600 kW. There has also been a growing interest in mega-chargers (1 MW) for larger vehicles [7].
- **EV Availability:** There is currently a limited selection of EVs, especially for larger vehicles like pick-up trucks or Sport Utility Vehicles (SUVs) [7]. A larger variety of EVs are expected to be made available in the near future [7].
- **The Influence of Ambient Temperature on EV Batteries:** Some research advocates that low ambient temperature can have an adverse effect on the driving distance of a fully charged EV. Colder conditions can cause batteries to discharge and degrade quicker than if exposed to warmer temperatures [21]. The ambient temperature can also increase the amount of auxiliary load associated with heating or air conditioning which can speed up the discharge rate of the battery.
- **Lack of Infrastructure:** Some areas of the world lack charging infrastructure which can certainly be a deterrent for a prospective buyer or tourist. The number of EV chargers is forecasted to increase dramatically over the coming years (See Figure 2-6 in Section 2.4.1) [7]
- **Impact on the Power Grid:** The large electrical demand associated with multiple EVs charging at once can potentially overload equipment on a power system if they are not properly integrated. This area of concern is one of the primary focuses of this thesis.

Economic Barriers

- **The MSRP of an EV:** The upfront cost of an EV is considerably higher than that of an ICEV, as discussed in Section 2.3.3. The TCO of an EV versus an ICEV is more comparable, but studies show that most consumers do not make their decisions based on this metric [10].
- **Battery Replacements:** There is a high cost associated with a battery replacement; however the battery is expected to outlive the EV and they are also covered under an extended warranty for most vehicles [13]. It is anticipated that improvements in battery technology will even further extend the life of a battery [7].
- **Depreciation:** Studies show that EVs tend to depreciate at a faster rate than ICEVs [17].

Political Barriers

- **Government Support:** Some governments may not fully support the conversion of ICEVs to EVs and will consequently provide less incentives or set targets.
- **Influence of Competing Industries on Government Decision Making:** Other competing and more influential industries, like the oil and gas sector, can pressure the government into making policies at the expense of the EV industry.

Environmental

- **Battery Production:** Batteries are comprised of rare metals that are scarce and their extraction can often be an intrusive process that can be harmful to the environment. Metal cobalt is a vital ingredient used for the creation of EV batteries. This mineral is predominantly extracted from rocks on the seabed using a process that has an adverse effect on marine life [22]. It is expected that by 2025, batteries will become less reliant on cobalt and use cathodes in the NMC family or advanced NCA batteries. [7]
- **Disposal of EV Batteries:** Damaged disposed batteries can release harmful toxic gases. Some of the rare metals inside a battery can be a catalyst for water pollution [7]. Recycling or reusing batteries is a green but costly approach to alleviate this issue.

2.4 Electric Vehicle Market Trends

This section will serve as a review of the current and future trends as it pertains to the penetration of EVs from an international, national and provincial perspective.

2.4.1 International Trends

The world's automobile fleet is still predominantly ICEVs, but the global adoption of EVs has been rapidly increasing. The total number of EVs by the end of 2018 was 5.1 million, a 70 percent increase from 2017 [7]. This movement is promising for the environment since the entire 2018 global EV fleet emits a total of about 40 Mt CO2 eq less than if they were ICEVs [7].

Figure 2-4 is a comprehensive and informative series of graphs that were obtained directly from the International Energy Agency (IEA) report, "Global EV Outlook 2019", and shows a regional breakout of the global sales and market share of EVs between 2013 and 2018 [7]. The bar graphs in Figure 2-4 represent new EV sales, while the line graphs designate the market share for each region over time. It is clearly evident from all the graphs that the growth in sales and market share of EVs is universal.

The country of Norway is a global leader in the area of EVs, with a market share of 46 percent as of the end of 2018, which is approximately 2.5 times higher than the next country (Iceland - 17.2%) [7]. The main reasons for the EV revolution in Norway can be attributed to their government's full commitment to zero emissions, aggressive targets and high taxation associated with the purchase and operation of ICEVs [7]. There are also additional incentives for EV owners in Norway, including the exemption from paying fees for parking, road tolls or ferries [7].

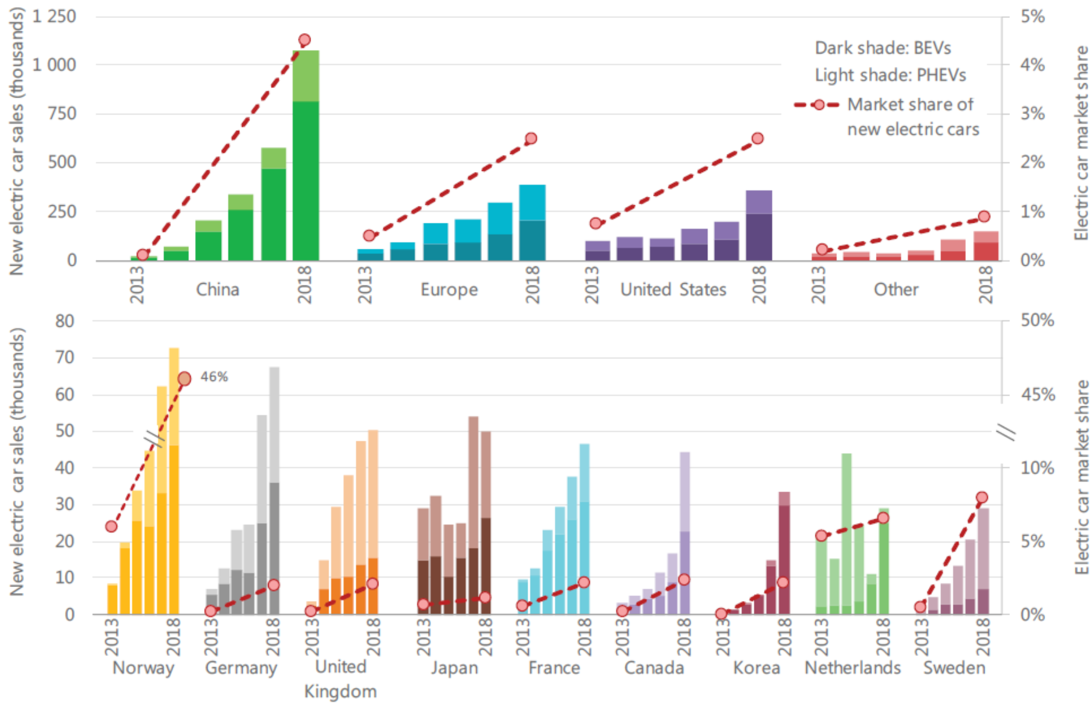


Figure 2-4: Global Electric Car Sales and Market Share (2013-2018)
Source: IEA [7][4]

The adoption rate of EVs has been increasing over the past few years, as shown in Figure 2-4, and this trend is expected to continue according to IEA. The Global EV Outlook 2019 report assesses two EV growth scenarios involving government intervention: New Policies Scenario and 30@30 campaign [7]. The New Policies Scenario aims to demonstrate the potential impact of all announced government policies as of the end of 2018 [7]. The 30@30 scenario considers the 30@30 campaign which is an initiative involving 11 countries with the objective to achieve a 30 percent market share by the year 2030 [7]. The participants of this campaign include; Canada, China, Finland, France, India, Japan, Mexico, Netherlands, Norway, Sweden and United Kingdom [7].

[4] Notes: Europe includes Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom. Other includes Australia, Brazil, Chile, India, Japan, Korea, Malaysia, Mexico, New Zealand, South Africa and Thailand. Sources: IEA analysis based on country submissions, complemented by ACEA (2019); EAFO (2019); EV Volumes (2019); Marklines (2019); OICA (2019) [7].

Figure 2-5 illustrates projections developed by IEA for each scenario from 2018 to 2030. In both cases EV sales and total stock are expected to increase exponentially. Total EV sales are anticipated to more than double and quadruple globally for the New Policies and 30@30 scenarios, respectively [7]. This analysis suggests that considerable growth in EV deployment is inevitable for the foreseeable future.

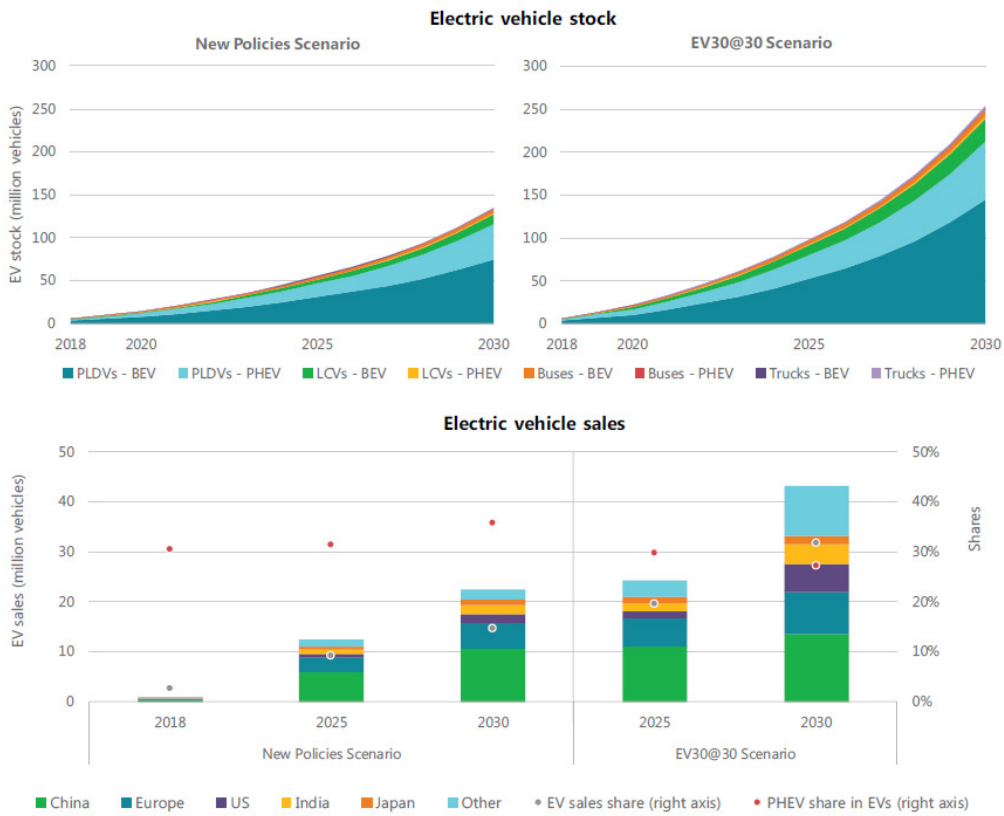


Figure 2-5: Expected Global Stock and Sales by Scenario (2018-2030)[5]
Source: IEA [7]

An increase in charging infrastructure across the globe will also help promote and accommodate escalation in EV sales. There were a total of 5.2 million EV chargers[6] at the end of 2018, 540,000[7] of which were publicly accessible [7]. The Global EV Outlook 2019 report predicts the number of publicly accessible chargers will reach 10 million and 20 million by the year 2030 for the New Policies and

[5] Note: PLDVs = passenger light-duty vehicles; LCVs = light-commercial vehicles; BEV = battery electric vehicle; PHEV = plug-in hybrid vehicle. Source: IEA analysis developed with the IEA Mobility Model [7]
[6] for light duty vehicles
[7] 150,000 fast chargers - 78% in China

30@30 scenarios, respectively [7]. Figure 2-6 shows the expected number, total power capacity and total energy consumption associated with EV chargers by the end of 2030 for both scenarios.

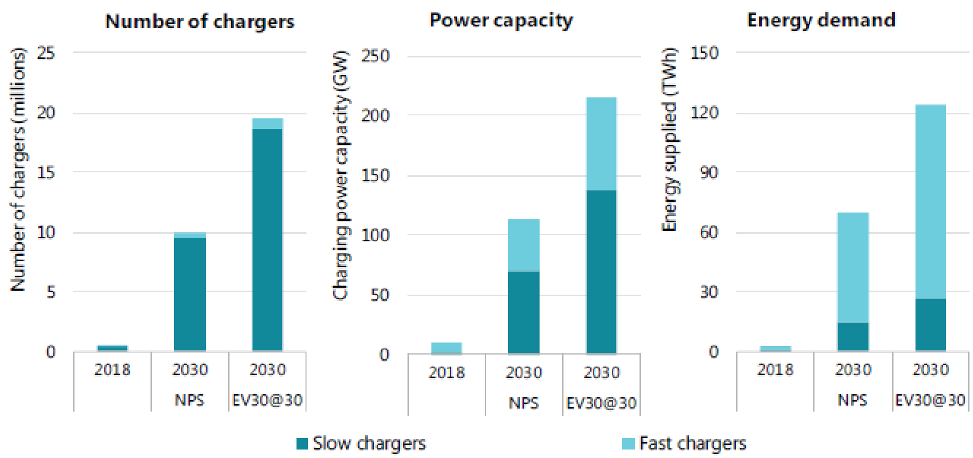


Figure 2-6: Number of Chargers[8], Power Capacity and Energy Demand by Scenario
Source: IEA [7][9]

2.4.2 National Trends

There is currently a relatively strong presence of EVs in Canada which can be largely attributed to progressive policy-making by the federal government. Canada has experienced steady growth in EV sales and market share between 2013 and 2018 as previously shown in Figure 2-4. The number of EVs sales in Canada by the end of 2018 was approximately 44,000, which eclipsed the 2017 total by more than double [7]. There were a total of 840 fast chargers in-service across Canada as of December 2018 to help facilitate this quantity of EVs [7]. Table 2-5 and Figure 2-7 provide the total and percentage breakout of EVs by province, respectively. The future trend for EVs in Canada is anticipated to grow for the foreseeable future as illustrated in Figure 2-8 [23]. The IEA forecasts that the total number of EVs in Canada will be in excess of 120 million by 2030. This projected growth rate can be attributed to the existing and prospective government policies promoting EVs within Canada, as well as a reduction in range anxiety through the advancement of battery and charging technology [23].

[8] Publicly Accessible
[9] Applicable to LDVs only. NPS = New Policies Scenario.

Table 2-5: EV Totals by Province
Source: EMC [24]

Province/Territory	2017 Sales	2018 Sales	'17-'18 Change	EVs Total
Alberta	392	926	+136%	2,078
BC	3,329	8,449	+154%	17,175
Manitoba	47	164	+249%	381
NB	43	59	+37%	175
NL	4	13	+225%	39
NWT	1	2	+100%	8
Nova Scotia	25	92	+268%	223
Nunavut	0	0	0%	1
Ontario	8,059	16,814	+109%	34,052
PEI	2	14	+600%	29
Québec	7,716	17,557	+128%	38,737
Saskatchewan	27	84	+211%	190
Yukon	0	1	-100%	3
Canada	19,645 EVs	44,175 EVs	+125%	93,091 EVs

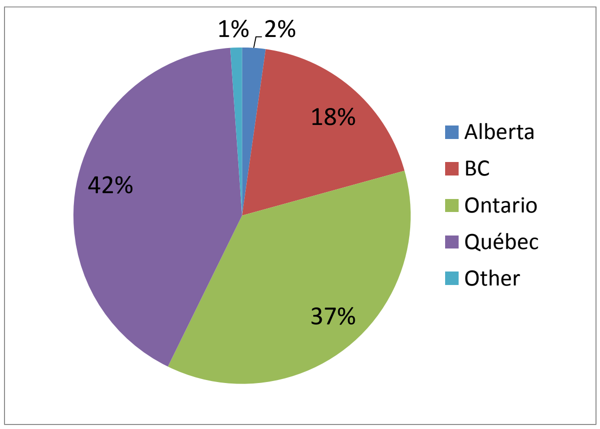


Figure 2-7: Total EV Breakdown by Province
Source: EMC [24]

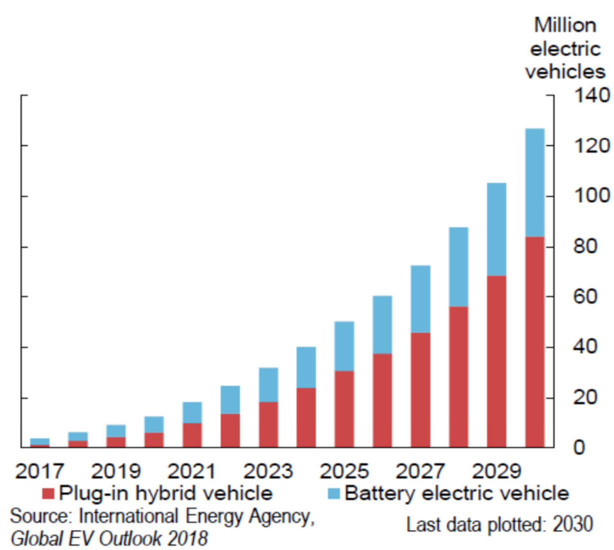


Figure 2-8: Forecasted EV Growth in Canada
Source: Bank of Canada [23]

Canada is committed to collaborate with other nations in its mission to increase the market share of EVs. According to the Global EV Outlook 2019 report, Canada is presently participating in the following joint ventures with other countries in an attempt to accomplish this goal: The Electric Vehicles Initiative (EVI), 30@30 campaign and the Global EV Pilot City Program. Canada has set a target of 30% market share of EVs by 2030, as part of the 30@30 campaign [7].

The Government of Canada has also pursued their own initiatives and developed policies, set targets and established incentives to promote the ownership of EVs and the expansion of charging infrastructure. Any Canadian resident who purchases or leases a ZEV, and meets a set of defined criteria, is entitled to either a $5,000 or $2,500 subsidy depending on the distance range of the vehicle [25]. EVs with a longer range are eligible for the full $5,000 rebate.

A select few provinces within Canada offer additional incentives on top of what is provided by the federal government. Quebec offers an extra $8,000 rebate for each EV sold and also provides financial incentives for the purchase of chargers. The province of Ontario contributes $3,000 to $14,000 depending the size and type of EV [26]. British Columbia has been the most ambitious by setting a provincial target of 100% EV sales by 2040 and also offers rebates between $2,500 and $5,000 [7] [26]. The following section will focus solely on the current and future EV outlook for the province of Newfoundland and Labrador.

2.4.3 Provincial Trends

Newfoundland and Labrador is lagging behind most of its provincial counterparts with respect to the adoption of EVs. According to the Department of Motor Vehicles (DMV), there were a total of 63 EVs[10] in Newfoundland and Labrador as of 2017, which accounts for approximately 0.017% of the total vehicles[10] in the province. This is noticeably less than the national EV market share of approximately 0.85% for the same year (See Figure 2-4). A more detailed collection of motor vehicle statistics for

[10] Gross Vehicle Weight Rating less than 4,500 kg

Newfoundland and Labrador is provided in Appendix C. The following are some of the primary reasons why there is a low uptake of EVs in Newfoundland and Labrador:

- **Lack of Fast Charging Infrastructure:** As of November 2019 there were no level 3 chargers in Newfoundland and Labrador. This is a major deterrent for any long distance travelling within the province by residents or potential tourists owning an EV. A report prepared by Electric Mobility Canada (EMC) claims that provinces who significantly invest in infrastructure see the most growth in EV sales [24]. The province of New Brunswick experienced an increase in tourism following the installation of their fast charging network [27]. In October 2019 it was announced that NL Hydro would install 14 chargers[11] across the province by the end of 2020 [28]. Federal funding of up to $50,000 per site will be provided by Natural Resources Canada (NRCAN) [27]. NL Hydro has also developed preliminary long-term plans for more charging infrastructure in the event EV penetration levels exceed expectations [27].
- **Lack of Provincial Policies/Incentives:** The provincial government is currently working on establishing its own EV policies [27] [29]. Further research and collaboration between utilities and government is required to finalize any provincial policy as it pertains to EVs. The Canadian provinces that have their own EV policies and incentives are experiencing the highest penetration levels [24]. New Provincial Environmental policy development will also help promote the increase in EV sales.
- **Weather:** Newfoundland and Labrador can be exposed to severe weather during the winter season. The cold ambient temperatures can reduce the range of an EV by up to approximately 50% [29]. The heavy snowfall commonly experienced in the province covers the roads and increases the demand for more powerful vehicles equipped with 4-wheel drive capability. There is currently a very limited selection of EVs that can safely navigate under these poor road

[11] Each site would be approximately 65km apart and would include a level 2 and 3 charger

conditions. The large amounts of snowfall could also present challenges for EV owners with outdoor chargers.

- **Public Perception and Lack of Awareness:** An EV is a foreign concept to a large percentage of the population and consequently there is generally a limited understanding of how they operate and charge. The majority of the drivers are much more familiar with the ICEV. The published report prepared by Bruce Power, the University of Waterloo, Pollution Probe and Plug'n Drive, indicates that 92% of Canadians believe there are very few charging locations outside the home, and 86% of Canadians are not even aware that charging an EV at home is a viable option [30].

A baseline projection for the adoption of EVs in Newfoundland and Labrador is shown in Figure 2-9 and was prepared by Dunsky Energy Consulting, as part of Conservation and Demand Management (CDM) potential study that was requested by NL Hydro and Newfoundland Power [31]. This baseline forecast was developed under the assumption that there would be no additions to existing policy or additional charging infrastructure beyond what has been approved by the end of 2019 [31]. Other EV growth scenarios will be developed and discussed in Chapter 5.

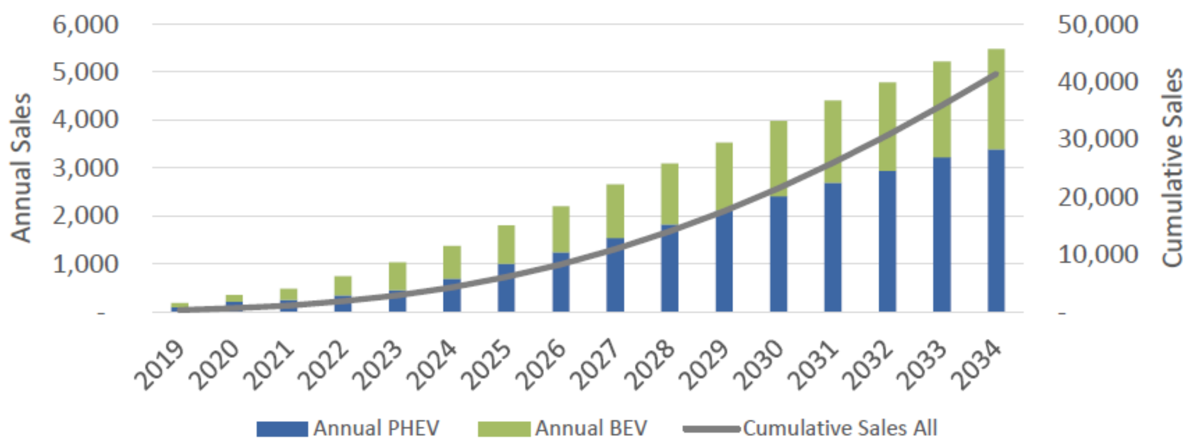


Figure 2-9: EV Adoption Projection in NL
Source: Dunsky Energy Consulting [31]

According to Figure 2-9, the expectation is that there will be substantial growth in EVs[12] sales over the next 15 years throughout the province with a total of 41,400 EVs[13] by 2034. An influx of this magnitude of EVs would naturally increase NL Hydro's overall customer energy and capacity requirements. Energy is the amount of electricity consumed over a period of time measured in watt-hours (Wh) and capacity is the demand for energy at any given time and is measured in watts (W) [32]. The NL power system is currently more equipped to support the incremental energy requirements attributed to a high penetration of EVs compared to the capacity or demand requirements [32]. The additional energy sales from charging EVs could increase revenue for NL Hydro to contribute to the rate mitigation effort. However, under the assumption that coordinated or utility controlled charging is not implemented by NL Hydro and EV owners, it is highly probable a mass adoption of EVs would create capacity shortfalls throughout the power system. Therefore the additional revenue generated through energy sales from charging EVs would likely be more than offset by capital costs necessary for capacity upgrades. The transmission system will be assessed in Chapter 6 to quantify the magnitude and timing of any equipment overloads for various growth scenarios.

2.5 Summary

The various topics discussed throughout this chapter clearly demonstrate that EVs are here to stay and will play a monumental role in the future of the automotive industry. There are a variety of barriers still prohibiting the mass adoption of EVs, but evidence suggests they could be temporary and it is imminent that they will be overcome.

Future EV sales projections suggest that it is highly probable that Newfoundland and Labrador could experience an exponential growth over the next decade. The energy and demand requirements associated with a high penetration of EVs in the province could put considerable strain on the power system. The power system analysis conducted in Chapters 6 and 7 will quantify the potential impact that the baseline

[12] Personal/Commercial Light-Duty Vehicles (LDV), Medium Duty Vehicles (MDV), Heavy-Duty Vehicles (HDV) and Buses
[13] Representing between 10-29% of annual sales depending on vehicle class [31]

EV sales forecast will have on the NL grid, as well as other EV growth scenarios developed in Chapter 5. Chapter 3 is essential in providing the reader with a high level understanding of the NL grid which is a prerequisite in comprehending the analysis performed in Chapters 6 and 7.

Chapter 3

Newfoundland & Labrador Power System

3.1 Introduction

The purpose of this chapter is to provide a comprehensive overview of the Newfoundland and Labrador power system. Although the system is relatively small, it is complex and has unique characteristics and nuances that will be discussed. Although the Labrador Interconnected System is not part of the scope of the study analysis, it plays an important role in the operation of the Island Interconnection System and therefore an overview is warranted.

The load flow and power system stability analysis that was conducted as an integral part of this thesis, and is outlined in Chapters 6 and 7, was performed using a computer model of the Island Interconnection System. This model was set up to replicate scenarios with increased penetration levels of EVs connected to the power system, and then simulated to assess the impact. It is important for the reader to understand the system being studied in order to explain and evaluate the impact.

3.2 Utility Overview

Newfoundland and Labrador Hydro "NL Hydro", a subsidiary of Nalcor Energy, is a crown corporation that is responsible for generating, transmitting and distributing power to the residents of Newfoundland and Labrador. NL Hydro is regulated by a quasi-judicial body of the Newfoundland and Labrador provincial government, the Public Utilities Board (PUB), which is mandated to ensure least cost and reliable electricity is provided to all residents of the province. On an annual basis NL Hydro generates and transmits over 80 percent of the electricity consumed by Newfoundlanders and Labradorians [33]. Figure 3-1 is the daily load profile of the entire Newfoundland grid during the peak day[14] in 2019. The

[14] February 20, 2019

graph also provides a breakdown of what type of generation was dispatched to meet the peak demand of 1,788 MW.

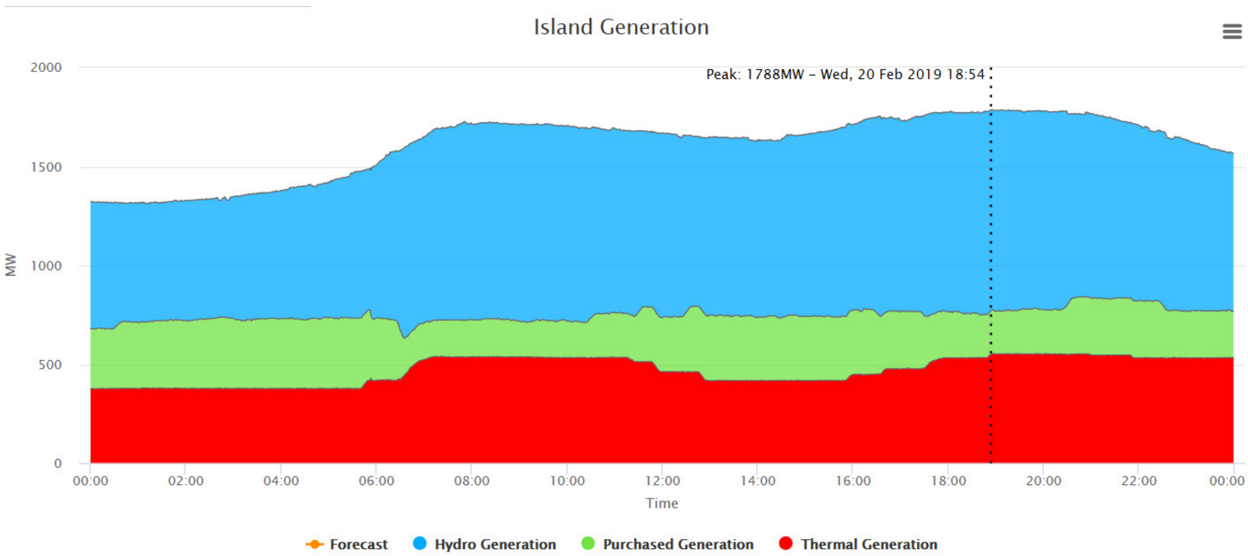


Figure 3-1: Island Interconnection System - 2019 Peak – Daily Load Profile (MW) [34]

With the recent electrical interconnection of Newfoundland to the North American grid, it has introduced the requirement for the provincial transmission network to be overseen by an independent system operator. Therefore the Newfoundland and Labrador System Operator (NLSO) was established to perform this role with its main priority to manage the bulk power systems and ensure customers in the province are provided a reliable supply of electricity [35]. A bulk power system is defined by the Northeast Power Coordinating Council (NPCC) as, "the interconnected electrical systems within northeastern North America comprised of system elements on which faults or disturbances can have a significant adverse impact outside the local area." [36]. Another function of the NLSO is providing open access of the bulk power system to potential users without any preferential treatment [35].

The Transmission Planning Group within the NLSO is responsible for the long-term operation of the NL transmission system by ensuring that it can support future changes in system demand in an attempt to avoid any unplanned outages or abnormal system conditions. Transmission Planning Group strictly follows a set of criteria and guidelines that are enforced by the PUB [36]. In the event the criterion is violated, capital investment is proposed to increase system capacity to meet forecasted demand for the foreseeable future.

There are two bulk power systems that are operated and managed by the NLSO which are the Island Interconnected System (IIS) and the Labrador Interconnected System (LIS) [37]. The following two sections provide a brief overview of these two interconnected systems.

3.3 Island Interconnected System (IIS)

The IIS serves the majority of large communities located on the island of Newfoundland, but the more rural communities are supplied by small isolated diesel plants. The IIS stretches from coast to coast with a total of over 3,700 kilometers of transmission line that typically operate at voltage levels of 66/69 kV, 138 kV or 230 kV [38]. These transmission lines connect the major generation sources to all the large load centers throughout the island portion of the province. The major generation sources on the IIS and LIS are described in more detail in Section 3.5. Appendix C provides a map of the IIS displaying the main transmission lines and generation sources.

The majority of power generated by NL Hydro is sold directly to Newfoundland Power (NLP) [33]. Newfoundland Power is another utility that is mainly responsible for delivering power to the residents of Newfoundland and is also regulated by the PUB. Their core business is the distribution of power directly serving approximately 90 percent of customers on the IIS [39]. NL Hydro also sells electricity to large industrial customers throughout Newfoundland and Labrador and distributes power to the remaining 10 percent of residential and commercial customers not supplied by Newfoundland Power [33]. Figure 3-2 is a map of Newfoundland that shows the service areas for NL Hydro and Newfoundland Power [40].

Figure 3-2: NL Hydro and Newfoundland Power - Service Areas [40]

3.4 Labrador Interconnected System (LIS)

The LIS serves the major load centers located in Labrador, which includes Happy Valley, Churchill Falls, Labrador City and Wabush (and their surrounding areas). The remaining isolated communities in Labrador are supplied by small diesel plants. The LIS spans across southern Labrador from Happy Valley Goose Bay to Labrador City. The primary source of generation for the LIS is the Churchill Falls Generation Station, which is owned and operated by another subsidiary of Nalcor called Churchill Falls Labrador Corporation Limited (CFLco). The majority of the power generated by Churchill Falls is sold to Hydro Quebec via three 735 kV transmission lines. NL Hydro is currently entitled to approximately 532 MW of recall capacity at the Churchill Falls Generation Station that is allocated for customers in Labrador.

The LIS is often graphically divided into two separate regions - Labrador West and Labrador East, with Churchill Falls considered the midpoint. The Labrador West system is comprised of any electrical infrastructure that is west of the community of Churchill Falls, which includes the towns of Wabush and Labrador City. There are two 230 kV lines that connect Churchill Falls to Labrador West and are designated as L23 and L24. The Wabush Terminal Stations steps-down the voltage from 230 kV to 46 kV and delivers power to existing mining developments and substations in Wabush and Labrador City.

The LIS system east of Churchill Falls is the Labrador East System and serves Happy Valley-Goose Bay and its surrounding area via one 138 kV transmission line (L1301/L1302). There are also two 315 kV lines (L3101/L3102) that allow for the transfer of power between Muskrat Falls and Churchill Falls Terminal Stations. Figure 3-3 is a simplified block diagram showing the system configuration of the LIS. Appendix C provides a map of the LIS displaying the main transmission lines and generation assets.

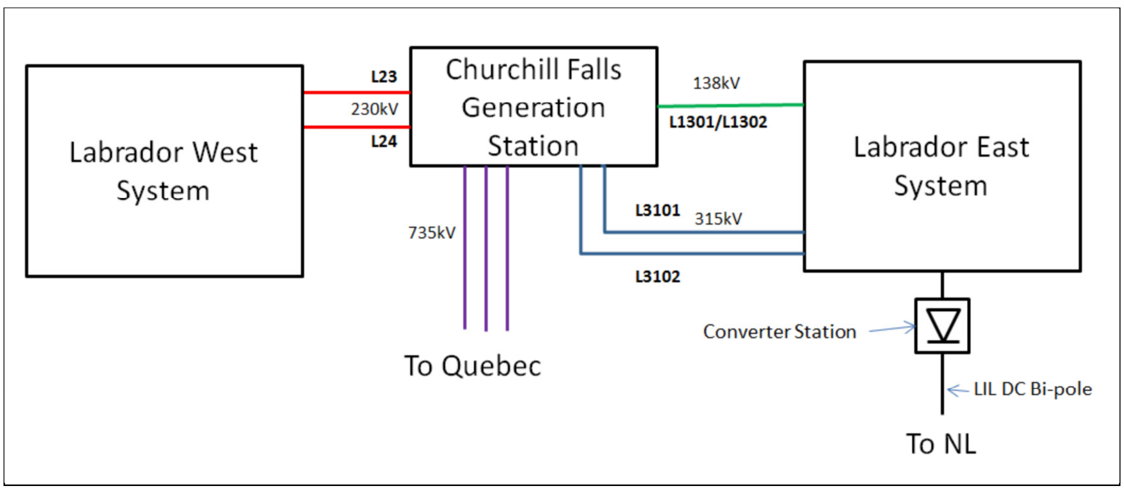


Figure 3-3: Labrador Island Interconnection System

3.5 Power Generation

NL Hydro is the primary producer of electricity to the residents of Newfoundland and Labrador, supplying a total of approximately 1,750 MW and 5,450 MW of installed generation capacity on the IIS and LIS, respectively [33]. There is an assortment of different forms of generation that are responsible for supplying power to the residents of province, the majority of which is clean and renewable hydroelectric generation. Table 3.1 provides a summary of the major[15] generating plants owned and operated by NL Hydro with their associated power output ratings [37]. There are other generation stations dispersed across the province are owned and operated by other parties like Nalcor and Newfoundland Power. Furthermore, NL Hydro currently has several power purchasing agreements with non-utility generators (NUGs), including two 27 MW wind farms located in St. Lawrence and Fermeuse [37]. There is currently a hydroelectric development under construction in Labrador that will serve as an additional generation source for the IIS which will be discussed in further detail in Section 3.6.

The two largest generation stations connected to the IIS are the Bay d'Espoir Hydro Plant and the Holyrood Thermal Plant. The Bay d'Espoir Hydro Plant is located in south central Newfoundland and has seven hydro units with a total capacity of 613 MW [37]. The Holyrood Plant is comprised of three thermal units, one gas turbine and eight diesel units, with a total capacity of 630 MW and is situated on the Avalon Peninsula near the largest load center [37]. The three large Holyrood thermal units burn 0.7% Sulphur bunker C oil and generate between 15 to 25 percent of the annual energy requirements of the electricity consumers in Newfoundland [41].

The LIS has two sources of generation, the Churchill Falls Generation Station and the Happy Valley Gas Turbine. The Churchill Falls Generation Station is located on the Churchill River in Labrador and is considered the second largest hydro development in North America, with a total installed capacity of approximately 5,400 MW [42]. Although Hydro Quebec is entitled to about 90% of the power generated at Churchill Falls, the remaining block of power (530 MW) is allocated for the NL Hydro customers on the LIS [37]. The gas turbine in Happy Valley serves as backup generation, but its primary function is a synchronous condenser to provide reactive power or voltage support to the Labrador East system.

Most of the AC power that is generated on the IIS and LIS operates at a frequency of 60 Hz. A large majority of the generators on both systems are synchronous machines that rely on governor systems to sustain a synchronous speed, with the objective of maintaining a system frequency at 60 Hz. The

[15] Greater than 5 MW capacity

following equation describes the relationship between a unit's mechanical speed (n) and system frequency (f), where P_f represents the number of generator field poles [43]:

$$n = \frac{120f}{P_f} \quad [3.1]$$

Variations in electrical demand or a system disturbance will cause the frequency to deviate from the nominal 60 Hz. All the synchronous generators on the system operating in speed mode will react to the frequency deviation by contributing to an overall change in total system generation. The Automatic Generation Control (AGC) is a centralized system within a utility's control center that coordinates this joint effort between synchronous generators in order to maintain acceptable frequency levels and avoid system instability [44].

Table 3-1: NL Hydro's Generation Stations (>5 MW)[16] [37]

Plant	Type of Generation	Capacity (MW)
ISLAND INTERCONNECTED SYSTEM (IIS)		
Bay d'Espoir Unit #1	Hydro	76.5
Bay d'Espoir Unit #2		76.5
Bay d'Espoir Unit #3		76.5
Bay d'Espoir Unit #4		76.5
Bay d'Espoir Unit #5		76.5
Bay d'Espoir Unit #6		76.5
Bay d'Espoir Unit #7		154.4
	Bay d'Espoir Total:	**613.4**
Upper Salmon	Hydro	**84**
Granite Canal	Hydro	**40**
Hinds Lake	Hydro	**75**
Cat Arm Unit #1	Hydro	67
Cat Arm Unit #2		67
	Cat Arm Total:	**134**
Paradise River	Hydro	**8**
Holyrood Unit #1	Thermal/Gas Turbine/Diesels	170
Holyrood Unit #2		170
Holyrood Unit #3		150
Holyrood Gas Turbine		123.5
Holyrood Diesel Back-up		14.6
	Holyrood Total	**628.1**
Hardwoods	Gas Turbine	50
Stephenville	Gas Turbine	50
Hawkes Bay	Diesels	5
St. Anthony	Diesels	9.7
	IIS TOTAL:	**1,700**
LABRADOR INTERCONNECTED SYSTEM (LIS)		
Churchill Falls #1	Hydro	493.5
Churchill Falls #2		493.5
Churchill Falls #3		493.5
Churchill Falls #4		493.5
Churchill Falls #5		493.5
Churchill Falls #6		493.5
Churchill Falls #7		493.5
Churchill Falls #8		493.5
Churchill Falls #9		493.5
Churchill Falls #10		493.5
Churchill Falls #11		493.5
	Churchill Falls Total:	**5,428**
Happy Valley	Gas Turbine	25
	LIS TOTAL:	**5,453**

[16] Bishop Falls and Grand Falls Generation (63 MW) are owned by Nalcor

3.6 Lower Churchill Project

The Lower Churchill Project is a two-phase project that is comprised of two separate hydroelectric developments, Muskrat Falls and Gull Island. Both of these sites are located in Labrador on the Churchill River downstream of the existing Churchill Falls generation facility [45]. The Muskrat Falls Project is the first phase of the Lower Churchill Project and is currently under construction and the latest schedule indicates it will be fully commissioned by late 2020 [45] [46]. As shown in Figure 3-4, the major assets that makeup the Muskrat Falls project includes an 824 MW hydroelectric plant, the Labrador-Island transmission-link (LIL) and the Maritime Link (ML) [45]. The LIL and ML are two High Voltage DC (HVdc) bipole links that will be discussed in more detail in Section 3.7. Additional system upgrades to the IIS were also required to accommodate the integration of these new assets, like the two 315kV lines built from Churchill Falls to Muskrat Falls.

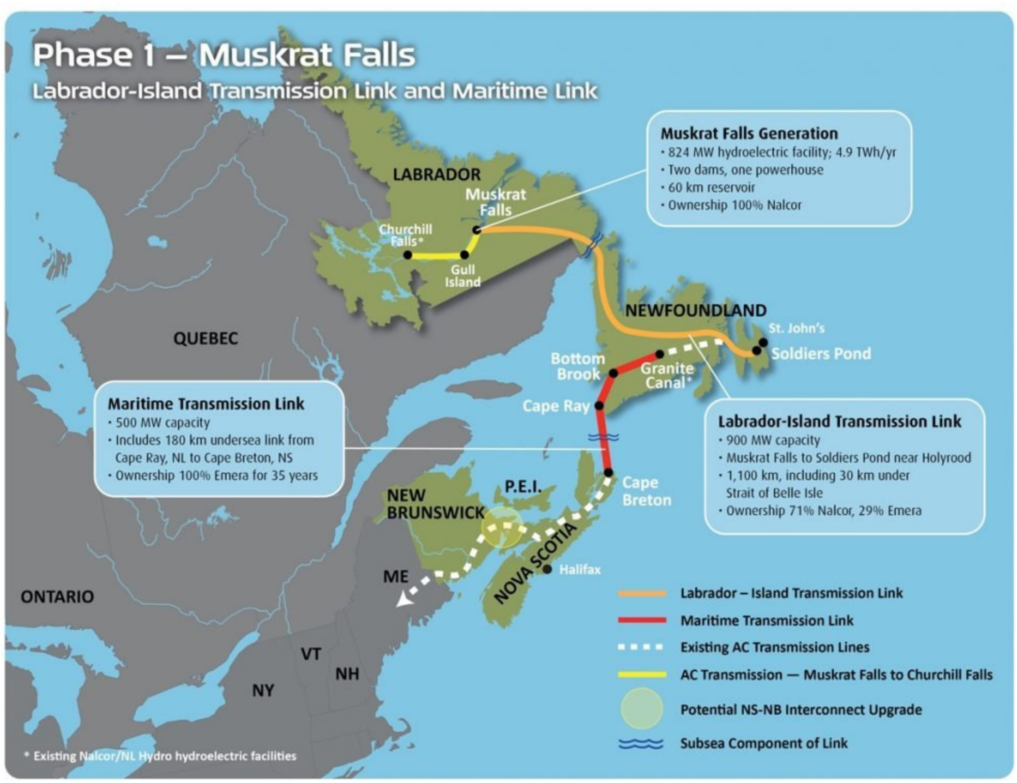


Figure 3-4: Lower Churchill Project (Phase 1 - Muskrat Falls) [45]

Although the Muskrat Falls Project is located in Labrador, its development was justified based on the need to meet the forecasted demand and improve the overall reliability of the IIS [37]. The age, condition and environmental footprint of the Holyrood Thermal Generation Station were also a driving force behind the justification for Muskrat Falls [37]. NL Hydro has previously concluded that the Holyrood plant is quickly approaching the end of its useful life and must be replaced or refurbished. NL Hydro's total power generation portfolio will be 98 percent renewable upon completion of the Muskrat Falls Project and the subsequent decommissioning of the Holyrood plant [37]. A percentage of the 824 MW produced at the Muskrat Falls Generation Station, approximately 20 percent, must be supplied to Nova Scotia as part of a contractual agreement with their utility, or Emera Inc. [37]. In exchange for this block of power, Emera constructed and manages the HVdc link required to deliver this power, which provides a pathway for Nalcor to sell power to the North American market [47]. The incentive of this agreement for Emera was to reduce their carbon footprint by replacing coal-fired generation with clean renewable power generated from Muskrat Falls.

The Gull Island Project is the proposed second phase of the Lower Churchill Project and has the potential to generate a total of approximately 2,250 MW [48]. There is currently no domestic or commercial need for this amount of power and therefore the development of the Gull Island Project is not economically justifiable at this time [48].

3.7 HVdc Interconnections

The completion of the Lower Churchill Project will electrically connect the IIS to the LIS and the Nova Scotia power grid via two HVdc bipole links. These two HVdc links will accommodate the sale of power to neighboring utilities and will also provide added system reliability and improved system frequency regulation for the IIS. Both bi-pole links have the ability to instantly adjust their power flow in order to help regulate the system frequency. This functionality is extremely beneficial as it significantly improves the stability of the power system and protects against under/over frequency events. Figure 3-5 is a map showing the general path of both HVdc links in Newfoundland and Labrador.

Figure 3-5: HVdc Links in Newfoundland and Labrador [32]

3.7.1 Labrador Island Link (LIL)

As of the summer of 2018, the IIS and LIS became electrically interconnected via an HVdc bipole link called the Labrador Island-Link (LIL) [49]. The LIL is 1,100 km long and stretches across the entire province of Newfoundland, connecting the Muskrat Falls Converter Station and Soldiers Pond (SOP) Converter Station [49]. The Muskrat Falls Terminal Station is located in Labrador next to the Muskrat Falls Generation Facility, while the Soldiers Pond Terminal Station is located on the Avalon Peninsula on the east coast of Newfoundland. Submarine cables were also necessary for the LIL in order to cross the Strait of Belle Isles as shown on the map in Appendix C.

The LIL operates at a DC voltage of +/- 350 kV with a total power transfer capacity of 900 MW [37]. The inverting and rectifying processes of the LIL are accomplished using a more traditional HVdc system based on Line Commutated Converter (LCC) technology. A LCC is a current source converter that relies on controlled or uncontrolled switching devices, such as thyristors, to produce the desired AC or DC waveform [50]. One of the most significant limitations of LCC technology is that the inverter consumes a considerable amount of reactive power [51]. The firing delay of the converter introduces a phase shift between the AC current and voltage. Consequently, the LIL cannot provide AC voltage control and therefore capacitor banks or AC filters are required at both converter stations to compensate for the absorbed reactive power [51].

The LIL can operate in a variety of different modes for operational flexibility to protect against large system disturbances. Although a single pole of the DC link is rated for 450 MW, a pole trip will instantaneously cause the LIL to switch to monopole mode (Continuous), allowing the other energized pole to operate at 2 per unit (900 MW) for ten minutes. After the ten minute interval, when the system has hopefully recovered, the LIL monopole will reduce to a rating of 1.5 per unit (675MW). Table 3-2 was supplied by NL Hydro and provides a summary of the various modes of operation for the LIL and their associated capacities.

Table 3-2: LIL Modes of Operation [52]

Mode of Operation	Capacity (MW)[17]
Bipole	900[18]
Monopole – Ground Return (10 min)	900
Monopole – Ground Return (Continuous)	675[19]
Monopole – Metallic Return	675
Monopole – Ground Return (1 Cable)	450
Monopole – Metallic Return	450

At the present time, the LIL is not fully commissioned and is only capable of operating in monopole mode at a de-rated capacity. The loss of the LIL monopole at higher power flows could result in an under-frequency event under the current configuration of the IIS, where the consequences could be the

[17] Sending end at Inverter Station (Muskrat Falls)
[18] 450 MW/pole
[19] 1.5 per unit (MW) – 450 MW plus 50% of pole rating = 450 + 425 = 675 MW

loss of customers through Under Frequency Load Shedding (UFLS). UFLS is a controlled strategy used by power utilities that involves shedding customer load after the loss of a large generation source in order to avoid under-frequency trips [43].

If a significant drop in system frequency is not quickly addressed, it could potentially result in a full system black-out. NL Hydro starts shedding load once the frequency drops below 58.8 Hz with the objective not to go below 58 Hz, at which time generation plants across the system may begin to trip on under-frequency [53]. An over-frequency event (greater than 62 Hz) is less common on the IIS/LIS since this would involve a sudden loss of a significant amount of customer load.

The LIL will eventually be equipped with a frequency controller which will provide better frequency regulation to the IIS following system disturbances. NL Hydro confirms the frequency controller will ensure the grid maintains a frequency between 59.7 Hz and 60.3 Hz (+/-0.3 Hz dead-band) and will inject or absorb the appropriate amount of active power to stay within this range. During the largest system disturbances, the LIL will also be capable of regulating frequency by performing instantaneous run-backs and run-ups, or significantly decrease or increase of power flow on the link, respectively. A scheme will eventually be developed to coordinate the HVdc run-backs and run-ups in attempt to lessen the impact of the most severe system disturbances. These frequency regulation techniques involving the instant exchange of active power into a power system demonstrates a new innovative concept known as virtual or synthetic inertia [54].

3.7.2 Maritime Island Link (ML)

The Maritime Link (ML) is another HVdc bipole link that was constructed as part of the Lower Churchill Project and electrically connects the IIS to the Nova Scotia (NS) power grid. The ML is approximately 500 km long and stretches across the Atlantic Ocean via two 170 km subsea cables, connecting the Bottom Brook Terminal Station in Newfoundland to the Woodbine Terminal Station in Nova Scotia, as shown in Figure 3-6 [47]. As previously discussed the ML serves two purposes. It provides a transmission path for Nalcor to sell power to the North American market and it allows Emera to reduce their carbon footprint by replacing coal-fired generation with clean renewable energy provided by Nalcor.

Figure 3-6: Maritime Link

The ML bipole is a more contemporary HVdc system that is based on Voltage Sourced Converter (VSC) technology and operates at a DC voltage of +/- 200 kV with a total power capacity of 500 MW[20] (export to NS) and 320 MW (import from NS) [37]. A VSC relies on controlled switching devices like Insulated-Gate Bipolar Transistors (IGBTs) for the conversion processes. In contrary to an LCC, a VSC has Static Var Compensator (SVC) capabilities and can therefore provide reactive power or voltage support to the connected AC systems. According to the Transmission Planning Group at NL Hydro, the ML also has a frequency controller and during an under-frequency and over-frequency event, the ML allows the IIS to absorb 150 MW (import power) or dissipate 60 MW (export power), respectively. Similar to the LIL, the ML will also be capable of power run-backs and run-ups.

The ML can also operate in a variety of different modes for operational flexibility and to protect against large system disturbances or abnormal voltage conditions. Table 3-3 was supplied by NL Hydro and

[20] 250 MW/pole

provides a summary of the various modes of operation for the ML and their associated active and reactive power capacities.

Table 3-3: ML Modes of Operation [52]

Mode of Operation	Capacity	
	Active (MW)	Reactive (MVar)
Bipole	500 (Export) 320 (Import)	+258 / -228
Monopole	250	+129 / -114
STATCOM (Bipole)	0	+258 / -228
STATCOM (Monopole)	0	+129 / -114

A pole trip will instantaneously cause the ML to switch to monopole mode allowing the other energized pole to operate at 1.0 per unit (250 MW). In contrast the LIL, there is no temporary overload capability associated with the ML. STATCOM is a mode in which the ML operates as a SVC and provides reactive power support to the connected AC systems.

The ML and LIL will eventually work in tandem to respond to significant deviations in system frequency, and eliminate the need for an UFLS scheme following any single contingency event[21]. This will be achieved with the help of both frequency controllers and/or by performing coordinated run-backs and run-ups on both HVdc links.

3.8 Summary

This chapter has provided the reader with the necessary background of the Newfoundland and Labrador power systems. The main objective of this thesis is to determine and measure the positive and negative effects of a hypothetical situation where the IIS is exposed to a massive penetration of EVs throughout the system. A working knowledge of the IIS and LIS is vital to understand the load flow and power system stability analysis outlined in Chapters 6 and 7.

[21] A UFLS scheme will be required for a double contingency event (eg. LIL bipole Trip)

Chapter 4

Power System Integration of Electric Vehicles

4.1 Introduction

This chapter provides an overview of some of the fundamental concepts pertaining to EVs, beginning with a short explanation of the operation and composition of a typical EV and a brief description of the three main types. This will be followed by a discussion on battery charging and how smart grid technology can be utilized to control and manage the process.

The primary objective of this chapter is to provide the reader with an understanding of how the integration of EVs onto a power system can collectively influence the grids day-to-day operation. This will involve a discussion on the technical advantages and disadvantages offered to the power system operator associated with the simultaneous connection of multiple EVs to the grid. This summary will provide the preliminary insight that will be necessary for the power system studies outlined in Chapters 6 and 7.

4.2 The Electric Vehicle

4.2.1 Operation

The composition of an EV is similar to that of an ICEV, with the exception of two key components, the engine and the fuel system. An EV utilizes the power of an electric motor to create torque that ultimately causes the axial to rotate and propel the vehicle, rather than relying exclusively on an internal combustion engine. Figure 4-1 is a simplified block diagram displaying the main components of a typical EV powered solely by batteries. The diagram also illustrates how each component interacts and plays a vital role in the overall operation of the vehicle.

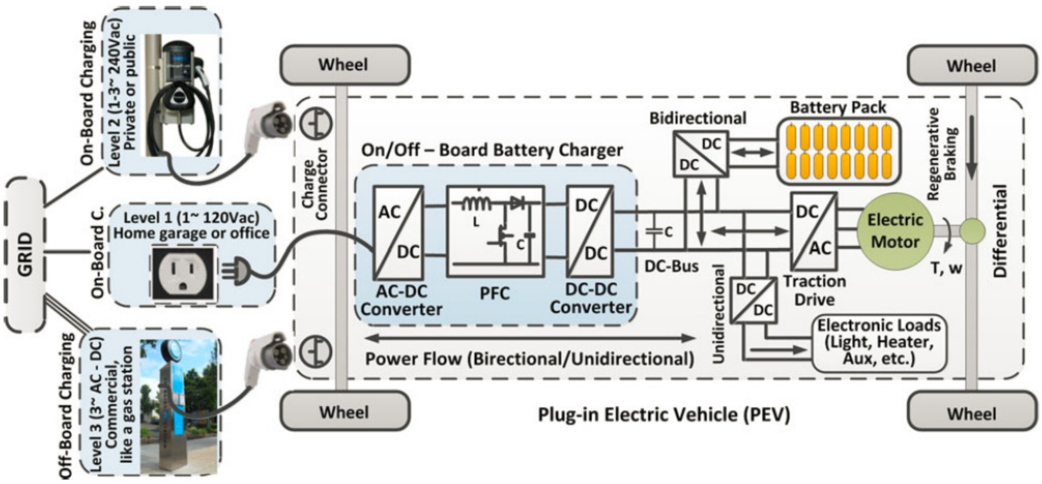


Figure 4-1: The Electric Vehicle – Block Diagram [55]

The electric motor within an EV can either be a DC brushless motor or AC induction motor, both of which have their advantages [56]. An AC induction motor provides more acceleration and better off-road performance and can also serve as a generator, giving it regenerative capability to help recharge the batteries during braking. A DC brushless motor and its associated equipment are generally more cost effective due to their size and weight [56].

All EVs rely to some degree on batteries as a source of energy. The energy stored in batteries is replenished by a battery charger that connects to an AC power supply. In order to charge the batteries from an AC supply, an AC/DC rectifier must convert the AC power from the grid into DC power. However, if DC power is directly supplied to the EV through an "Off-Board" charger, the "On-Board" AC/DC conversion process is bypassed.

Since batteries supply DC power, a DC/AC inverter ("Traction Drive") is essential to the operation of an EV with an AC induction motor. The inverter can also manipulate the frequency and magnitude of its AC output waveform and therefore provide the capability of controlling the car's speed and power [19].

An electric vehicle also utilizes DC/DC converters, which substitutes the traditional alternator and supplies DC power to low voltage circuits throughout the vehicle (eg. ancillary loads). A DC/DC converter is to DC power as a transformer is to AC power, as they are both used to adjust the voltage to a more desired level for specific applications.

As shown in Figure 4-1, power flow within an EV can be bidirectional and energy stored can be delivered back to the power grid. This concept is referred to as Vehicle-to-Grid (V2G) and will be discussed in further detail in Section 4.3.

4.2.2 Types of Electric Vehicles

There are three main types of EVs which differ based on their energy source(s). These three types of EVs are described as follows [57]:

1. **Battery Electric Vehicle (BEV[22]):** A vehicle that is solely powered by batteries that drive an AC or DC electric motor. The batteries of a BEV can be charged via Level 1, 2 or 3 charging, as described in Section 4.2.3.
2. **Hybrid Electric Vehicle (HEV):** Utilizes an internal combustion engine and an electric motor that work in tandem to minimize the vehicle's overall fuel consumption. The batteries are recharged by the combustion engine and/or through regenerative braking.
3. **Plug-in Hybrid Electric Vehicle (PHEV):** Similar to a HEV, but relies more heavily on the electric motor, since there they have more battery storage. The batteries are initially charged like a BEV, through a standard electrical outlet or DC charger. Once the battery's charge is fully depleted, the vehicle operates like a HEV and recharges the batteries using the combustion engine or regenerative braking.

The focus of the thesis will be on BEVs, since they have the largest impact on power systems. The following section will provide further details on the battery charging process and how the different charging configurations (or levels) can dictate the supply voltage and electrical demand requirements.

[22] Also commonly referred to as EVs

4.2.3 The Battery Charging Process

The battery charging process involves converting electrical energy into stored chemical energy. The energy stored within the batteries is eventually discharged as an electric current to operate an EV's electric motor. The following are the main sources of electrical energy that can be used as an input into the battery charging process:

1. **Power Grid:** Electrical energy is provided directly from the grid in the form of AC and/or DC power. The power from the grid can be transferred to EV's on-board charging system through conductive or inductive charging. Conductive charging uses a direct metal connection to transfer the power, while inductive charging delivers the power through magnetic induction [2].
2. **Regenerative Braking:** During the braking process, the AC induction motor of an EV can act as a generator and produce AC current. The AC power created can then be converted to DC power and used to charge the batteries.
3. **Combustion Engine:** EVs with traditional combustion engines ("Hybrids" or "HEVs"), use the engine to generate electricity for the purpose of charging their batteries.

This section will concentrate on the charging process involving the power grid as the energy source, since the primary objective of this chapter is to discuss the aggregated effect of multiple EVs simultaneously charging and/or discharging through the grid.

The most important specification of an EV is the distance it can travel on a full charge, which is largely dependent on the total energy capacity of its battery cells. The charging time of the on-board batteries is also crucial to the practicality of an EV, and is a function of the expected power level of the charger and the battery capacity of the vehicle. As summarized in Table 4-1, there are three types of charging power levels for EVs that are classified based on charging time that ranges from 12 minutes (Level 3) and 36 hours (Level 1). In contrast, ICEVs can be completely fueled up in less than five minutes. This has been one of the main drawbacks of EVs in comparison to their fuel-driven counterparts, from a technical and operational standpoint. However, constant advancements in the areas battery technology and power electronics indicate that the driving range and charging times for an EV will continue to progress and could presumably become comparable to that of an ICEV.

Table 4-1: Charging Power Levels (2013) [55]

Power Level Types	Charger Location	Typical Use	Energy Supply Interface	Expected Power Level	Charging Time	Vehicle Technology
Level 1 (Opportunity) 120 Vac (US) 230 Vac (EU)	On-board 1-phase	Charging at home or office	Convenience outlet	1.4kW (12A) 1.9kW (20A)	4–11 hours 11–36 hours	PHEVs (5-15kWh) EVs (16-50kWh)
Level 2 (Primary) 240 Vac (US) 400 Vac (EU)	On-board 1- or 3-phase	Charging at private or public outlets	Dedicated EVSE	4kW (17A) 8kW (32 A) 19.2kW (80A)	1–4 hours 2–6 hours 2–3 hours	PHEVs (5-15 kWh) EVs (16-30kWh) EVs (3-50kWh)
Level 3 (Fast) (208-600 Vac or Vdc)	Off-board 3-phase	Commercial, analogous to a filling station	Dedicated EVSE	50kW 100kW	0.4–1 hour 0.2–0.5 hour	EVs (20-50kWh)

Level 1 or 2 charging requires only 120Vac or 240Vac, respectively, and therefore is currently technical viable to be installed at the residential level. The fast-charging method, or Level 3 (Charging Station), requires specialized equipment that is not anticipated to be easily implemented or cost effective at the residential level within the foreseeable future [19]. Although the charging times can be much slower for Level 1 and 2 charging in comparison to Level 3, these forms of charging are more convenient for an EV owner to charge their vehicle at home. Level 3 charging stations are commercially being installed all over the world to accommodate the need for fast charging in an attempt to replicate the fill up time of a traditional automobile to support long travel distances. The EV charging times associated with Level 1 or 2 require significantly longer wait times to recharge, therefore it is not practical for an EV owner looking to travel far and quick. The widespread deployment of Level 3 charging stations will ultimately be crucial to the adoption rate of EVs throughout the world.

The demand requirements for charging an EV also depends on the type or level of charging, where the faster the charging time the higher the electrical demand [19]. As per Table 4-1, which was developed in 2013, the electrical demand required for charging an EV can range between 1.4 kW (Level 1) to 100 KW (Level 3). Since 2013 there have been advancements in the area of DC fast chargers in an attempt to reduce charging times, which has resulted in the development of chargers with demand levels as high as 350 kW [58]. Technical standards have been developed for chargers with demand levels up to 600 kW [7].

The electrical demand associated with charging a single EV is relatively small; however the aggregated effect of multiple EVs charging at once could result in a significant drain on a power grid. This potential strain could become even more pronounced if the EVs are being charged during normal peak conditions in the morning or at suppertime. Power utilities often use demand side management (DSM) techniques to reduce total system demand at the customer level during peak conditions and help alleviate the stress on a power system. The following section will highlight a DSM strategy that uses smart grid technology to control and manage the charging and discharging process of EVs connected to the grid.

4.3 Smart Grid and Vehicle-to-Grid Technology

The connection of multiple EVs to a grid has the potential to considerably impact the overall reliability of a power system. A power system could become overloaded and/or experience a deficit in generation capacity if the large aggregated demand associated with thousands of EVs charging simultaneously is neglected. It is therefore imperative that power utilities look at cost effective ways to avoid this potential strain on their power systems. One of the most popular approaches currently being explored involves the use of smart grid technology to manage EV charging and discharging.

A smart grid is a more automated grid that uses smart devices in an attempt to support the bi-directional flow of power and communication between the utility and customers with the objective to improve overall system reliability and better manage the exchange of energy. The Canadian Electricity Association (CEA) has defined the term Smart Grid as follows:

"An automated, widely distributed energy delivery network, the Smart Grid will be characterized by a two-way flow of electricity and information and will be capable of monitoring everything from power plants to customer

preferences to individual appliances. It incorporates into the grid the benefits of distributed computing and communications to deliver real-time information and enable the near-instantaneous balance of supply and demand at the device level" [59]

Smart grid technology has modernized and decentralized power systems by giving utilities more control at the distribution level. The idea of a smart grid was conceived decades ago, but its application is new and emerging due to society's desire to be more energy efficient. Utilities that have the ability to control and monitor demand at the customer level permits them to better balance supply and demand. The growing appeal for EVs and the emergence of smart grid technology should motivate utilities to start being proactive and look to leverage the energy storage capability of EVs to help improve the reliability of their power systems. A large scale deployment of EVs with smart grid technology would make coordinated charging and discharging much more advantageous for power utilities, while having minimal adverse effects on EV owners.

There are three developing concepts as it relates to smart grid technology with regards to the control of charging and discharging of EVs [16] and are illustrated Figure 4-2:

1. **Vehicle to Home (V2H)** – Supports the transfer of power from an EV's battery to the home. This type of control would permit homeowners to supply power to their homes during extended power outages.
2. **Vehicle to Vehicle (V2V)** – Allows for the transfer of power amongst multiple EVs. This type of control would mainly be used by an organization with a fleet of EVs in attempt to optimize the overall charging process to minimize energy consumption and prolong battery life.
3. **Vehicle to Grid (V2G) or Grid to Vehicle (G2V)** – Allows for the bi-directional transfer of power between and EV's battery to the power grid. V2G will be the focus of the remainder of this section.

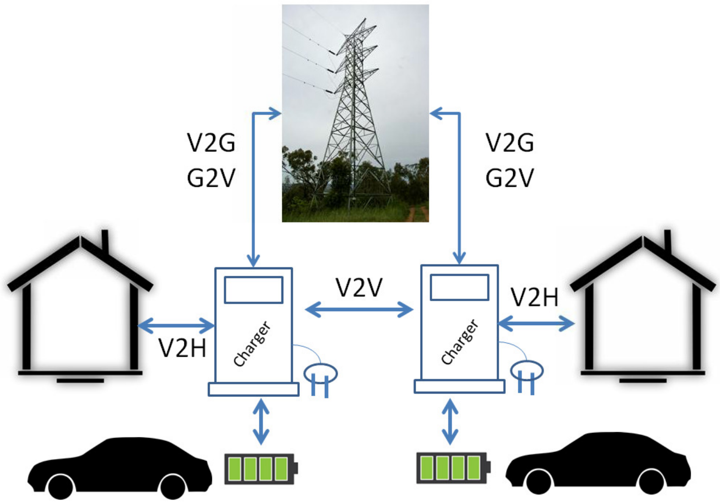


Figure 4-2: EV Smart Grid Technology

V2G provides the capability of bidirectional energy exchange between EVs and the grid which can offer several advantages to a power system [16]. V2G technology would essentially give the utility access to multiple small batteries, which could be used for peak load shaving, load leveling, harmonics filtering, reactive power compensation, generation spinning reserve and system frequency regulation [16]. The interconnection and utility control over multiple batteries would also facilitate the integration of more intermittent renewable energy sources to the grid. The power output associated with a V2G charger is dependent on battery size, the state-of-charge (SOP) of the battery, dispatch duration and the current rating of the charger[23] [60]. The rating of the charger is typically the most limiting factor for the power output[24].

V2G can also be unidirectional (or "V1G") by supporting just the control and management of a series of charging of EVs. Bidirectional V2G is more advantageous to a utility, but coordinated charging using V1G is still an extremely viable and less invasive DSM strategy. Coordinated charging allows the system operator to control the block of load associated with the charging EVs, giving them the ability to shift the

[23] The circuit breaker or conductor supplying the charger could be the limiting factor
[24] A 32A charger can provide 7.7 kW

demand away from peak periods when the system is more stressed. This type of control can defer or eliminate the requirement for future capacity upgrades or the operation of back-up generation.

V2G or V1G technology can also provide financial benefits to EV owners, since compensation is provided by the utility whenever power is supplied back to the grid. V1G technology also allows customers to take full advantage of Time-Of-Day (TOD) or Time-Of-Use (TOU) rates. TOD rates work by billing for the actual cost of consuming electricity at specific times of day where power is more expensive during peak conditions when demand is at its highest, and cheaper when demand is low [61]. Coordinated charging can schedule the charging of vehicles to times when electricity rates are low, translating into lower monthly energy bills to the customer. V2G chargers like the one designed by OVO Energy, have the capability of manually setting a charging schedule and a minimum charge level to ensure the vehicle always has enough stored energy to commute [62]. These chargers also provide EV owners the ability to automatically deliver power to the grid, allowing them to maximize their returns on export energy sales [62].

There are apprehensions accompanying the constant charging and discharging of the EV batteries using smart grid technology that it could shorten the life of the battery cells. However, studies show that this is not necessarily the case and depending on the charging/discharging patterns, battery degradation can actually be decelerated using smart grid technology [63] [64].

The benefits of smart grid technology and the expectation that the life cycle costs of EVs could eventually become more favorable in comparison to its counterparts, conceivably making EVs more prominent in the relatively near future. Therefore the widespread implementation of V2G technology should be pursued since it helps promote a mutually beneficial situation for EV owners, the utility and the environment.

4.4 The Impacts on the Grid

The connection of multiple EVs to an electrical grid can create opportunities and challenges for a power utility, since an EV can behave as an electrical load (charging) or an energy source (discharging). Some of the more common technical advantages and disadvantages are outlined in this section. Power system analysis using PSS®E was performed in Chapters 6 and 7 to further assess the impacts on the Newfoundland grid as it relates to some of the topics discussed in this section. The results of this analysis will help NL Hydro better understand and quantify the potential impacts as it specifically relates to their power grid.

4.4.1 Challenges

The prevalence of more EVs means power utility companies must ensure their power systems are capable of supporting the additional electrical demand associated with the charging of thousands of EVs. The adoption of EVs is expected to drastically increase on a global scale as identified extensively in Chapter 2. This trend will have a significant influence on power utilities throughout the world, since capital investment will be required to support the increased electrical energy and demand requirements. The following sections summarize some of the challenges that utilities must consider in the event there is a massive adoption of EVs.

4.4.1.1 Equipment Overloads

The demand requirements associated with an EV depends on the method of charging, as alluded to in Section 4.2.3. Therefore the type of charging being deployed by EV users will be a key variable in determining the potential strain they could have on the power system. However, regardless of the charging power level, a massive uptake in EVs will eventually cause existing electrical infrastructure to become overloaded and therefore could threaten power system reliability. The acceleration of equipment overloads would be much more rapid if fast charging technology became more utilized.

An increase in electrical demand driven by EVs would initially have more of an impact on power utility's distribution assets. According to a study conducted by Deloitte, "Charging Ahead: The Last Mile", it concluded the following:

> *"Our research revealed that utilities will not likely need to upgrade or expand transmission or generation capacity in the next ten years specifically to meet electric demand from EVs at projected adoption rates....However, the research did identify near-term impacts to the electric infrastructure that deserve further study at the local distribution level, 'the last mile,' including possible clustering of EVs on low-capacity distribution transformers, such as 25 kVA , and the potential impact on local transformers of any capacity if clusters of EVs charge simultaneously during hours of peak electric demand. The research also showed that utilities are studying and addressing these impacts".* [65]

These concerns can be alleviated by providing customers the means and incentives to charge their EVs during off-peak conditions [66]. Smart charging technology and TOD rates are two mechanisms used for DSM that a power company could utilize to shift most EV charging to off-peak periods [66]. This approach could avoid overloads to distribution transformers and feeders and thereby defer capital upgrades of the local distribution system. A substantial penetration of EVs could translate into overloads further upstream on transmission equipment, but they could also be mitigated using the same DSM strategies. Chapter 6 will investigate potential overloads on the Newfoundland transmission system that could arise from a large penetration of EVs.

4.4.1.2 Power Quality Concerns

A key objective for all electric utilities is to ensure their product meets quality standards based on a well-defined set of criteria approved by their regulatory body. Voltage is one of the parameters that define the quality of power. Voltage levels throughout a power system must remain within a prescribed range to avoid adverse effects on customer's electrical equipment. NL Hydro ensures that all steady state voltage levels on all their buses are constantly within at least +/-5% of nominal (0.95 per unit to 1.05 per unit)

[36]. However, following a contingency event or an emergency situation, it is acceptable for voltages to slightly deviate and can remain within +/-10% of nominal (0.9 per unit to 1.1 per unit) [36].

The addition of a significant amount of electrical load in the form of charging EVs could result in a drop in voltage levels across a power system. The extent of this reduction depends on the location and amount of electrical load connected [43]. Voltage levels tend to collectively be at their lowest during peak conditions when the system is experiencing the highest demand. Once voltage planning criteria is violated on any bus, and cannot be operationally mitigated, capital upgrades must be executed to improve power quality for customers. Similar to equipment overloads, low voltage conditions can be mitigated by using the same DSM strategies discussed in the previous section. Chapter 6 will investigate the potential low voltage conditions that could arise from the connection of a large number of EVs on the IIS.

The power electronics associated with EV charging equipment and their nonlinear nature can also present power quality issues for power utilities in the form of total harmonic distortion. Harmonics as it relates to power systems are higher-order frequency signals superimposed on the respective fundamental frequency waveform and are produced primarily by non-linear loads, which are loads that draw a non-sinusoidal current [67]. The introduction of harmonics to a power system can cause electrical equipment to overheat and have the potential to adversely affect the operation of protection [67]. The issue of harmonic distortion becomes even more pronounced for larger nonlinear loads like fast-charging stations (level 3) [68]. The effects of harmonics caused by EVs will not be evaluated as part of this thesis, but it is certainly a subject worth investigating for any future research involving EVs on the IIS.

4.4.1.3 Power Generation Requirements

A charging EV is considered an electrical load since it consumes energy from the grid to replenish the batteries. Power utilities must have an adequate amount of power generation to match forecasted load.

Therefore, an increase in the forecasted demand and energy requirements triggered by a large uptake of EVs could drive the need for more generation.

Similar to equipment overloads and low voltage conditions, generation expansion can be deferred or avoided by using DSM strategies as briefly discussed in Section 4.4.1.1. The requirement for more generation due to a large uptake of EVs will not be assessed as part of this thesis, but it is certainly a topic worth investigating as part of any future research involving EVs on the IIS.

4.4.2 Opportunities

Despite the fact EVs present their share of challenges to power utilities, they have also demonstrated their proficiency to improve the reliability and stability of a power system. An EV can be a controlled load and also act as an energy source by discharging power to the grid on the command of the utility with the aid of V2G technology. The following section briefly summarizes some of the benefits associated with V2G or V1G technology.

4.4.2.1 Peak Shaving

Peak shaving is a technique commonly used by power utilities to minimize the strain on a power system during peak conditions by reducing customer demand [69]. The objective of peak shaving is to help utilities avoid or defer the capital investment required to increase system capacity and/or reduce operational costs associated with back-up generation [69]. Although expensive to operate, diesel generators or gas turbines are generally used as back-up generation, because they are inherently the quickest form of generation to put into service. Peak conditions are not always predictable and therefore back-up generation must be capable of dispatching immediately.

V2G or V1G technology provides the capability to peak shave, allowing a power utility to signal each EV to discharge or charge on request [16]. This approach can essentially reduce the overall peak demand on the system and therefore avoid equipment overloads or minimize the need to dispatch expensive back-up generation.

4.4.2.2 Integration of Renewable Energy Sources

The integration of renewable energy sources into a power system is an environmental initiative for utilities to pursue in order to reduce their carbon footprint. However, most renewable energy sources are intermittent by nature and without the appropriate energy storage technology; less clean energy can be captured and stored. V2G systems can be setup to help store any excess energy produced by an intermittent renewable energy source like wind or solar radiation [18]. Smart meters can detect the production of excess energy which can then be directed into the batteries of EVs that are not fully charged [18]. All the batteries with the EVs on the grid could work together to help maximum the energy production of these intermittent renewable energy sources.

4.4.2.3 Improved Power System Stability

The stability of a power system refers to its ability to maintain a desired state of equilibrium in order to maintain a reliable and quality supply of power to its customers, even when exposed to a severe disturbance. The criterion for equilibrium is defined in terms of system parameters that determine power quality which include voltage and frequency. Frequency and voltage fluctuations will likely occur when power systems are exposed to large disturbances such as faults and line trips. The magnitude of these fluctuations will vary depending on the severity of the disturbance. In order to maintain stability, severe disturbances must be cleared within the critical clearing time that is defined by the parameters of a given system [70].

Power system engineers have discovered ways to leverage smart grid technology, including the concept of V2G to help lessen the negative effects caused by disturbances to the power system [70]. Frequency and voltage fluctuations can be reduced and critical clearing times can be extended by controlling the power output of each EV on a power grid, and thereby improving power system stability [70]. Chapter 7 will investigate and quantify the prospective power stability improvements on the Newfoundland transmission system that could be offered by leveraging the V2G technology linked to thousands of EVs connected across the province.

4.4.2.4 Reactive Power Compensation

The nonlinear nature of an EV charger introduces harmonic distortion to the grid, but they do have the ability to improve power quality in other ways. An EV can provide reactive power compensation, since chargers can operate in all four[25] quadrants of the P-Q plane [71]. This capability would allow utilities to use EVs for Power Factor Correction (PFC) and voltage regulation, therefore functioning as small portable SVCs. The benefits of reactive power support that can be provided by EVs will not be assessed in this thesis, but it is certainly a topic for future potential research involving EVs on the IIS.

4.5 Summary

This chapter has provided the necessary context as it relates to the impacts of integrating a substantial number of EVs onto a power grid. This overview has provided the appropriate background critical for understanding the analysis outlined in Chapters 6 and 7. The analysis conducted in these chapters quantifies some of the potential advantages and disadvantages associated with a massive adoption of EVs in Newfoundland.

[25] Assuming the charger is bi-directional (V2G)

Chapter 5

Power System Studies - Preface

5.1 Introduction

The purpose of this chapter is to serve as a preamble for the power system studies outlined in Chapters 6 and 7. The discussion will begin with a brief description of the computer modelling software that will be utilized to conduct the load flow and transient stability analysis. This will be preceded by an outline of each developed EV penetration case that will be simulated and evaluated to determine the positive and negative impacts that each scenario has on the IIS. The chapter will conclude with an overview of the assumptions and methodology used for the power system analysis presented in the proceeding chapters.

5.2 Power System Simulator for Engineers (PSS®E)

Power System Simulator for Engineers, or PSS®E, is a computer modelling software package that is capable of performing a wide variety of power system analysis to reproduce or predict real-life events, including load flow and dynamic/transient stability simulations [72]. PSS®E was developed by Siemens PTI and is considered the industry standard for transmission planning throughout the world [72]. NL Hydro's Transmission Planning group uses PSS®E[26] to perform detailed power system analysis on their transmission systems. The analysis described in chapters 6 and 7 were also completed using PSS®E in an effort to maintain consistency.

A power system can be digitally re-constructed and analyzed using PSS®E, with load flow analysis being its core functionality involving the calculation of three phase voltages and power flow throughout the modelled system. Figure 5-1 shows a portion of the IIS following a load flow simulation. The graphical representation of a system in PSS®E is referred to as a slider diagram.

[26] Version 33

PSS®E also has a comprehensive library of models that replicate the dynamic behavior of equipment such as, but not limited to; generators, exciters, turbines, governors, HVdc converters and PSSs. The dynamic and transient simulations performed by PSS®E heavily rely on the interaction of these models to accurately predict the response of a power system following various types of disturbances.

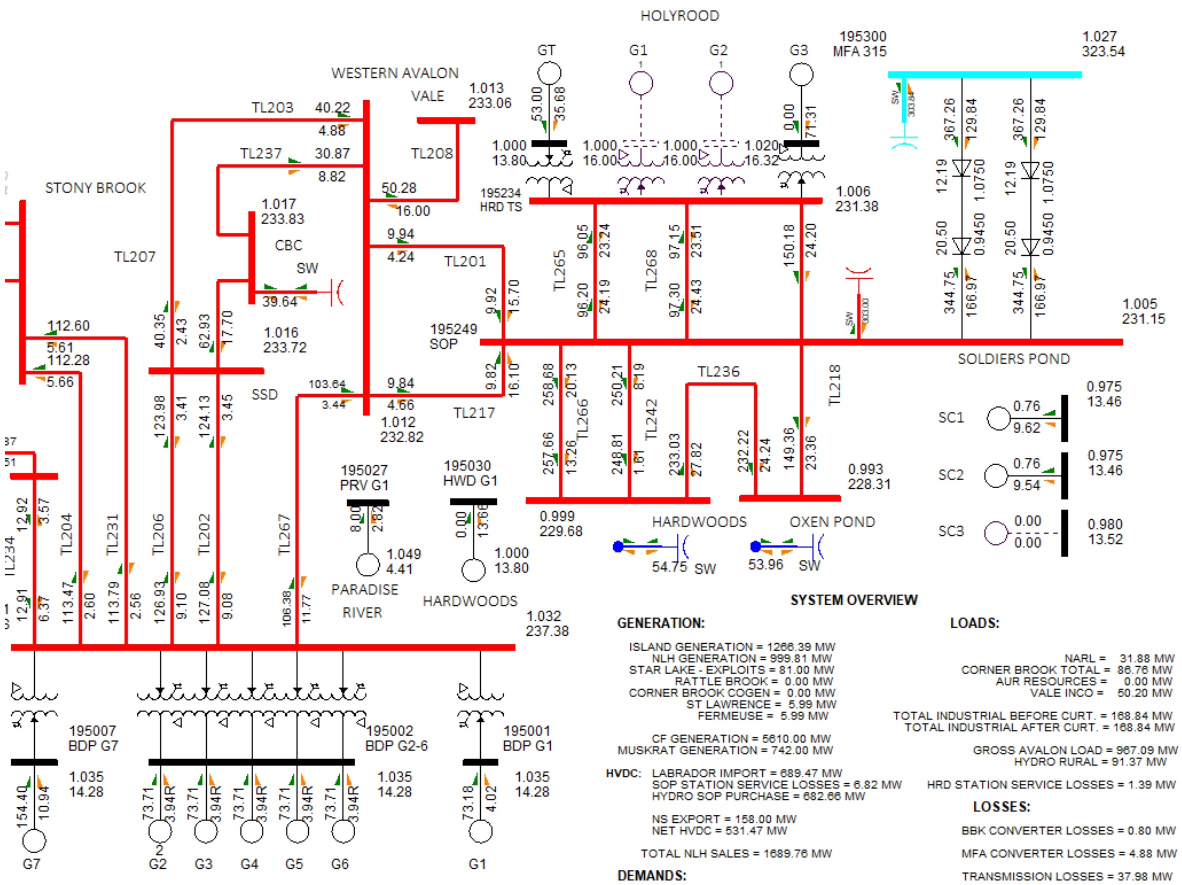


Figure 5-1: PSS®E Slider Diagram (Portion of IIS)

5.3 Forecast Development

NL Hydro's Operating Load Forecast is an input into the NLSO's Annual Planning Assessment of the Newfoundland and Labrador transmission system [73]. Each forecast is modelled in PSS®E and simulated to determine the timing of possible future capacity upgrades over a ten year horizon [73]. The load flow analysis in Chapter 6 will be guided by a similar process and will assess the potential impacts associated with each forecast scenario summarized in the following sections.

5.3.1 Baseline Forecasts

5.3.1.1 NL Hydro Baseline Forecast

On an annual basis, NL Hydro prepares an energy and demand forecast for the IIS and LIS. The examination of economic and industry trends allows NL Hydro to predict the total expected energy consumption and the aggregated peak demand over the next five years for both interconnected systems. The demand forecast is extended to 20 years for planning purposes, to assess the IIS and LIS to ensure they can support projected demand for the foreseeable future. The 20-year extended demand forecast for the IIS and LIS can be referenced in Appendix D. The system peaks for the IIS and LIS occur during the winter season due the high penetration of electric heat in Newfoundland and Labrador. It is estimated that approximately 45 to 50 percent of the system winter peak can be contributed to electric heat [74]. The system tends to experience two peaks throughout the day, one in the morning and one at suppertime.

NL Hydro's long-term capital plan is driven by their operating load forecast, which is a key input into the establishing electricity rates, and therefore NL Hydro does not include any prospective customer load growth in its forecast based on speculation. For this reason, NL Hydro has forecasted a much slower adoption rate of EVs over the next 20 years in comparison to Dunsky [75]. NL Hydro is projecting approximately 8,300 new EVs by 2039 which is expected to add approximately 6.7 MW to the total IIS peak demand, as shown in Figure 5-2.

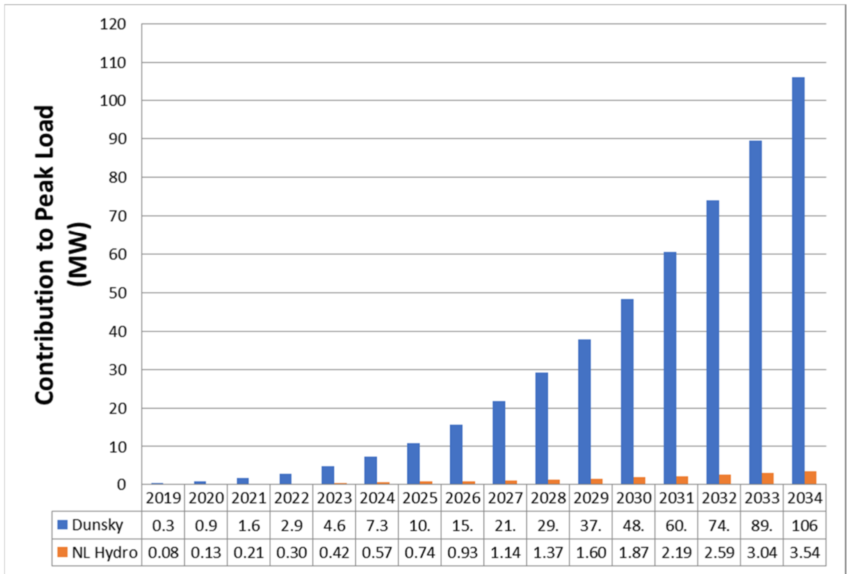
The aggregated demand contribution of all EVs on a power system during peak conditions can naturally be reduced by the application of TOD rates, since they provide the financial incentive for EV owners to charge their vehicles during off peak times. The introduction of TOD rates is currently being considered by NL Hydro, as per the Reliability and Resource Adequacy Study submitted to the PUB in November 2018 [32]. However, without any official approval from the utility regulator, the impact of TOD rates cannot be included in NL Hydro's demand forecast and therefore was not considered for the power system studies in Chapters 6 and 7.

5.3.1.2 Dunsky Baseline Forecast

A CDM study was completed by Dunsky Energy Consulting and filed to the PUB in August 2019. An assessment of the potential EV adoption in Newfoundland and Labrador and its corresponding impact on system peak demand was performed as part of this study [31]. Dunsky Energy Consulting developed a 15 year forecast of the peak demand contributions of EVs and is shown in Figure 5-2 [31]. The bar graph indicates that the total contribution to the IIS and LIS peak demand which is expected to be 106 MW by 2034. An extrapolation of Figure 5-2 to 2039 (Year 20) would translate into a total EV contribution of 177 MW, 168 MW[27] of which would be applied to the IIS. This corresponds to approximately 65,000 EVs, where 91% of them would be LDV.

Figure 5-3 is the projected load profile of a peak day in Newfoundland and Labrador in the year 2034, where the shaded blue area under the graph represents the incremental increase due to EVs. This profile was conservatively developed by not considering coordinated EV charging or TOD rates, which would undoubtedly reduce the peak demand contribution of EVs. The Dunsky report states each light duty and medium/heavy duty EV is estimated to individually contribute 1.5 kW and 13.3 kW to the IIS peak, respectively [31].

[27] 95 % of vehicle sales in the province are in Newfoundland [78]



	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Dunsky	0.3	0.9	1.6	2.9	4.6	7.3	10.	15.	21.	29.	37.	48.	60.	74.	89.	106
NL Hydro	0.08	0.13	0.21	0.30	0.42	0.57	0.74	0.93	1.14	1.37	1.60	1.87	2.19	2.59	3.04	3.54

Figure 5-2: Forecasted Demand Contributions from EVs (MW) [31] [75]

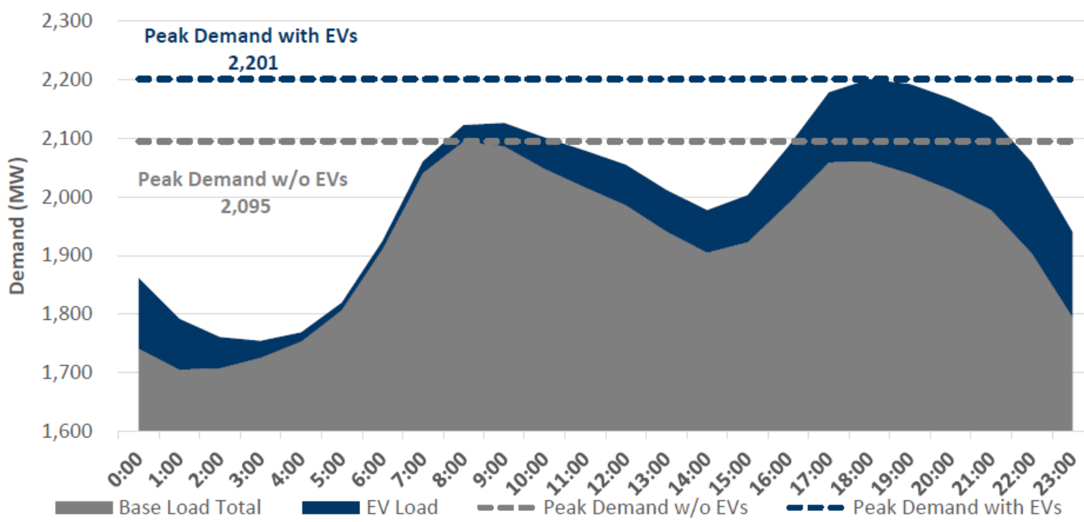


Figure 5-3: 2034 Load Profile with and without EVs (No Coordinated Charging or TOD Rates) [31]

5.3.2 *Sensitivity Forecasts*

Sensitivity analysis is often performed on a demand forecast to quantify the impact of a sudden change in the local economy or consumer behavior. This type of proactive approach is often conducted by NL Hydro to establish a contingency plan in the event the hypothetical scenarios were to become a reality. The following are the sensitivity cases that will be considered for the load flow analysis:

- 250 MW EV Contribution to System Peak – Estimated 97,600 EVs[28]
- 300 MW EV Contribution to System Peak – Estimated 117,100 EVs
- 400 MW EV Contribution to System Peak – Estimated 156,100 EVs
- 500 MW EV Contribution to System Peak – Estimated 195,200 EVs

Note: 91% of EVs are expected to be LDV, while the remaining EVs would be MDV, LDV or buses [31]

5.4 Study Cases and Assumptions

In order to facilitate the power system analysis, multiple PSS®E cases were developed to represent the forecast scenarios described in Section 5.3. These study cases are specifically setup to reflect the 2039 (Year 20) forecasted peak demand with varying amounts of charging EVs connected to the IIS. Each PSS®E case is a modified version of the 2029 peak case created by NL Hydro's Transmission Planning Group and are summarized in Table 5-1. An appreciable uptake of EVs in Newfoundland is not anticipated for 15-20 years as indicated in Figure 5-2, and therefore the 2039 peak forecast (Year 20) was used as a starting point for the development of the PSS®E case models. The difference in total system peak demand associated with general customer growth (no including EVs) between 2020 and 2039 is expected to be approximately 170 MW.

[28] Comparable to the $20 Million Investment Case developed by Dunsky [31]

A set of study assumptions must be established to maintain consistency throughout the load flow and power stability analysis and applied to each case listed in Table 5-1. The EV and system specific assumptions for the analysis in Chapters 6 and 7 are provided in Table 5-2.

Table 5-1: Study Cases

Case ID	Case Description	IIS Demand (MW)			Island Total Generation (MW)	HVdc Import/Exports(MW)		New Generation Installed (MW)[29]
		General Customer Demand[30]	EV Demand	Total Demand		ML	LIL[31]	
BASELINE CASES								
EV1	Status Quo (NL Hydro)	1,947	6.5	1,953	1,387	158 Export	730 Import	125
EV2	Status Quo (Dunsky)	1,971	168	2,139	1,574	158 Export	730 Import	310
SENSITIVITY CASES								
EV3	250 MW of EV Peak Contributions	1,978	250	2,228	1,663	158 Export	730 Import	400
EV4	300 MW of EV Peak Contributions	1,983	300	2,283	1,719	158 Export	730 Import	450
EV5	400 MW of EV Peak Contributions	1,997	400	2,397	1,831	158 Export	730 Import	565
EV6	500 MW of EV Peak Contributions	2,009	500	2,509	1,945	158 Export	730 Import	680

[29] Generation added to accommodate the increase in general customer demand and EV penetration. The actual generation requirement would have to be determined through an additional supply and resource adequacy study. The assumption for this analysis is new gas turbines at Soldiers Pond Terminal Station.
[30] Including transmission losses and station service loads
[31] As measured at Soldiers Pond

Table 5-2: Study Assumptions

EV Specific	System (IIS) Specific
Power factor (pf)[32]: • Load Flow Analysis: 0.95 pf lagging • Stability Analysis: 1.00 pf (unity)	ML will only export power at a value of 158MW[33] for the load flow analysis. Runbacks will be maximized following LIL bipole trip
The system-wide peak load impact of the total LDV and MDV/HDV EV population is estimated at 1.5 kW and 13.3 kW[34] per EV, respectively. These demand values were derived based on the diversity in vehicle utilization and charging patterns [31].	The ML frequency controller will be enabled with a frequency dead-band of +/-0.5 Hz (59.5 Hz/60.5 Hz). The ML frequency controller can instantaneously provide up to 150 MW of frequency support during an under-frequency event on the IIS, assuming there is enough import capacity. The frequency controller action is not available following a ML runback of greater than 150 MW
Peak Demand for EV (Level 2 Charging) : • LDV: 7.7kW[35] • MDV/HDV: 13.3kW[36] (average)	LIL imports were set to 730 MW and 900 MW for the load flow and transient stability analysis, respectively
EV charging patterns remain consistent throughout the year. There is more EV usage over the summer season, but it is assumed this is offset by additional charging required in the winter for EV auxiliary loads	The following demand-side management strategies were not considered for the load flow analysis: • TOD rates • Coordinated charging
EV breakout by type [31]: • LDV: 90.8% • MDV/LDV: 9.2%	Additional generation requirements to meet increased demand will be modelled in the form of gas turbines on the Avalon Peninsula in Soldiers Pond[37]. The 13.8 kV bus voltage will be held to 1.0 p.u.
All EVs will have V2G capability for the power system stability analysis	Spinning Reserve Requirement: Greater than or equal to the real power output of the largest unit on IIS – 206 MW Muskrat Falls Unit
V2G output per EV will be considered the same as their individual contributions to the system peak (LDV: 1.5 kW and MDV/HDV: 13.3 kW)	Coincident Factors[38]: • Newfoundland Power Systems: 99% • NL Hydro Systems: 93% The assessment of transformer and line loading will consider non-coincident and coincident peaks, respectively
V2G time delay: Instantaneous (<1 cycles) V2G frequency dead-band: +/-0.4 Hz (59.6 Hz,60.4 Hz)	Distribution System Losses[36] • Urban Systems: 1.8% • Rural Systems: 4.7%
Stability cases have 100 MW of EVs charging throughout the system pre-disturbance	Hardwoods and Stephenville gas turbines are retired
The distribution of EVs across the province for each case was derived from new vehicle registrations statistics (2017) per economic zone as outlined in Appendix E	Two Soldiers Pond Synchronous Condensers in-service.
All connected EVs are considered BEVs	Power System Stabilizers (PSSs) are not activated

[32] A bidirectional EV charger has the capability to operate in all four quadrants of the P-Q curve [66]
[33] Emera Block
[34] This is a calculated average between MDVs and HDVs based on information provided in the Dunsky Report.
[35] Level 2 - 32A charger (LDV)
[36] Calculated based on information provided in Dunsky Report [31]
[37] New gas turbine governors will operate in "Power Mode" and will not provide system frequency support
[38] Provided by NL Hydro's Transmission Planning Group

5.5 Study Methodology

5.5.1 Load Flow Analysis

The power system analysis summarized in Chapter 6 involves the performance of multiple load flow simulations on each of the study cases described in Section 5.4. Figure 5-4 is a screenshot from PSS®E showing the simulation parameters that were set for the entire load flow analysis. The peak contributions associated with EVs were added as electrical loads to every load bus throughout the IIS. The EV contributions were proportional scaled for each model case in accordance to the breakout provided in Appendix E.

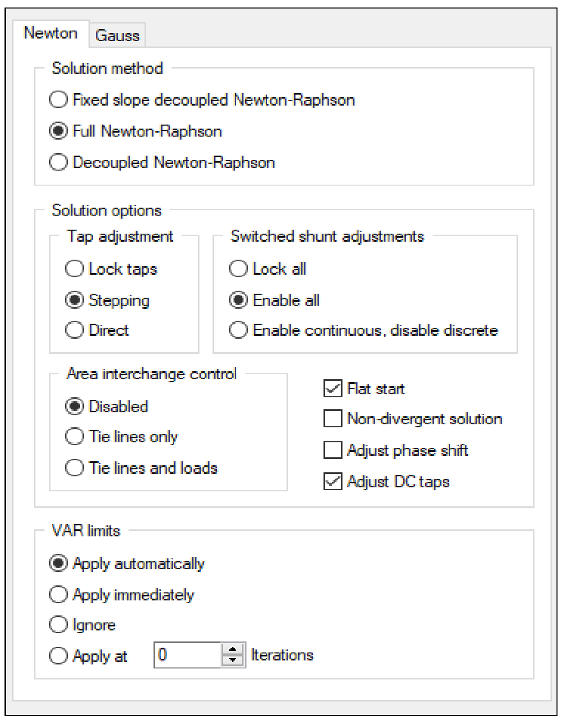


Figure 5-4: Load Flow Parameters

Each PSS®E load flow simulation calculates the voltage at every bus and the real and reactive power flow through each transmission line. The results of each simulation will be compared against NL Hydro's Transmission Planning Criteria as described below [76]:

Pre-Contingency Criteria (N-0): With all equipment in-service (system intact) on the IIS there should be no transmission overloads and all bus voltages must be between 0.95 and 1.05 per unit.

Single Contingency Criteria (N-1): The IIS must also be capable of withstanding the loss of a single element. Equipment must remain below 100% of its rating and all bus voltages must be between 0.9 and 1.1 per unit. The single elements that will be considered include:

- A Transmission line (not supplying a radial[39] system)
- A Generator[40]
- A Synchronous Condenser
- A Transformer
- Shunt Reactive device (capacitor or reactor)
- One pole of an HVdc bipole system

The loss of a transmission line or power transformer supplying a radial system is deemed acceptable by the NLSO from a planning perspective [76]. The single contingency analysis will be performed using the AC contingency calculation (ACCC) function built into PSS®E.

When a violation is identified on the IIS, operational modifications will be the first strategy to improve voltage conditions or eliminate the equipment overload(s). These actions will include the following:

- Change generation dispatch
- Adjust transformer tap settings
- Adjust HVdc imports/exports levels (if possible)
- Load curtailment
- Change system confirmation - Line switching/Load transferring

In the event the violation cannot be removed operationally during the analysis, it will be recorded and a capital upgrade will be recommended to alleviate the abnormal condition(s). The scope of the analysis will primarily focus on NL Hydro assets and not NLP assets.

[39] A detailed definition of a radial system is provided in the NLSO Transmission Planning Criteria document (TP-S-007) [35]
[40] The lose of generation is addressed by maintaining a spinning reserve. This contingency is assessed to determine impact on voltage levels and overloads of equipment upstream of generation

5.5.2 *Transient or Frequency Stability Analysis*

The purpose of the power system stability analysis is to quantify the benefit of multiple EVs connected to the IIS using V2G technology providing frequency regulation in the of event of a large system disturbance. The additional frequency regulation provided by V2G chargers could reduce the amount of UFLS experienced on the IIS following the sudden loss of the LIL bipole.

Previous studies confirm that UFLS should not occur on the IIS following the loss of the largest online generation unit or a HVdc pole [77]. ML runbacks and frequency controller action can instantaneously supply an adequate amount of real power to avoid under-frequency; given operating limits are not exceeded [77]. The sudden loss of the LIL bipole is the only system disturbance that NL Hydro accepts UFLS since it is categorized as a double contingency event; however frequency must still remain above 58 Hz to ensure the IIS remains stable [77]. NL Hydro's UFLS scheme has recently been updated in preparation for a fully commissioned LIL bipole and is presented in Table 5-3.

The primary objective of the power system stability analysis discussed in Chapter 7 is to quantify the amount of EVs that would have to be connected to the IIS with V2G capability to avoid UFLS for various system conditions and configurations. This relationship will be established by performing numerous PSS®E stability simulations for various load conditions and ML export levels. The simulation parameters for each simulation are shown in Figure 5-5.

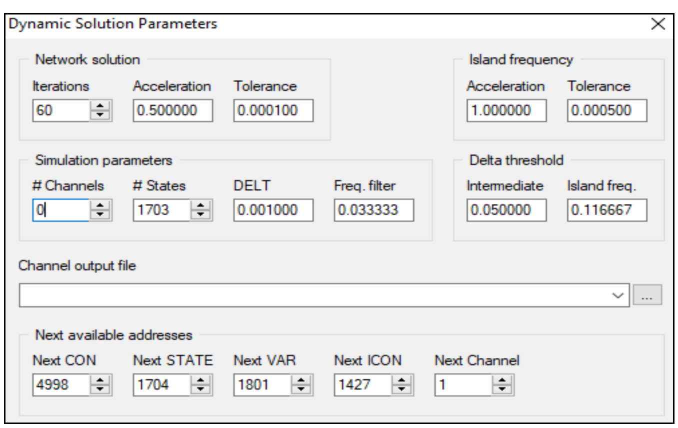


Figure 5-5: Dynamic Solution Parameters

Table 5-3: NL Hydro UFLS Scheme (Year 2039)[41]

Frequency Block (Hz)	PSS®E Bus Number	Bus Description	Estimated Load (MW)[42]	Block total (MW)
59.0	196565	Kenmount (KEN)	53.2	64.8
	195135	Glovertown (GLV)	11.6	
58.9	196546	Blaketown 66 kV (BLK)	36.7	50.6
	196221	Greenhill (GRT)	13.9	
58.8	195624	Massey Drive (MDR)	90.8	186.3
	196570	King's Bridge (KBR)	42.0	
	196561	Chamberlains (CHA)	53.5	
58.6	195144	Clarenville (CLV)	57.7	209.5
	196568	St. John's Main (SJM)	49.7	
	196563	Glendale (GDL)	58.2	
	196574	Pulpit Rock (PUL)	37.0	
	195432	St. Alban's (BDE)	6.9	
58.4	195126	Grand Falls (GFL)	42.9	114.3
	196572	Ridge Road (RRD)	39.7	
	195133	Gambo (GAM)	31.7	
58.3	195132	Gander (GAN)	24.7	197.1
	196573	Virginia Waters (VIR)	67.9	
	195655	Hardwoods (HWD)	87.2	
	195157	Marystown (MSY)	17.3	
58.2	195409	Parson's Pond (PPD)	0.8	197.1
	195407	Rocky Harbour (RHR)	4.0	
	195408	Cowhead (CHD)	1.9	
	195130	Cobb's Pond (COB)	33.9	
	195165	Blaketown 138 kV (BLK)	12.0	
	195167	Bay Roberts (BRB)	23.9	
	196562	Broad Cove (BCV)	25.4	
	196564	Goulds (GOU)	25.9	
	196560	Kelligrews (KEL)	22.6	
	196567	Stamp's Lane (SLA)	46.7	
58.1	195435	Conne River (CRV)	2.7	12.7
	195436	English Harbour West (EHW)	2.7	
	195437	Barachoix (BCX)	7.3	
			Total:	**1,032**

The dynamic behavior of V2G technology can be replicated using a PSS®E standard dynamic model called LDSHBL. The parameters or CONs associated with the LDSHBL model are shown in Table 5-4. This is a load model that is typically used for UFLS, but it can be manipulated to switch loads from absorbing to delivering real power at particular frequency thresholds (CON J) by specifying the load shed percentage (CON J+2) greater than 100%. The activation of V2G technology will be triggered at

[41] Courtesy of NL Hydro. Pickup time delay is assumed to be 1 cycle or 0.0167 seconds. 100% of load is shed for each block with the exception of the 58.2 Hz and 58.1 Hz, which shed 80%

[42] NL Hydro's Preliminary UFLS Scheme that is subject to change. Demand values based on 2039 Load Forecast

particular frequency threshold (59.6 Hz), and will be included in the proposed under-frequency action plan for the loss of the LIL bipole as shown in Table 5-5.

Table 5-4: LDSHBL Dynamic Model

CONs	Value	Description
J		f_1, first load shedding point (Hz)
J+1		t_1, first point pickup time (sec)
J+2		$frac_1$, first fraction of load to be shed
J+3		f_2, second load shedding point (Hz)
J+4		t_2, second fraction pickup time (sec)
J+5		$frac_2$, second fraction of load to be shed
J+6		f_3, third load shedding point (Hz)
J+7		t_3, third point pickup time (sec)
J+8		$frac_3$, third fraction of load to be shed
J+9		T_b, breaker time (sec)

Table 5-5: Under-Frequency Action Plan – LIL Bipole Trip (Proposed)

Step	Frequency Threshold (Hz)	Strategy	Load Shed (MW)	Real Power Supplied (MW)	Time delay (cycles)
#1	60.0	ML Runback	Variable[43]	-	<1
#2	59.6	V2G	100% of Charging EVs[44]	Variable	<1
#3	59.5	ML Frequency Control[45]	N/A	0-150	<1
#4	59.0 - 58.1	UFLS	See Table 5-3	N/A	1

The frequency threshold for V2G was derived based on frequency data provided by NL Hydro shown in Figure 5-6. During the month of January 2020 the frequency predominantly stayed within the range of 59.6 Hz and 60.4 Hz during normal operation. The frequency is only expected to drop below 59.6 Hz during a system disturbance, and therefore it has been established as a threshold for V2G activation.

A series of PSS®E dynamic simulations will be performed at various ML export levels to establish a relationship between IIS frequency response and the number of connected EVs following a LIL bipole trip during high power operation (900 MW). The four different ML export levels that will be considered include; 0 MW, 158 MW, 300 MW and 500 MW. The system load conditions will also be varied to determine if there is a correlation between EV transient contributions and total online generation.

[43] Depends on available ML export levels. Runbacks apply when exports exceed 150 MW.
[44] Assumed to be 100 MW of EVs charging for each case
[45] Activated when ML output less than 150 MW

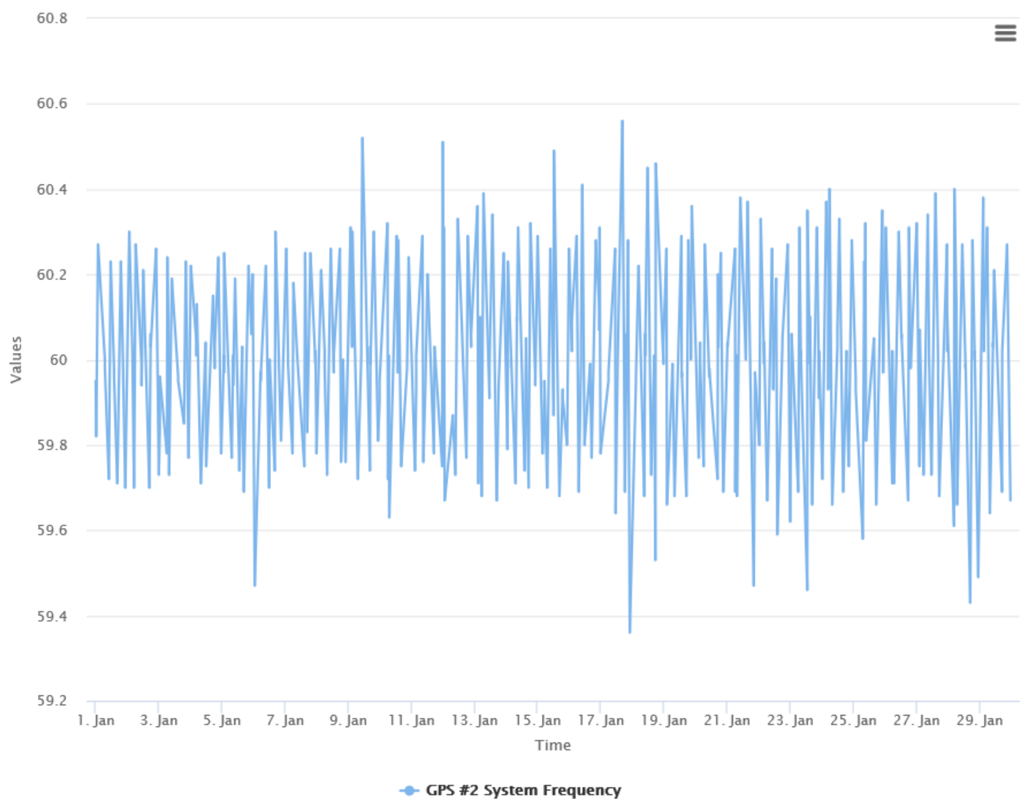


Figure 5-6: IIS System Frequency - January 2020 [34]

5.6 Summary

This chapter has presented the scope and detailed plan for the power system analysis that will be the primary focus of the subsequent chapters. The study cases, assumptions and methodology have been defined to help guide and ensure consistency throughout the load flow and stability analysis.

Chapter 6

Load Flow Analysis: Impact of High EV Penetration

An increase in electrical load on the IIS in the form of charging EVs could potentially result in equipment thermal overloads or abnormal voltage conditions on the IIS. This chapter will assess each scenario defined in Chapter 5 and conduct load flow analysis using PSS®E to determine if there are any violations to NL Hydro's planning criteria as it relates to voltage levels and equipment overloads. The IIS will be reviewed for each study case in the fully intact state (N-0) and following the loss of each single transmission element (N-1). Technically viable solution(s) will be proposed to alleviate the identified violations, but economic analysis will not be conducted to determine the lowest cost option.

The implementation of coordinated charging and/or TOD rates would eliminate or defer any violation caused by a significant increase in EV penetration. However, the objective of this analysis is to demonstrate the importance of these DSM strategies by showing the potential capital upgrades that would be required without them. This will also be demonstrated by showing how the deployment of EVs with V2G capability on the IIS can shave the total system peak and could theoretically reduce or defer NL Hydro's requirement for generation expansion.

6.1 Load Flow Overview

Load-flow studies are one of the main tasks performed by power system engineers for future planning and operational purposes. They involve the execution of numerical methods to determine the steady-state real and reactive power flow through the various elements in a power system and the voltage levels at each bus in the phasor domain. These parameters are compared against a set of criteria defined by the utility that must be enforced. The two most commonly used numerical methods for load-flow analysis include Newton Raphson and Gauss-Seidel [78]. Full Newton-Raphson will be the approach used by PSS®E for this analysis, as indicated in Figure 5-4 in Chapter 5.

All current carry elements on a power system have a thermal rating that define it's withstand capability and is often dependent on ambient temperature [78] [79]. All of NL Hydro's equipment ratings are defined in the NLSO Facility Rating Guide (TP-S-001) [79]. The analysis performed in this chapter will compare the load flow results against these ratings for the scenarios outlined in Section 5.4. An equipment overload (N-0 or N-1) would trigger the need for capacity upgrades or operational alterations to reduce the loading and ensure system reliability for the foreseeable future.

The bus voltage levels throughout a power system inherently fluctuate due to changes in reactive power flow and voltage drop. Voltage drop is a function of current flow through electrical impedance resulting in the dissipation of energy or I^2R losses [78]. An AC power system requires reactive power to support the delivery of real power across a transmission line by maintaining the desired voltage levels [78]. The supply of reactive power from AC generators, capacitors, SVCs and line charging intrinsically boosts the voltage on the system. Line charging is a phenomenon in which a lightly loaded transmission line behaves like a capacitor and supplies reactive power [78]. Inductive loads absorb reactive power which has an opposing effect and contributes to the reduction of bus voltages.

Low voltage levels are more prone during peak load conditions when more real and reactive power is being absorbed by customers. Table 6-1 presents some of the operational and capital strategies that are commonly deployed by utilities to alleviate thermal overloads and low voltage conditions.

Table 6-1: Mitigating Measures to Eliminate Thermal Overloads and Low Voltage Conditions [73] [76]

Strategy	Thermal Overloads	Low Voltage Conditions
Capital	• Replace overloaded element with higher rated equipment • Install generation downstream of overloaded equipment • Install equipment parallel with overloaded element to offset load	• Install On-Load Tap Changers (OLTC) on Transformer(s) • Install Shunt Devices - Capacitors, Reactors, SVCs and/or STATCOM • Install generation for voltage regulation • Install additional lines/transformers to reduce voltage drop
Operational	• Dispatch Generation downstream of overloaded equipment (or Re-dispatch) • Load curtailment • System reconfiguration – line switching, load transferring	• Adjust Transformer Tap Settings/Positions • Dispatch Generation or Synchronous Condenser(s) • Switching of Shunt Devices - Capacitors, Reactors, SVCs and STATCOM • Load curtailment • System reconfiguration – line switching, load transferring

6.2 Load Flow Analysis - Results

6.2.1 Pre-Contingency Analysis (N-0)

This section will provide the results of the pre-contingency steady state analysis for the fully intact IIS. Tables 6-2 and 6-3 include load flow results for the transmission line and transformer loading as a percentage for each case, respectively. Lines or transformers dedicated for a single industrial customer, generation stations or are normally out-of-service were not assessed. The cells highlighted red in Tables 6-2 and 6-3 designates a thermal overload, while the yellow cells indicate a loading between 90 and 100 percent.

Table 6-2: Transmission Line Loading (%)

Line	From	To	Rating (MVA)[2]	CASES					
				EV1	EV2	EV3	EV4	EV5	EV6
TL201	Western Avalon	Soldiers Pond	322	15.7%	32.7%	35.8%	38.5%	45.8%	53.0%
TL202	Bay D'Espoir	Sunnyside	370	24.9%	21.4%	20.5%	19.5%	16.1%	13.0%
TL203	Western Avalon	Sunnyside	347	2.5%	18.3%	19.0%	20.8%	25.8%	30.9%
TL204	Bay D'Espoir	Stony Brook	470	27.1%	30.8%	32.9%	34.3%	36.6%	38.8%
TL205	Stony Brook	Buchans	322	17.3%	20.2%	21.5%	22.3%	24.1%	25.7%
TL206	Bay D'Espoir	Sunnyside	370	24.8%	21.3%	20.5%	19.4%	16.1%	13.0%
TL207	Sunnyside	Come-By-Chance	460	5.2%	18.0%	22.3%	22.4%	23.1%	24.3%
TL209	Stephenville	Bottom Brook	370	14.6%	16.0%	16.7%	17.1%	17.9%	18.8%
TL210a	Stony Brook	Glenwood	144	42.6%	44.0%	45.9%	47.3%	48.7%	49.7%
TL210b	Glenwood	Cobb's Pond	144	38.7%	39.7%	41.2%	42.4%	43.4%	44.1%
TL211	Massey Drive	Bottom Brook	322	19.9%	19.2%	18.5%	18.4%	18.2%	18.8%
TL212a	Sunnyside	Monkstown	112	18.9%	21.4%	22.9%	23.7%	25.3%	26.9%
TL212b	Monkstown	Bay L'Argent	112	22.1%	24.7%	26.0%	26.8%	28.4%	30.0%
TL212c	Bay L'Argent	Linton Lake	112	17.2%	19.4%	20.5%	21.1%	22.5%	23.8%
TL214	Doyles	Bottom Brook	112	24.3%	28.4%	30.6%	31.9%	34.7%	37.3%
TL215	Doyles	Grand Bay	46	49.0%	56.9%	60.7%	63.2%	67.7%	72.7%
TL217	Western Avalon	Soldiers Pond	454	11.4%	23.6%	25.9%	27.8%	33.1%	38.3%
TL218	Holyrood	Oxen Pond	370	45.8%	51.6%	53.9%	55.7%	58.9%	62.7%
TL219	Sunnyside	Salt Pond	162	13.7%	15.3%	16.4%	16.8%	17.9%	18.9%
TL220a	Bay D'Espoir	Conne River	56	24.6%	27.4%	28.8%	29.7%	31.5%	33.2%
TL220b	Conne River	EHW	56	19.2%	21.4%	22.5%	23.1%	24.5%	25.8%
TL220c	EHW	Barachoix	56	14.0%	15.5%	16.3%	16.8%	17.7%	18.6%
TL222a	Stony Brook	South Brook	112	9.8%	11.7%	13.6%	15.6%	17.9%	22.4%
TL222b	South Brook	Springdale	112	5.7%	5.0%	6.4%	8.3%	10.2%	14.2%
TL223	Springdale	Indian River	93	14.2%	9.8%	7.9%	6.5%	3.8%	2.6%
TL224	Howley	Indian River	93	40.7%	39.5%	38.9%	37.9%	37.3%	34.7%
TL225a	Deer Lake Power	Deer Lake Sub	54	6.0%	7.1%	6.0%	5.7%	3.9%	3.5%
TL225b	Deer Lake Sub	Deer Lake - NLH	54	36.8%	39.9%	42.4%	43.6%	46.9%	49.6%
TL226a	Deer Lake	Wiltondale	54	12.2%	13.6%	14.3%	14.7%	15.6%	16.5%
TL226b	Wiltondale	Rocky Harbour	54	7.8%	8.7%	9.2%	9.5%	10.1%	10.7%
TL227a	Berry Hill	Sally's Cove	54	3.8%	4.2%	4.4%	4.5%	4.8%	5.0%
TL227b	Sally's Cove	Cow Head	54	3.7%	4.1%	4.4%	4.5%	4.7%	5.0%
TL227d	Parson's Pond	Daniel's Harbour	54	1.5%	1.7%	1.8%	1.8%	1.9%	2.0%
TL228	Buchans	Massey Drive	290	21.6%	26.0%	28.0%	29.0%	31.4%	33.5%
TL229	Wiltondale	Glenburnie	53	4.1%	4.6%	4.8%	5.0%	5.2%	5.5%
TL231	Bay D'Espoir	Stony Brook	470	27.0%	30.7%	32.9%	34.2%	36.5%	38.7%

TL232	Stony Brook	Buchans	470	12.7%	14.8%	15.8%	16.4%	17.7%	18.8%
TL233	Buchans	Bottom Brook	370	18.3%	19.7%	20.5%	20.8%	21.8%	22.7%
TL234	Upper Salmon	Bay D'Espoir	470	1.3%	1.7%	3.3%	3.9%	5.4%	6.9%
TL236	Hardwoods	Oxen Pond	460	53.7%	60.2%	65.3%	67.3%	70.5%	75.8%
TL237	Western Avalon	Come-By-Chance	460	2.6%	15.8%	15.9%	16.9%	19.8%	22.7%
TL239	Deer Lake	Berry Hill	162	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
TL241	Peter's Barren	Plum Point	161	13.6%	15.8%	17.2%	18.0%	19.7%	21.6%
TL242	Soldiers Pond	Hardwoods	460	9.0%	11.9%	13.3%	14.2%	16.0%	17.9%
TL244	Plum Point	Bear Cove	113	59.8%	67.5%	71.1%	73.4%	78.3%	82.9%
TL245	Deer Lake	Howley	112	8.8%	11.2%	12.7%	13.6%	15.4%	17.5%
TL248	Massey Drive	Deer Lake	467	31.2%	30.7%	30.9%	31.8%	32.2%	34.7%
TL250	Bottom Brook	Grandy Brook	162	29.3%	27.9%	27.4%	27.2%	26.5%	26.1%
TL251	Howley	Hampden	56	4.8%	4.8%	4.8%	4.9%	4.9%	4.9%
TL252a	TL252 Tap	Jackson's Arm Tap	56	5.5%	6.0%	6.2%	6.3%	6.6%	6.9%
TL252b	Jackson's Arm Tap	Jackson's Arm	56	2.7%	3.0%	3.1%	3.2%	3.4%	3.6%
TL254	Boyd's Cove	Farewell Head	81	2.7%	3.1%	3.2%	3.3%	3.5%	3.7%
TL256	Bear Cove	St. Anthony A/P	161	8.0%	8.8%	9.2%	9.5%	10.0%	10.5%
TL257a	St. Anthony A/P	Main Brook	56	5.3%	5.2%	5.8%	6.1%	6.6%	7.4%
TL257b	Main Brook	Roddickton	56	6.4%	7.6%	8.2%	8.6%	9.4%	10.2%
TL259	Berry Hill	Peter's Barren	162	4.9%	5.9%	6.4%	6.7%	7.4%	8.0%
TL260	Seal Cove	Bottom Waters	162	12.4%	14.5%	15.8%	16.6%	18.2%	19.9%
TL261	St. Anthony A/P	St. Anthony	77	6.0%	6.6%	7.0%	7.2%	7.6%	8.0%
TL262	Peter's Barren	Daniel's Harbour	54	3.0%	5.6%	5.8%	6.5%	8.5%	11.3%
TL263	Granite Canal Tap	Upper Salmon	370	3.7%	4.1%	4.3%	4.4%	4.7%	4.9%
TL265	Soldiers Pond	Holyrood	460	21.5%	24.7%	26.3%	27.3%	29.4%	31.5%
TL266	Soldiers Pond	Hardwoods	794	20.7%	25.4%	26.5%	27.6%	30.1%	32.5%
TL267	Bay D'Espoir	Western Avalon	454	35.9%	40.5%	42.7%	44.1%	47.0%	49.8%
TL268	Soldiers Pond	Holyrood	460	15.2%	10.7%	9.9%	8.9%	6.1%	3.5%
TL269	Bottom Brook	Granite Canal Tap	454	20.4%	25.1%	26.2%	27.3%	29.8%	32.2%

Notes:

1. Non-coincident peaks were compared against MVA ratings for transmission lines
2. Winter Ratings

Table 6-3: Transformer Loading (%)

Station	Unit	Rating (MVA)	CASES					
			EV1	EV2	EV3	EV4	EV5	EV6
Barachoix (BCX)	T1	10/13.3/16.7	49.6%	51.5%	53.9%	55.4%	58.3%	61.3%
Bay d'Espoir (BDE)	T10	15/20/25	46.4%	48.5%	50.9%	52.5%	55.7%	58.8%
	T12	15/20/25	46.1%	48.1%	50.6%	52.1%	55.3%	58.3%
	T11	10/13.3/16.7	46.4%	47.8%	50.0%	51.3%	53.9%	56.5%
Bear Cove (BCV)	T1	10/13.3/16.7	35.8%	37.4%	39.3%	40.6%	43.0%	45.5%
Berry Hill (BHL)	T1	15/20/25	8.8%	9.0%	9.5%	9.7%	10.3%	10.8%
Bottom Brook (BBK)	T1	25/33.3/41.7	66.7%	77.9%	84.1%	87.8%	95.9%	103.5%
	T3	25/33.3/41.7	18.5%	18.5%	18.5%	18.6%	18.8%	19.0%
	T4	40/53.3/66.6	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
Bottom Waters (BWT)	T1	10/13.3/16.7	65.7%	67.6%	70.7%	72.7%	76.6%	80.6%
Buchans (BUC)	T1	40/53.3/66.6	22.9%	23.3%	23.3%	23.1%	22.9%	23.2%
	T2	5/6.6/8.3	34.9%	34.7%	34.7%	34.7%	34.7%	34.7%
Conne River (CRV)	T1	2.5	92.1%	95.5%	100.0%	102.7%	108.2%	113.7%
Cow Head (CHD)	T1	5/6.7/8.3	25.7%	26.8%	28.2%	29.0%	30.7%	32.4%
Daniel's Harbor (DHR)	T1	1/1.3	48.1%	50.2%	52.9%	54.5%	57.7%	61.0%
	T2	1	47.7%	49.8%	52.3%	54.0%	57.1%	60.4%
Deer Lake (DLK)	T1	25/33.3/41.7	27.2%	29.8%	30.0%	30.7%	30.8%	32.2%
	T2	45/60/75	37.8%	25.3%	25.0%	25.4%	25.4%	25.5%
Doyles (DLS)	T1	25/33.3/41.7	66.1%	76.5%	81.7%	85.1%	91.4%	98.2%
English Harbour West (EHW)	T1	5/6.7	45.6%	47.3%	49.6%	50.9%	53.6%	56.3%
Farewell Head (FHD)	T1	10/13.3/16.7	41.0%	42.1%	44.1%	45.3%	47.6%	50.0%
Glenburnie (GLB)	T1	1.5/3.3	70.4%	73.6%	77.5%	79.9%	84.7%	89.5%
Grandy Brook (GBK)	T1	7.5/10/12.5	43.6%	44.2%	46.2%	47.5%	49.9%	52.4%
Hampden (HDN)	T1	2.5/3.3/4.0	38.3%	39.6%	41.5%	42.7%	45.0%	47.3%

Hardwoods (HWD)	T1	75/100/125	83.0%	92.9%	95.9%	99.2%	107.1%	112.3%
	T2	40/53.3/66.6	79.3%	88.9%	91.7%	94.9%	102.4%	107.4%
	T3	40/53.3/66.6	85.7%	96.0%	99.1%	102.4%	110.6%	115.9%
	T4	75/100/125	82.3%	92.2%	95.2%	98.4%	106.3%	111.4%
Holyrood (HRD)	T5	15/20/25	91.7%	100.5%	109.2%	109.5%	116.6%	122.8%
	T10	15/20/25	89.3%	97.8%	106.3%	106.6%	113.5%	119.6%
	T6	25/33.3/41.7	20.4%	24.9%	26.2%	27.3%	30.0%	32.2%
	T7	25/33.3/41.7	34.8%	42.5%	44.7%	46.5%	51.1%	54.9%
	T8	75/100/125	19.8%	24.1%	25.4%	26.4%	29.0%	31.2%
Howley (HLY)[3]	T2	7.5/10/12.5	26.0%	26.6%	27.7%	28.3%	29.6%	31.0%
Jackson's Arm (JAM)	T1	5/6.6/8.3	20.0%	20.7%	21.7%	22.3%	23.5%	24.7%
Main Brook (MBK)	T1	1.5	54.1%	61.0%	66.2%	69.3%	75.7%	82.1%
Massey Drive (MDR)	T1	75/100/125	41.4%	44.7%	45.7%	46.0%	47.0%	47.7%
	T2	40/53.3/66.6	54.2%	60.0%	62.9%	64.7%	68.3%	71.9%
	T3	75/100/125	51.3%	56.7%	59.5%	61.2%	64.6%	68.0%
Oxen Pond (OPD)	T1	75/100/125	67.3%	74.4%	79.6%	82.0%	86.1%	91.9%
	T2	150/200/250	64.9%	71.8%	76.8%	79.1%	83.0%	88.7%
	T3	150/200/250	67.3%	74.4%	79.6%	82.0%	86.1%	91.9%
Parson's Pond (PPD)	T1	1/1.3	65.5%	68.4%	72.1%	74.3%	78.7%	83.1%
Peter's Barren (PBN)	T1	15/20/25	9.8%	10.0%	10.2%	10.5%	10.9%	11.3%
Plum Point (PPT)	T1	10/13.3/16.7	25.5%	26.7%	28.1%	29.0%	30.8%	32.6%
Rocky Harbour (RHR)	T1	5/6.6/8.3	53.2%	55.7%	58.7%	60.6%	64.3%	67.9%
Roddickton (RWC)	T2	5/6.6/8.3	58.8%	66.4%	72.1%	75.7%	82.7%	89.7%
South Brook (SBK)	T1	5/6.6/8.3	95.7%	97.4%	101.6%	104.1%	109.3%	114.4%
Stephenville (SVL)	T3	40/53.3/66.6	82.1%	89.9%	93.5%	95.7%	100.2%	105.2%
Stony Brook (STB)	T1	75/100/125	81.5%	90.3%	95.1%	98.8%	103.5%	109.0%
	T2	75/100/125	80.5%	89.2%	94.0%	97.6%	102.3%	107.7%
St. Anthony Airport (STA)	T1	15/20/25	25.1%	26.7%	31.7%	34.6%	40.4%	47.4%
Sunnyside (SSD)	T1	75/100/125	65.6%	78.7%	83.6%	86.3%	93.7%	101.6%
	T4	75/100/125	66.1%	79.2%	84.2%	86.9%	94.4%	102.3%
	T5	15/20/25	50.0%	56.0%	59.0%	60.8%	64.4%	68.0%
Western Avalon (WAV)	T1	15/20/25	67.2%	69.2%	71.9%	73.6%	76.4%	81.0%
	T2	15/20/25	68.5%	70.5%	73.2%	75.0%	77.8%	82.5%
	T3	25/33.3/41.7	33.6%	33.2%	34.4%	34.7%	34.5%	35.5%
	T4	25/33.3/41.7	33.4%	33.0%	34.3%	34.5%	34.3%	35.3%
	T5	75/100/125	32.7%	32.3%	33.5%	33.7%	33.5%	34.5%
Wiltondale (WDL)	T1	1.0	4.7%	4.9%	5.2%	5.3%	5.7%	5.9%

Notes:
1. Generator step up transformers and converter transformers are not included as these units have been sized for the full unit capability
2. Non-coincident peaks were compared against MVA ratings for transformers
3. Rattle Brook assumed to in operation at 4 MW

Table 6-2 indicates there are no pre-contingency transmission line overloads in any of the cases studied. The load flow analysis did identify transformer overloads with the IIS fully intact and are shown in Table 6-3. These transformer overload violations are listed in Table 6-4 with proposed or suggested solution(s). The actual solution would have to be determined by performing a cost benefit analysis to select the lowest cost option. A PSS®E load flow diagram demonstrating a transformer overload at Hardwoods Terminal Station is shown in Figure 6-1. This transformer overload is driven by EV growth in St. John's and its surrounding area in case EV6.

Table 6-4: Transformer Overloads (N-0)

Impacted Area/Equipment	Effected Cases	Proposed Solution(s)
HRD-T5 & T10	EV2-EV6	Line Switching: Open 66 kV line between HRD and HWD
CRV-T1	EV3-EV6	Replace with a 5MVA Transformer
SBK-T1		Replace with a 15MVA Transformer
HWD-T1,T2,T3 and T4	EV4-EV6	Replace T2 and T3 with a 125MVA Transformer
SVL-T3	EV5-EV6	Line Switching: Establish a 66 kV loop between SVL and BBK
STB-T1 & T2		Replace T1 or T2 with a 250MVA Transformer
SSD-T1 & T4	EV6	Replace T1 or T4 with a 250MVA Transformer
BBK-T1		Dispatch downstream generation

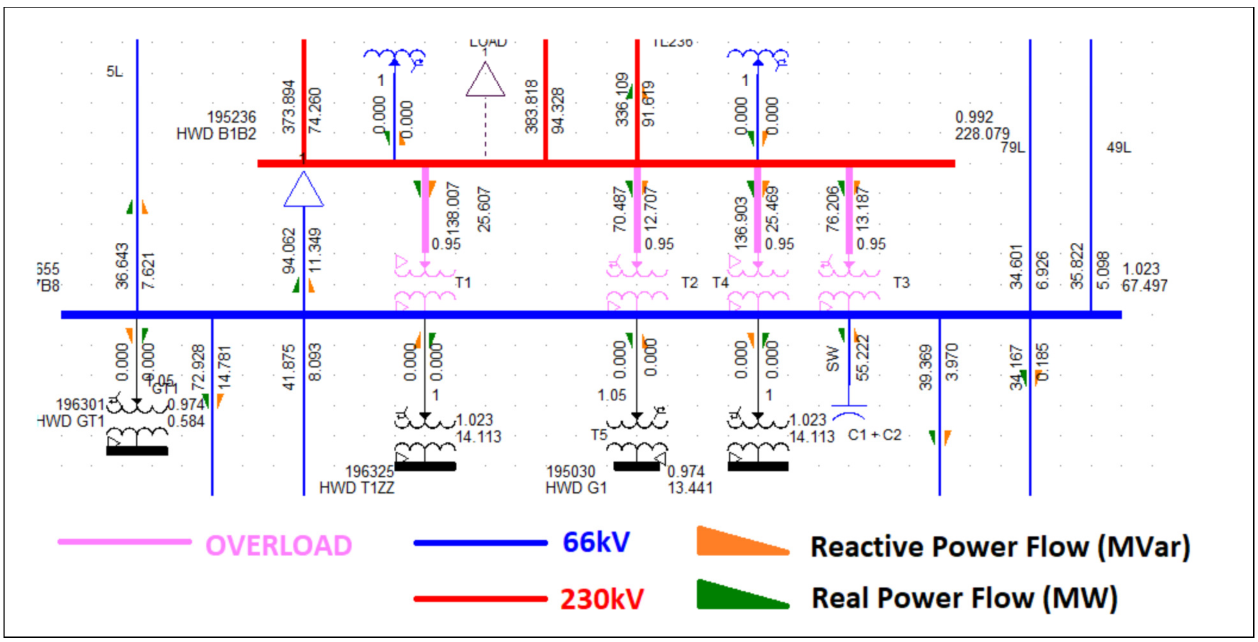


Figure 6-1: Hardwoods Terminal Station – Slider Diagram – Transformer Overloads

Additional generation was modelled at the Soldiers Pond Terminal Station to provide the real power necessary to support the number of EVs assumed for each PSS®E case (EV1-EV6). Each violation listed in Table 6-4 could be eliminated with the installation of this new generation downstream of the overloaded transformer. It should be emphasized that the results in Tables 6-2 and 6-3 would change if the new generation were installed at another site. The placement of any new generation could also influence the voltage levels throughout the system, since generation also provides reactive power support which inherently improves voltages. A comprehensive generation expansion study would be required to determine the economic feasibility of the amount and location of any incremental generation, which is outside the scope of this thesis. The Soldiers Pond Terminal Station was selected to keep the analysis consistent.

The load flow analysis also calculated the voltage levels at every high voltage bus for each case. The pre-contingency voltage violations identified from this analysis are listed in Table 6-5. These voltage violations could possibly be mitigated if new generation were installed in close proximity of the low voltage condition.

Table 6-5: Low Voltage Violations (N-0)

<table>
<tr><th>Impacted Area</th><th>Effected Cases</th><th>Proposed Solution(s)</th></tr>
<tr><td>Gander/Gambo Area</td><td rowspan="2">EV2-EV6</td><td>• Installation of switchable capacitor banks on the 138 kV bus in Gander Substation (Approx. 40 MVar)
• New 138 kV line from Stony Brook to Gander Station</td></tr>
<tr><td>BWT
(25 kV Bus)</td><td>Change Transformer Tap Position (BWT-T1)</td></tr>
<tr><td>Burgeo
(25 kV Bus)</td><td>EV3-EV6</td><td>Change Transformer Tap Position (GBK-T1)</td></tr>
<tr><td>Grand Bay (GBY)
(12.5 kV bus)</td><td rowspan="2">EV5- EV6</td><td>• Change Transformer Tap Position (GBY-T1)
• Dispatch generation downstream
• Installation of switchable capacitor banks on the 66 kV bus at Grand Bay Substation (Approx. 10 MVar)</td></tr>
<tr><td>Great Northern Peninsula
(GNP)</td><td>• Change Transformer Tap Positions
• Modify the switching scheme and operating procedures for shunt devices in the area</td></tr>
<tr><td>Lewisporte Area</td><td rowspan="2">EV6</td><td>Change Transformer Tap Positions</td></tr>
<tr><td>Long Lake Substation
(66 kV bus)</td><td>Installation of switchable capacitor banks on the 66 kV bus at GBY substation (Approx. 10 MVar)</td></tr>
</table>

6.2.2 Single Contingency (N-1)

This section will provide the load flow results of the single contingency steady state analysis for each transmission element. The loss of a transmission line or power transformer supplying a radial system is considered acceptable from a planning perspective and therefore was not included in this analysis. Table 6-6 provides the transformer loading for multi-transformer stations and loop systems following the loss of the largest transformer (N-1). In a loop system the power transformers at each terminal station share the load within the loop. Figure 6-2 is a simplified single line diagram of the Stony Brook/Sunnyside 138 kV loop.

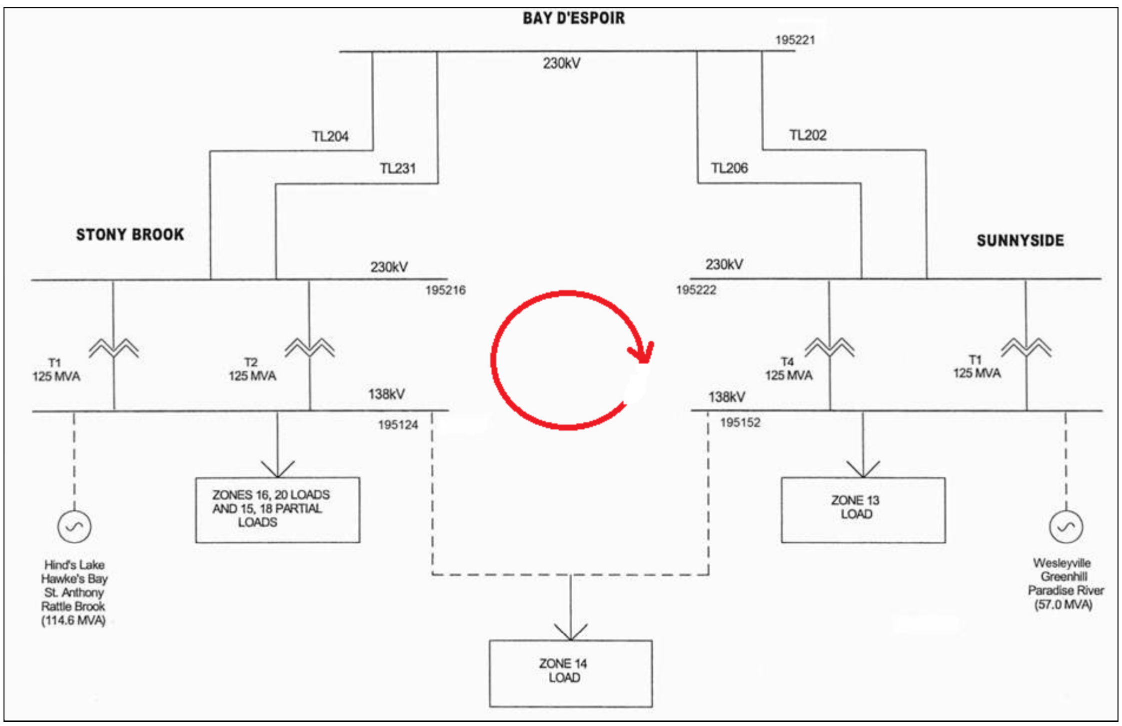


Figure 6-2: Stony Brook/Sunnyside 138kV Loop

Transmission lines or transformers that are dedicated for a single industrial customer, generation stations or are normally out-of-service were not assessed. The loss of generation supply is accounted for by maintaining a spinning reserve equal to the output of the largest in-service unit. The cells in the tables highlighted red indicates a thermal overload (> 100%), while the yellow cells specify a loading between

95 to 100%. Any cell with an entry ‘VC’ designates a simulation that experienced non-convergence or voltage collapse. The results of Table 6-6 are summarized in Table 6-7.

The loss of a single pole for each HVdc bipole link (LIL and ML) was evaluated for each case and no violations were identified from a steady state load flow perspective, which was anticipated given the fact that the loss of a pole has more of an effect on power stability or system frequency response. The impact of EVs on power system stability will be discussed in further detail in Chapter 7.

Table 6-6: Single Contingency Transformer Loading (%)

Station	Unit	Rating MVA	Cases EV1	EV2	EV3	EV4	EV5	EV6
Multi-transformer Stations								
Bay d’Espoir	T10	15/20/25	*Out-of-Service*					
	T12	15/20/25	95.2%	106.2%	111.7%	115.3%	122.6%	129.9%
Bottom Brook[2]	T1	25/33.3/41.7	66.7%	78.0%	84.2%	87.6%	95.7%	103.2%
	T3	25/33.3/41.7	*Out-of-Service*					
Daniel’s Harbour	T1	1/1.3	*Out-of-Service*					
	T2	1	95.8%	106.5%	111.7%	114.9%	121.3%	127.8%
Holyrood[3]	T5	15/20/25	55.1%	61.7%	64.5%	67.0%	70.5%	74.7%
	T10	15/20/25	*Out-of-Service*					
Massey Drive[4]	T1	75/100/125	*Out-of-Service*					
	T2	40/53.3/66.6	85.1%	94.2%	98.1%	100.8%	107.7%	114.3%
	T3	75/100/125	76.4%	84.5%	88.0%	90.4%	96.6%	102.6%
Western Avalon	T1	15/20/25	98.0%	104.0%	112.0%	118.0%	123.0%	126.0%
	T2	15/20/25	*Out-of-Service*					
Looped Systems[5]								
Hardwoods – Oxen Pond 66 kV Loop								
Hardwoods	T1	75/100/125	96.4%	110.9%	112.6%	115.8%	123.0%	131.9%
	T2	40/53.3/66.6	95.9%	111.7%	112.0%	115.2%	123.8%	132.9%
	T3	40/53.3/66.6	103.6%	120.6%	120.9%	124.4%	133.7%	143.5%
	T4	75/100/125	99.3%	115.6%	115.9%	119.2%	128.2%	137.6%
Oxen Pond	T1	75/100/125	93.0%	103.8%	108.9%	112.6%	119.2%	125.9%
	T2	150/200/250	89.7%	104.3%	105.1%	110.1%	118.1%	126.5%
	T3	150/200/250	*Out-of-Service*					
Holyrood - Western Avalon 138 kV Loop								
Holyrood	T6	25/33.3/41.7	23.0%	27.9%	28.2%	29.5%	31.7%	34.7%
	T7	75/100/125	38.7%	45.7%	48.1%	50.2%	54.0%	58.3%
	T8	75/100/125	22.0%	26.0%	27.3%	28.5%	30.7%	33.1%
Western Avalon	T1	15/20/25	72.5%	75.8%	75.2%	75.8%	80.4%	87.9%
	T2	15/20/25	73.8%	77.2%	76.6%	77.2%	81.9%	89.6%
	T3	25/33.3/41.7	66.3%	70.4%	74.5%	72.1%	76.0%	70.7%
	T4	25/33.3/41.7	66.0%	70.0%	74.1%	71.7%	75.6%	70.4%
	T5	75/100/125	*Out-of-Service*					
Stony Brook - Sunnyside 138 kV Loop[6]								
Sunnyside	T1	75/100/125	83.1%	94.9%	100.4%	VC	VC	VC
	T4	75/100/125	84.7%	96.7%	101.1%	VC	VC	VC
Stony Brook	T1	75/100/125	*Out-of-Service*					
	T2	75/100/125	115.1%	125.2%	131.0%	VC	VC	VC
Stephenville – Bottom Brook 66kV Loop								
Stephenville	T3	40/53.3/66.6	*Out-of-Service*					
Bottom Brook	T4	40/53.3/66.6	88.8%	98.7%	104.0%	107.5%	115.0%	123.1%

Notes:

1. The loading provided is with the largest transformer in the station removed from service and back up generation on line where applicable. Non-coincident peaks were compared against MVA ratings for transformers
2. Bottom Brook 138 kV bus tie switch B2B3 is closed
3. 66 kV line between Holyrood and Hardwoods is opened
4. 66 kV bus tie B2B4-1 closed
5. The operation of each loop of transformers assumes the loss of the largest unit contained within the loop at each end to provide for maximum operational reliability. If there is more than one transformer with the same rating, the one with the lowest impedance is chosen to be switched off. In scenarios where there is a transformer overloaded, it may be mitigated by breaking the loop in various locations to offload the overloaded transformer.
6. The following generation is assumed to be online within this 138 kV loop: Greenhill Gas Turbine, Paradise River, Wesleyville Gas Turbine, St. Anthony Diesels, Hind's Lake, Hawke's Bay Diesel and Rattle Brook. With the loss of a transformer, the 138 kV loop would also have to be opened to offload the remaining transformers within the loop.

Table 6-7: Transformer Overloads (N-1)

Impacted Area/Equipment	Case	Suggested Solution(s)*
STB/SSD 138 kV Loop**	EV1-EV6	Increase transformation at STB and/or SSD
HWD/OPD 66 kV Loop**		Increase transformation at HWD and/or OPD
BDE-T12	EV2-EV6	Increase transformation at BDE
DHR-T2		Increase transformation at DHR
BBK-T4	EV3-EV6	Increase transformation at BBK
MDR-T2 and T3	EV4-EV6	Increase transformation at MDR
WAV-T2	EV1-EV6	**EV1:** Line Switching – Open 66 kV loop between WAV and HRD **EV2-EV6:** Increase transformation at WAV
*Downstream generation is a technically viable option for each violation **Pre-existing violations that are expected to occur prior to the year 2039. Not triggered by high EV penetration.		

The overloads on the STB/SSD 138kV and HWD/OPD 66kV Loops are considered pre-existing violations that NL Hydro would address prior to the year 2039 and is not driven by a high penetration of EVs.

The single contingency analysis for transmission lines was performed using the ACCC PSS®E routine. The voltage and thermal violations associated with the loss of each transmission line are summarized in Table 6-6 and the load flow reports for each case are provided in Appendix F.

Table 6-8: ACCC Results Summary[46]

Contingency	Violation Type	Case	Effected Equipment	Suggested Solution(s)
Loss of TL248	Overload	EV1-EV6	• DLK-T1 & T2 • TL224 & TL225	Cross-trip TL247
Loss of 138 kV NLP lines/transformers within HRD/WAV Loop	Overload	EV1-EV6	WAV-T1&T2 (Increases flow on 66 kV)	EV1-EV2: Line switching **EV3-EV6: Increase 230 kV/66 kV Transformation at WAV**
Loss of MDR-T1	Overload	EV1-EV6	DLK -T1	Close tie switch at MDR
		EV5-EV6	TL225	
		EV4-EV6	STB Transformer(s)	**Addressed by a prior violation (See Table 6-6/6-7)**
Loss of TL266	Overload	EV1-EV6	TL242	**EV1:** Cross-trip TL236 **EV2-EV6: Upgrade SOP to HWD transmission corridor (Thermal Upgrade or New Line)**
			HRD -T5 & T10	Line switching
Loss of TL236	Overload	EV1-EV6	TL218	**EV1:** Line switching **EV2-EV6:Thermal upgrade of TL218**
			HWD Transformers	**EV1:** Line switching **EV2-EV6: Increase transformation capacity in HWD/OPD Loop**
Loss of TL218	Overload	EV1-EV6	HRD -T5 & T10	Line switching
		EV2-EV6	TL236	**Construct second line from HWD to OPD**
			HWD Transformer(s)	**Increase transformation capacity in HWD/OPD Loop**
Loss of TL242	Overload	EV1-EV6	HRD -T5 & T10	Line switching
Loss of HWD/OPD Transformer (s)	Overload	EV1-EV6	HRD -T5 & T10	Line switching
Loss of HRD -T5 & T10	Overload	EV2-EV6	HWD Transformer(s)	Line switching
Loss of Various 66 kV NLP Lines within HWD/OPD Loop	Overload	EV1-EV6	Various 66kV NLP lines within HWD/OPD Loop	Line switching **Potential Thermal Line Upgrades**[47]
		EV3-EV6	HWD Transformer(s)	**Addressed by a prior violation (See Table 6-6/6-7)**
Loss of TL224 or TL243	Overload	EV2-EV6	STB Transformer(s)	Line switching , dispatch Generation
Loss of NLP Generation downstream of HWD Transformer(s)	Overload	EV3-EV6	HWD Transformer(s)	**Addressed by a prior violation (See Table 6-6/6-7)**
Loss of Generation/66 kV lines downstream of SVL-T3	Overload	EV4-EV6	SVL-T3	Line switching
Loss of TL202,TL228, TL205, TL206, TL225, TL232, TL233, or TL247	Overload	EV4-EV6	STB Transformer(s)	**Addressed by a prior violation (See Table 6-6/6-7)**
Loss of TL225	Overload	EV4-EV6	DLK-T1	Line switching, adjust generation at CAT
Loss of Various NLP/NLH Lines and Generation within STB/SSD Loop	Overload/ Low Voltages	EV1-EV6	Overload: STB/SSD Transformers overloaded	**EV1-EV3:** Line switching **EV4-EV6:** Addressed by a prior violation (See Table 6-6/6-7)

[46] The red text designates solutions that involve capital upgrades
[47] Would have to be assessed by NLP

			Low voltages: Various buses within STB/SSD Loop	**EV2-EV6: Installation of capacitor banks within loop or a new 138 kV line**
Loss of TL204 or TL231	Overload/ Low Voltages	EV5-EV6	STB Transformer(s)	**Addressed by a prior violation (See Table 6-6/6-7)**
Loss of TL219	Low Voltage	EV3-EV6	Various buses on the Burin Peninsula	**Installation of capacitor banks or generation on Burin Peninsula**
Loss of Generation on GNP	Low Voltage	EV5-EV6	Low voltages on the GNP	**Installation of SVC or generation on GNP**
Loss of TL207	High Voltages	EV3-EV6	High Voltages at Come by Chance	Switch off capacitor bank(s) in CBC

6.2.3 Peak Shaving

Peaking shaving is an effective technique commonly used to reduce the overall demand on a power system for the purposes of avoiding equipment thermal overloads, abnormal voltage conditions and minimize the use of expensive back-up generation. EVs with V2G capability can be used to facilitate peak shaving by discharging their batteries and injecting real power into the grid during high load conditions. EVs would essentially act like a negative load when discharging their batteries, which would in turn offload equipment upstream and reduce the requirement for generation. Figure 6-3 quantities the impact of peak shaving for cases EV2 to EV6, in the event that all EVs electrically connected to the IIS were forced to use V2G technology and supply real power. This capability would give NL Hydro the flexibility to dispatch cheaper, abundant and cleaner generation sources during peak conditions and could theoretically defer the need for future generation expansion. However, the economic feasibility of this approach would have to be assessed, as it may not be the least cost option to address a generation capacity deficit.

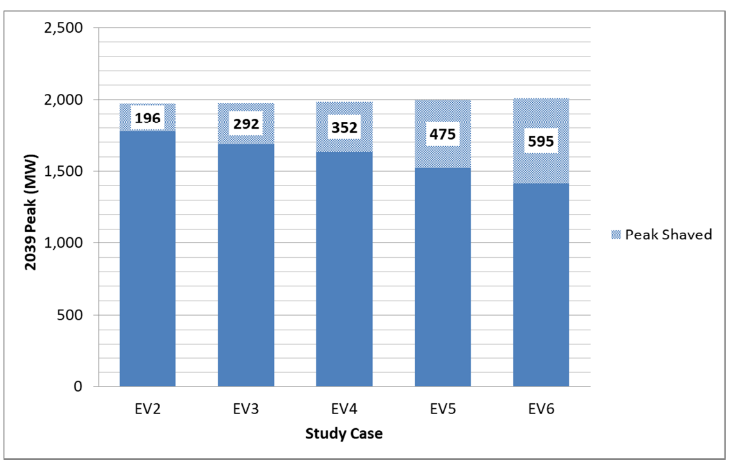


Figure 6-3: Peak Shaving using EVs on the IIS

6.3 Summary

This chapter has clearly demonstrated, through load flow analysis, that a high penetration of EVs in Newfoundland could have an enormous effect on the flow of power throughout the IIS. The results presented in Tables 6-2 to 6-8 have all been consolidated and put into Table 6-9 to summarize all the violations for various EV penetration levels that would merit capital upgrades. It can be derived from Table 6-9 and the Operating Load Forecast (Appendix D) that it could take an estimated 70,000 to 135,000 EVs to trigger capital upgrades at this present time.

These results were profoundly dependent on many factors, especially the distribution of the EVs and the location of any new generation sources required to accommodate the incremental demand of EVs. DSM strategies were also not considered in this analysis, which if correctly applied has the potential to mitigate all the listed violations. Consequently, projecting an exact number of EVs that would trigger capital upgrades is difficult and therefore further sensitivity analysis can be justified to fully understand the influence that these factors could have on the load flow results.

Table 6-9: Load Flow Analysis Results Summary

EV Penetration Level	Violation (N-0 or N-1)	Suggested Capital Upgrade
6.5 MW	**Transformer Overload*:** STB/SSD Loop HWD/OPD Loop	Installation of additional transformation at STB and/or SSD Installation of additional transformation at HWD and/or OPD
6.5 MW (EV1) – 168 MW (EV2)	**Low Voltages:** STB/SSD Loop	Installation of capacitor banks in the Gander Area (Approx. 40 MVar). More transformation in STB/SSD may improve voltage
	Transformer Overloads: WAV T1 & T2 (230 kV/66 kV) BDE T10 & T12	Installation of additional transformation at applicable terminal stations
	Transmission Line Overloads: TL242, TL218,TL236	Upgrade thermal capacity: SOP/HWD corridor, TL218, HWD/OPD corridor
168 MW (EV2) – 250 MW (EV3)	**Transformer Overloads:** CRV-T1, SBK-T1, BBK-T4	Installation of additional transformation at applicable terminal stations
	Low Voltages: Burin Peninsula	Installation of capacitor banks in Mary's Town Area (Approx. 25 MVar)
250 MW(EV3) – 300 MW (EV4)	**Transformer Overloads:** MDR	Installation of additional transformation at MDR
300 MW(EV4) – 500 MW (EV6)	**Low Voltages:** GBY Area, GNP Area	• Installation of capacitor banks on the 66 kV bus at Grand Bay Substation (Approx. 10 MVar) • Installation of SVC or generation on the GNP

*Pre-existing violations. These overloads are expected to be triggered by general load growth prior to 2039

Chapter 7

Power System Stability Analysis: Impact of High EV Penetration

7.1 Introduction

The sudden loss or trip of the LIL HVdc bipole would be categorized as a major system disturbance on the IIS and without precautionary measures in place, system frequency would considerably drop and power system instability would inevitable. The severity of this event is dependent on the amount of power flow on the LIL from the LIS to the IIS prior to the trip. NL Hydro defines a bipole trip as a double contingency event and therefore customer outages are deemed acceptable in order to preserve power system stability.

This chapter will begin with an overview on power system stability followed by a discussion on some of the techniques used by power utilities to regulate system frequency following a large disturbance. One of these techniques combines the use of smart grid and V2G/V1G technology to create virtual or synthetic inertia to help regulate system frequency. The purpose of this chapter is to simulate this unconventional approach using PSS®E, to quantify the amount of connected EVs on the IIS necessary to avoid under-frequency load shedding following a trip of the LIL under various load conditions and system configurations.

7.2 Power System Stability Overview

Power system stability is defined as the desired state of equilibrium of a power system that must be achieved in order to ensure a reliable supply of power to customers, even after the exposure to large system disturbances [80] [81]. The stability of the power system can be divided into two categories based upon the magnitude of disturbances:

1. **Steady-State Stability:** a form of stability that is achieved by a power system following small disturbances on a power system, such as slight fluctuations in electrical load [43]. These small disturbances usually go unnoticed by residential customers, but may temporarily reduce power quality. Dynamic stability is an extension of steady-state stability that focuses on the oscillations of synchronous machines in the presence of automatic control devices [43]. The failure of dampening oscillations will cause the system to become dynamically unstable [43].
2. **Transient Stability:** a form of stability that is achieved by a power system after a major disturbance like electric faults or the sudden loss of a transmission line, generating source or large load. Protection devices and schemes are deployed throughout a power system to help isolate electrical faults from the rest of the electrical network to avoid instability. Protective relays and circuit breakers must respond to a fault within the designed critical clearing time in order to prevent the system from becoming unstable and evade any further customer outages [78]. Generator loading or transmission line flows are often restricted to ensure system stability and frequency can be maintained if the equipment trips. A trip of the LIL bipole would be an event that could lead to transient or frequency instability if not mitigated using techniques described in Section 7.3 [80].

The equilibrium state of a power system is defined in terms of system parameters which include frequency, voltage and rotor angular displacement [43]. NL Hydro's Planning Criteria as it pertains to power system stability is defined based on these system parameters [36]:

- System frequency must remain within 58 Hz and 62 Hz
- All oscillations in voltage, current and angle must be adequately damped to avoid unplanned equipment tripping or equipment damage
- Generators must not lose synchronism with the grid following any system disturbance
- Generator pole slipping is unacceptable

- Transient under voltages following fault clearing should not drop below 70%. The duration of the voltage below 80% following fault clearing should not exceed 20 cycles

A deviation in system frequency is expected following any form of disturbance where there is a disparity between total system demand and generation. This imbalance in power will cause all online synchronous machines to absorb or inject kinetic energy to counteract the resulting frequency deviation [82]. The rate of change of frequency (ROCOF) can be expressed by rearranging the swing equation [7.1] [43].

$$\frac{d\Delta f}{dt}(t) = ROCOF = f_o \frac{P_m(t) - P_e(t)}{2H_{sys}} \qquad [7.1]$$

$$H_{sys} = \sum_i H_{gen,i} \qquad [7.2]$$

where,

$$H_{gen} = \frac{1}{2}\frac{J\omega^2}{VA_{base}} \qquad [7.3]$$

$P_m(t) - Mechancial\ Power\ [W]$
$P_e(t) - Electrical\ Power\ [W]$
$H_{sys} - System\ Inertia\ [MW * s]$
$H_{gen} - Inertia\ Constant\ for\ a\ single\ generator\ [MW * s]$
$f_o - Nominal\ Frequency\ [Hz]$
$J - Moment\ of\ Inertia\ [kg * m^2]$
$\omega - angular\ velocity\ [rads/s]$
$VA_{base} - Apparent\ Power\ [VA]$

It is evident from [7.1] that ROCOF is inversely proportional to the total system inertia ($\boldsymbol{H_{sys}}$), which is the sum of the inertia constants of all the synchronous machines connected to a power system as per equations [7.2] and [7.3] [82] [43]. This would mean that a higher ROCOF is expected when there is a smaller amount of total system inertia connected to the system, since there is less rotating mass on the system to facilitate the balance of energy. This relationship is illustrated in Figure 7.1 for three separate total system inertias ($H_1 < H_2 < H_3$) for the same under-frequency event (loss of generation). The same behavior for an over-frequency event (loss of load) is comparable with respect to system inertia.

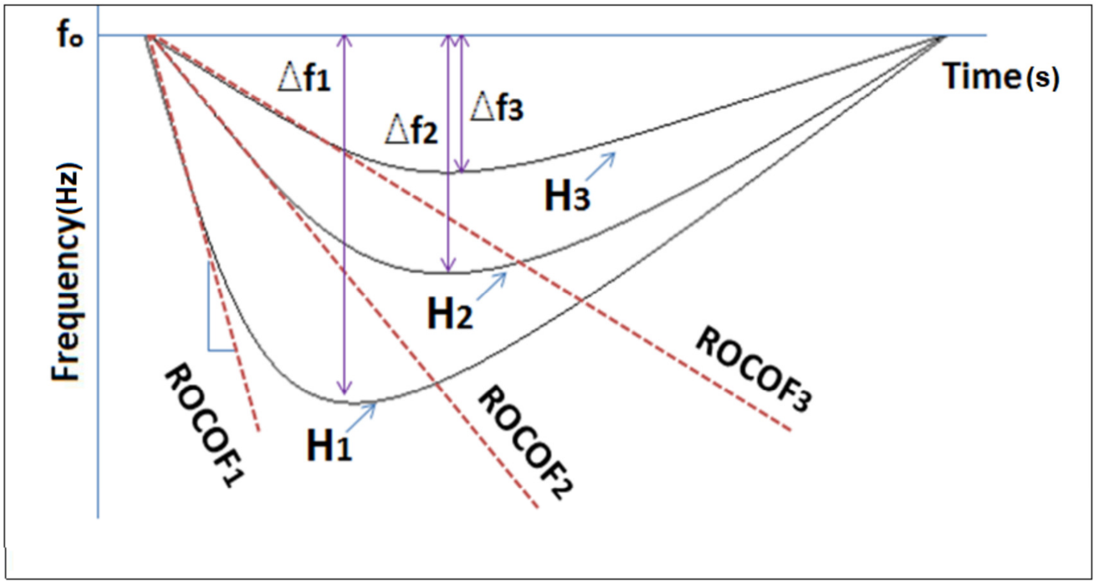


Figure 7-1: Under-Frequency Responses with varying System Inertia Values

$$\boldsymbol{ROCOF_1 > ROCOF_2 > ROCOF_3} \quad [\mathbf{7.4}]$$

$$\boldsymbol{\Delta f_1 > \Delta f_2 > \Delta f_3} \quad [\mathbf{7.5}]$$

Equations [7.4] and [7.5] demonstrate that a lower ROCOF translates into a better system frequency response, since there is more of a gradual drop in frequency leading to a smaller deviation ($\boldsymbol{\Delta f}$). Hence it can be concluded that a system with more online inertia is more stable and better equipped to withstand a disturbance or imbalance between demand and generation. A large disturbance may require further intervention to avoid instability which will be discussed in the next section.

7.3 Frequency Regulation

A drastic deviation in system frequency will activate protective relays that are designed to trip generating units to avoid damage, but will further compound the problem and likely result in a complete system collapse. Therefore the system frequency should be held within a specified range to reduce the probably of under or over-frequency trips. There are many different approaches that power utilities use to regulate system frequency which include:

- Under-frequency load shedding (UFLS)
- Increase Online Generation (Spinning Reserve)
- Special Protection Scheme (SPS)
- HVdc Runbacks and Frequency Controllers
- Application of Virtual or Synthetic Inertia

The following sections will provide more detail on each of these frequency regulation strategies.

7.3.1 Under-frequency Load Shedding

A sudden loss of generation on a system will inherently cause the frequency to decrease. The magnitude of the deviation is a function of the amount of generation disconnected from the grid and the quantity of online inertia at the time of the event. UFLS is a controlled technique to offset the loss of generation by removing customer load once the frequency drops to a predetermined threshold [83].

While UFLS is a cost effective approach to regulating frequency, the tradeoff is widespread customer outages. Depending on the severity of the generator trip, the duration of the outage could be prolonged if additional generation sources are not available to be dispatched. Independent of the amount of inertia on a system, most utilities will typically have an UFLS scheme as a contingency to other frequency control strategies [83].

7.3.2 *Increase Spinning Reserve*

The majority of power utilities must design their system to withstand the loss of the largest in-service generator by ensuring there is additional unloaded generation available within a short period of time. This supplementary online generation is commonly referred to as spinning reserve [84]. The criterion for spinning reserve varies amongst utilities, but in order to maintain reliability, there should be enough to keep the system intact following the loss of the largest online generator. Spinning reserve has a dual purpose in that it can also provide quick frequency response during a system disturbance [84]. The addition of more online synchronous generation provides more inertia to the system and therefore improves frequency stability.

This approach can be costly depending on the form of generation being allocated for spinning reserve. Although system reliability and stability is enhanced by having spinning reserve, it is at the expense of increased fuel costs or inefficiency operating hydro generation plants.

7.3.3 *Special Protection Scheme (SPS)*

The implementation of an SPS is another more traditional approach taken by utilities to help regulate the frequency of a power grid. The North American Electric Reliability Corporation (NERC) has recently defined an SPS as:

> *"An automatic protection system designed to detect abnormal or predetermined system conditions, and take corrective actions other than and/or in addition to the isolation of faulted components to maintain system reliability. Such action may include changes in demand, generation (MW and MVar), or system configuration to maintain system stability, acceptable voltage, or power flows. An SPS does not include (a) under-frequency or under-voltage load shedding or (b) fault conditions that must be isolated or*

(c) out of step relaying (not designed as an integral part of an SPS). Also called Remedial Action Scheme (RAS)." [85]

An abnormal or predetermined system condition could be the loss of a specific generator or load that could result in an undesirable change in system frequency. The corrective action to restore system frequency following this type of event could be the controlled removal of load or generation. Neighboring utilities often facilitate an SPS by permitting the sudden adjustment of power imports or exports through a tie line.

SPSs can lead to widespread outages if a transmission line is tripped as part of a planned scheme, which is similar to UFLS. A SPS could also result in the disruption or reduction in power exports, and therefore a decrease in revenue to the utility. There could be a significant effort or cost to implement, depending on the required design or scope of a SPS.

7.3.4 Application Virtual or Synthetic Inertia

The majority of renewable energy sources do not use synchronous generator and therefore lack the ability to contribute inertia to a power system. This decline in system inertia could have an adverse effect on a power system and its ability to maintain stability [54]. In order to facilitate a large penetration of renewable energy sources, system inertia must be increased or emulated.

The concept of virtual inertia (or synthetic inertia) is a relatively new and innovative technique that artificially emulates the inertia of a synchronous generation for the purpose of improving system frequency response subsequent to a large system disturbance [86]. This approach lacks the inherit stabilizing properties associated with a large rotating mass, but they can be replicated using a combination of an energy storage system, power inverter/converter and a controller to instantaneous exchange of active power [87]. HVdc systems and EV charging infrastructure have these components and therefore are equipped to be a source of virtual inertia.

An HVdc converter can immediately change the magnitude and direction of power flow on a HVdc link by means of coordinated run-backs/run-ups or frequency controller action [54]. HVdc run-ups/run-backs are typically used as part of an SPS in which a large predetermined change in power order is triggered following a particular event. The purpose of an HVdc frequency controller is to regulate frequency on an AC system by automatically adjusting the power order on the HVdc link when frequency goes outside a predetermined dead-band or range. EVs share these same capabilities as an HVdc system, but at a much smaller scale and must work in tandem to have an appreciable influence on frequency regulation.

The power system stability analysis outlined in the next section utilizes the concept of virtual inertia using EVs and HVdc systems in order for the frequency to remain 59 Hz and avoid UFLS.

7.4 Power System Stability Analysis – Summary of Results

The frequency response of the IIS is a function of ML power flow (MW), total system inertia or island generation (MW), and EV transient contributions (MW). The objective of each simulation is to increase the amount of EVs contributions until the frequency does not drop below 59 Hz, the trigger point for UFLS. Island generation was minimized and generators with lower moments of inertia were prioritized for each simulation to reflect a worst case scenario from a total system inertia perspective. A recap of each transient stability simulation is provided in Appendix F.

The analysis assessed four different ML export levels; 0 MW, 158 MW, 300 MW and 500 MW which can also be expressed in terms of NET DC, or the difference between LIL import and ML export levels:

$$\boldsymbol{NET\ DC} = |\boldsymbol{P_{LIL}} - \boldsymbol{aP_{ML}}| \qquad [\mathbf{7.1}]$$

$$a = 1: \ ML\ Exporting$$
$$a = -1: \ ML\ Importing$$

$$\boldsymbol{P_{LIL}} - \ LIL\ Import(MW)^{48}$$
$$\boldsymbol{P_{ML}} - \ ML\ Import/Export\ (MW)$$

[48] Set to 900 MW for this analysis

Cases with the ML importing, or power flow from Nova Scotia to the IIS, were not evaluated since it is not a practical scenario when the LIL is at full capacity. ML runbacks are enabled when exports exceed 150 MW and are activated following a LIL bipole trip, where ML exports are instantly ran back to 0 MW, acting as a first attempt to offset the 900 MW imbalance. The larger the runback, the greater the 900 MW deficit can be instantly reduced and therefore improving frequency response. There could initially be a harmless spike in frequency, depending on the magnitude of the ML runback.

The EV transient contributions come in the form of the disconnection of charging EVs or the supply of real power through discharging EVs using V2G chargers. The simulations activate EV contributions at 59.6 Hz, subsequent to the ML Runback, to further offset the loss of 900 MW LIL bipole. There is opportunity to optimize the V2G switching scheme to further improve frequency response.

The frequency controller is activated with a frequency dead-band of +/-0.5 Hz when the ML is exporting less than150 MW pre-disturbance and runbacks are disabled. In the event that the frequency decreases below 59.5 Hz, the ML frequency controller forces 150 MW to be imported from Nova Scotia in a final attempt to offset the 900 MW imbalance.

A comparison between the IIS frequency response with and without EV contributions is shown in Figure 7-2, where both plots assume a full ML Runback. This particular simulation has the ML exporting the Emera block (158 MW) during peak conditions. A trip of the LIL at 900 MW will cause the system frequency to drastically drop, but with EV transient contributions the frequency does not decrease below 59 Hz due to an instant injection of 560 MW[49] at 59.6 Hz for this particular case. The ROCOF decreases after the activation of all the V2G chargers across the IIS, since this would be an increase in total system inertia due to the sudden supply of virtual inertia. The frequency spike at approximately 1.1 seconds is caused by the sudden injection of active power caused by a 158 MW runback on the ML.

[49] Equivalent to 370,000 light duty EVs during peak conditions

The frequency plot without EV contributions increases beyond 60 Hz, since too much load was shed, confirming that NL Hydro's UFLS scheme needs to be optimized. The switching scheme for the V2G chargers could also be optimized by increasing the frequency threshold or activating them in segments. However, this increases the probability of activating EV contributions since the IIS frequency tends to fluctuate between 59.7 Hz and 60.3 Hz during normal system operation (See Figure 5-6 – Chapter 5).

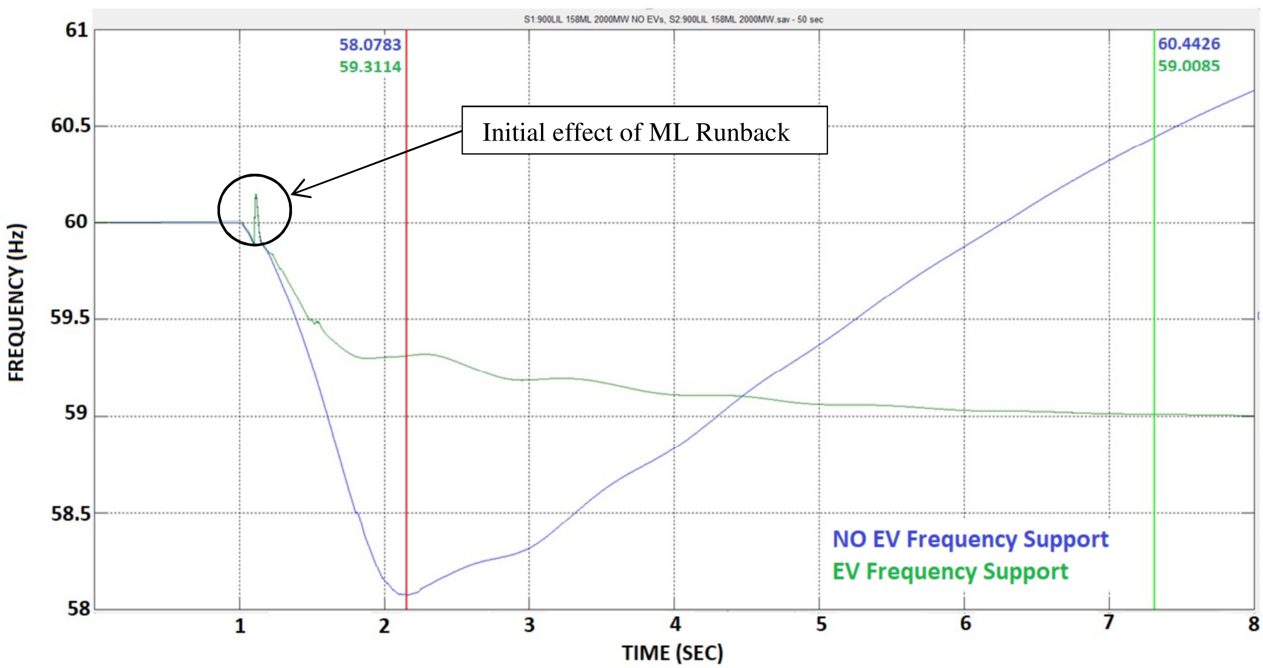


Figure 7-2: Frequency Plot (After LIL Bipole Trip with and without EVs)

The 230 kV voltages and relative rotor angles were also monitored following the simulation of a LIL bipole trip at 900 MW for this same simulation. The voltages suddenly increase following the trip, but the generator exciters across the system help reduce and stabilize the voltage, as shown in Figure 7-3. The voltage change appears to be higher on the east side of the IIS, since this is closer proximity to the termination point of the LI to the system. Voltage could be further improved by running the third synchronous condenser in-service at SOP and therefore providing reactive power support.

The relative rotor angle for each large unit (greater than 40 MW) is plotted in Figure 7-4. The rotor oscillations for each unit dampen over time and hence no angular instability subsequent to a LIL bipole trip. These oscillations can be further dampened by enabling the Power System Stabilizer (PSS) of each unit. PSSs are control devices within an excitation system that help improve the overall stability of a power system by dampening generator electromechanical oscillations [81]. The dynamic response of the units could also be improved through the performance of governor system tuning.

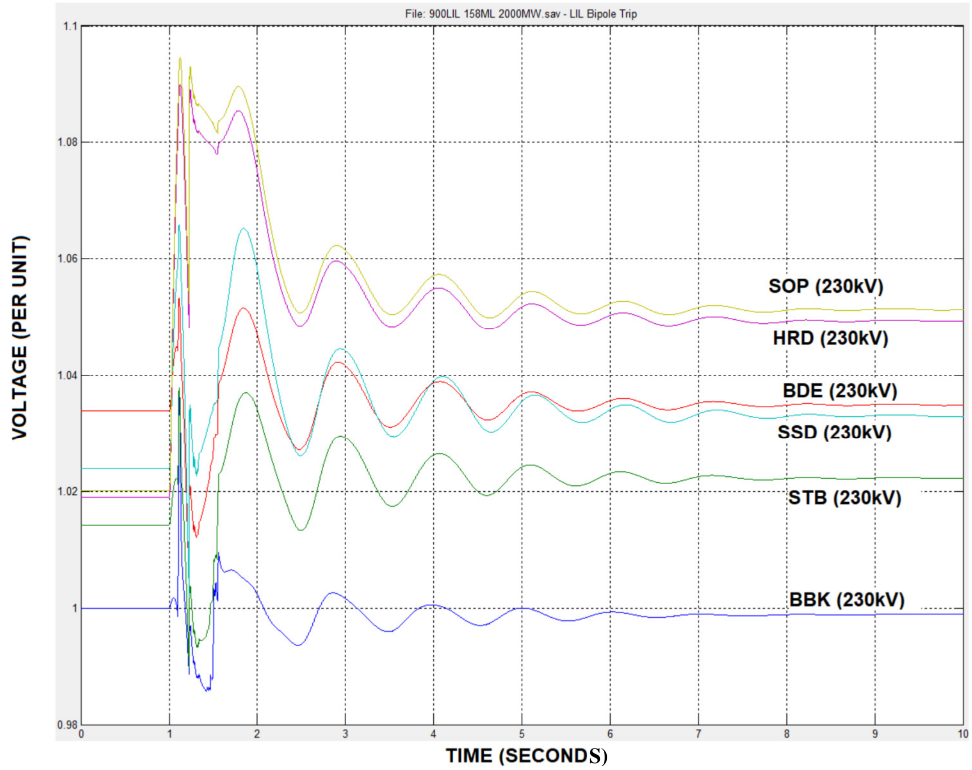


Figure 7-3: 230 kV Voltage Plots

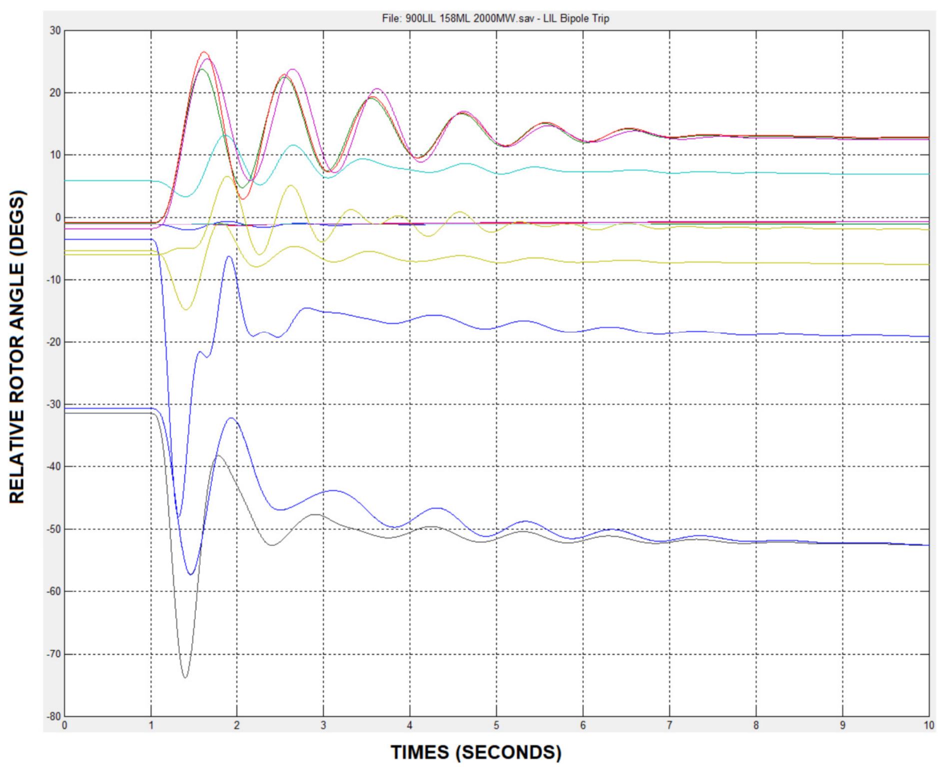


Figure 7-4: Relative Rotor Angle – All Large Generation Units on IIS (>40 MW)

The results of each simulation are consolidated into one graph shown in Figure 7-5, where each plot represents a particular ML export level. The system and EV specific assumptions for all the simulations were provided in Table 5-2 in Chapter 5. Each point on the graph required multiple dynamic simulations to determine the EV contribution that prevented the system frequency from going below 59 Hz. The data associated with this graph is provided in Appendix F.

The plots appear to be relatively flat within a tight band as demonstrated by the bar graph in Figure 7-6. There is a marginal change in EV contributions over the range of IIS generation, but there appears to be no specific pattern or correlation. It was expected that more EV contributions would be required at lower IIS generation levels to avoid UFLS; given there is less online inertia. However, since the ROCOF is higher with less inertia the frequency drops to 59.6 Hz faster and therefore EV contributions are initiated quicker. Figures 7-5 and 7-6 show that the higher the NET DC, the more EV contributions are necessary to eliminate UFLS on the IIS. The graphs demonstrate a value of 500 MW NET DC corresponds to 400 MW of EV transient contributions. This means that if the LIL and ML operate at a difference of 500 MW, 400 MW of EVs would have to instantaneously supply active power to the IIS following a LIL bipole trip to prevent UFLS. Under the same scenario, less EV transient contributions would still be beneficial since they could help minimize the amount of UFLS.

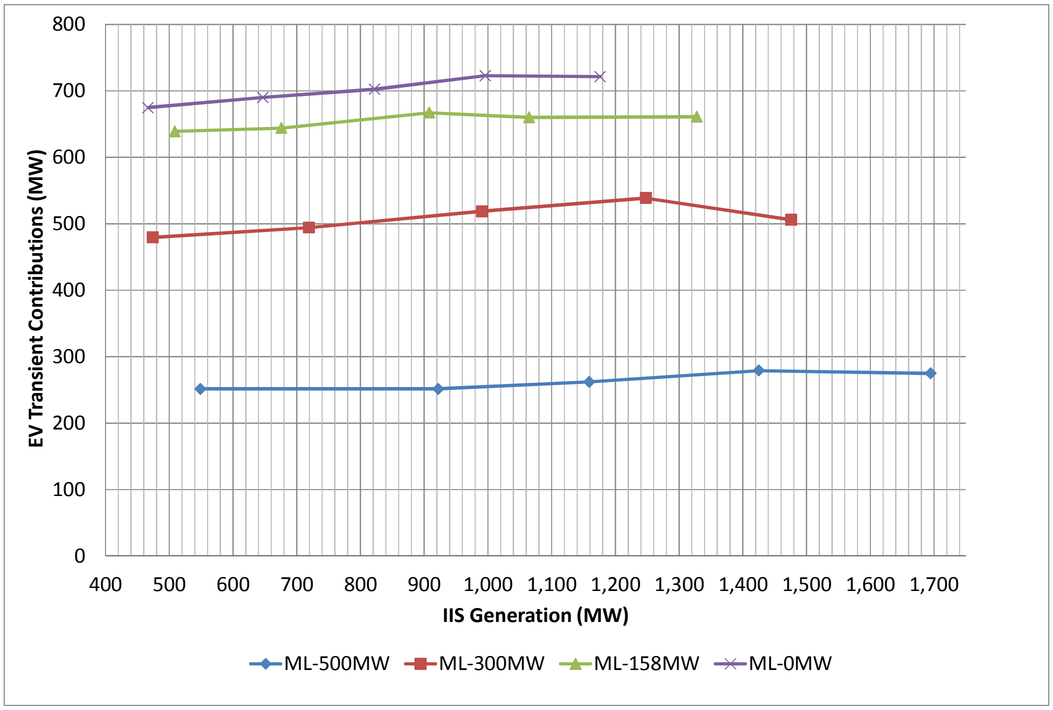


Figure 7-5: EV Transient Contributions vs. IIS Generation

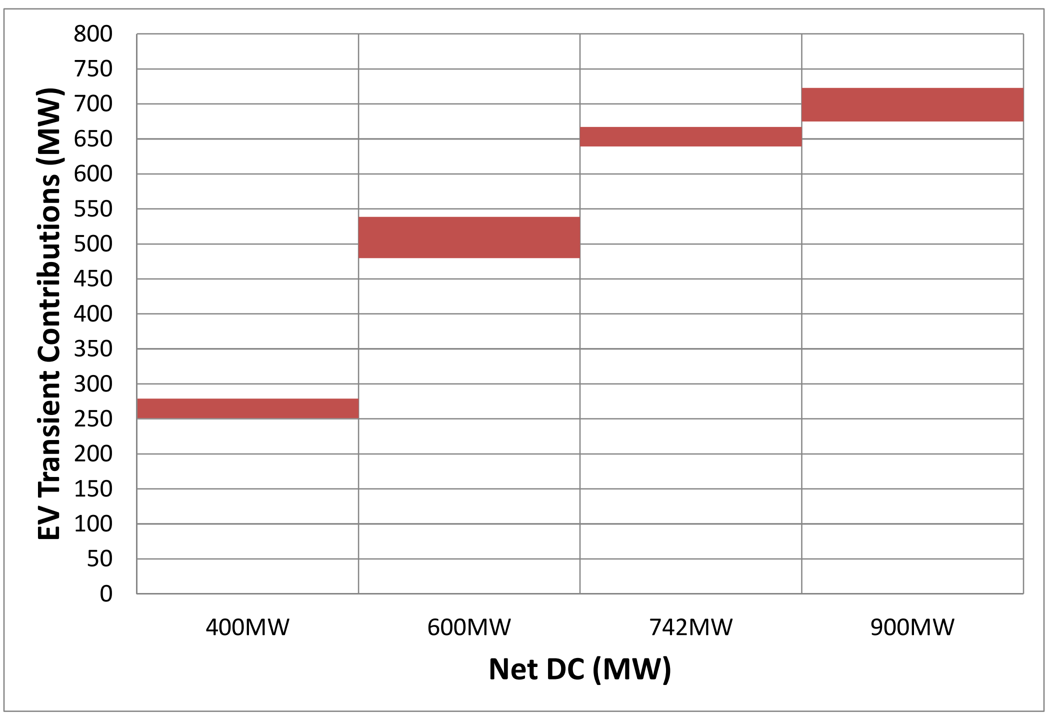


Figure 7-6: EV Transient Contributions vs. Net DC

When eliminating the variable of IIS generation, which under the circumstances has little influence on frequency response, there appears to be a strong correlation between EV transient contributions and NET

DC and is shown in Figure 7-7. After applying a trend line (y = 0.8321x – 14.154) to this relationship, the coefficient of determination or R-Squared (R^2) value is 0.9785. For every 100 MW increase in NET DC, 83 MW of EV contributions must be applied following a LIL bipole trip to prevent the frequency from decreasing below 59 Hz. The red points on the plot in Figure 7-7 signify two additional simulations that were completed to verify the trend line.

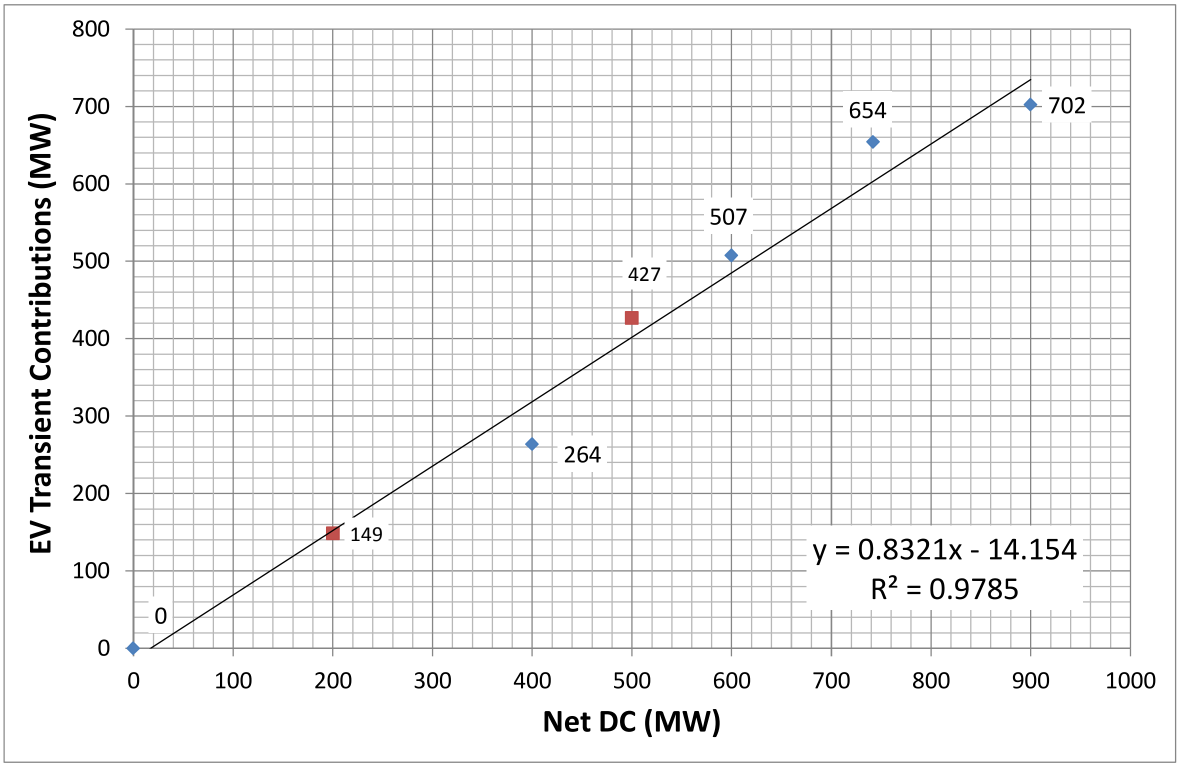


Figure 7-7: EV Transient Contributions vs. Net DC (Correlation)

7.5 Summary

The power system stability analysis presented in this Chapter has proven that a high penetration of EVs in Newfoundland could present the prospect of significantly improving the frequency response of the IIS following a large system disturbance. Multiple dynamic simulations were performed using PSS®E to establish the relationship in Figure 7-7, which illustrates a strong correlation between NET DC and EV transient contributions. The higher the difference between ML and LIL imports levels (NET DC) the more EV transient contributions are required to keep the frequency above 59 Hz and avoid UFLS.

Chapter 8

Conclusion and Recommendations

The transportation industry appears to be electrifying at a rapid pace based on the current and projected trends discussed in Chapter 2. In the event that these projections materialize, NL Hydro could be faced with many challenges and opportunities. The increased demand of EVs at a large scale without the implementation of DSM strategies, like TOD or coordinated EV charging, would eventually result in multiple transformer overloads and low voltage conditions throughout the IIS. A comprehensive summary of the potential violations attributed to increased EV demand was provided in Table 6-9 in Chapter 6. It can be concluded from the analysis in Chapter 6 that DSM strategies are vital for the successful integration of EVs into the IIS, which aligns with the same conclusion of the CDM potential study completed by Dunsky Energy Consulting.

The load flow analysis estimated it could take between 70,000 to 135,000 EVs to trigger capital upgrades at this present time. A projection of the exact number of EVs that could initiate capital upgrades would be difficult to develop, given the many different factors influencing the flow of power throughout the IIS. It is recommended that further sensitivity analysis be completed to fully understand these factors and how they could alter the load flow results in Chapter 6.

The power system studies performed in Chapter 6 and 7 demonstrated that with the appropriate integration of EVs to the IIS, system reliability could be improved or capital investments could be postponed. Section 6.2.3 revealed that with aid of V2G technology and EV coordinated charging, the system peak could be significantly reduced, which could theoretically defer generation capacity deficits. However, a cost benefit analysis would have to be performed to determine the economic feasibility of this approach in comparison to other generation expansion options. Chapter 7 showed that V2G/V1G technology could be utilized to considerably reduce or even eliminate customer outages due to system disturbances causing under frequency.

The primary outcome from the power system stability analysis in Chapter 7 was the establishment of a relationship between EV transient contributions and the parameter NET DC shown in Figure 7-7. This relationship states that for every 100 MW increase in NET DC, 83 MW of EV contributions must be applied at a frequency threshold of 59.6 Hz following a LIL bipole trip to completely avoid UFLS.

The principal recommendation of this thesis is that NL Hydro should collaborate with the Government of NL and Newfoundland Power in order to develop a plan that ensures a potential high penetration of EVs will not jeopardize overall power system reliability and avoid unnecessary capital expenditures. All stakeholders should further investigate the technical and prospective economic benefits associated with the power system integration of EVs to help minimize customer outages and future electricity rates.

8.1 Contributions

The main contribution of this thesis was providing awareness for the importance of establishing a comprehensive plan for a potential high penetration of EVs in Newfoundland. The following are some of the other key contributions associated with the research and analysis conducted as part of this thesis:

1. The performance of a detailed power system study of the IIS for the purpose of investigating the impacts of a mass adoption of EVs in Newfoundland. This study facilitated the development of long-term capital plan assuming the absence of DSM strategies.
2. The quantification of the <u>technical</u> benefits associated with implementing V2G/V1G technology on the IIS for various levels of EV penetration; including:
    a) The reduction of system peak ("Peak Shaving")
    b) The improvement of IIS frequency response following a large system disturbance (eg. LIL bipole trip)
3. The discovery of a strong correlation between EV transient contributions and the parameter NET DC on the IIS. This relationship states that for every 100 MW difference between ML exports and LIL imports, there must be 83 MW of EV transient contributions to avoid UFLS on the IIS.

4. A demonstration of the importance of DSM strategies for the successful integration of EVs on the IIS. This conclusion aligns with the CDM potential study completed by Dunsky Energy Consulting in 2019 [31].
5. The verification that NL Hydro's UFLS scheme must be optimized in preparation for the completion of the Lower Churchill Project.

8.2 Future Research

Research in the area of EVs and their influence on power transmission systems is in its infancy. This investigation was exploratory in nature and is a first look at the impact of EVs on the Newfoundland transmission system; thus there are many opportunities for further research. Some of the recommendations for future research based on this investigation and the contents of this thesis are summarized as follows:

1. Assess the impact of a high penetration of EVs on the various distribution systems throughout Newfoundland and Labrador. An increase in electrical demand driven by EVs would initially have more of an impact on power utility's distribution assets [65].
2. The development of more detailed demand forecasts for EV growth with consideration of various DSM strategies.
3. Perform a generation expansion study for various EV penetration levels with consideration for DSM strategies; specifically TOD rates and/or coordinated EV charging.
4. Investigate the effect of the harmonics caused by a high penetration of EVs on the IIS. The introduction of harmonics to a power system can cause electrical equipment to overheat and have the potential to adversely affect the operation of protection devices [63].
5. Quantify the benefits that EVs could provide the IIS from a voltage regulation standpoint. An EV can provide reactive power compensation, since chargers can operate in all four quadrants of the

P-Q plane [67]. This capability would allow utilities to use EVs for Power Factor Correction (PFC) and voltage regulation, therefore functioning as small portable SVCs.

6. Replicate the analysis performed in Chapter 6 assuming different locations for the new generation sources required to accommodate increases in demand associated with high EV growth.
7. Assess the potential impacts of a high penetration of EVs on the LIS
8. Perform further research in the area of battery degradation caused by using V2G technology for frequency regulation. There is some concern that the constant use of EVs for frequency regulation could promote battery degradation. However, some studies show that this is not necessarily the case and depending on the charging/discharging patterns, battery degradation can actually be decelerated using smart grid technology [63] [64].
9. The V2G switching scheme used for the analysis in Chapter 7 could be further optimized to leverage the collective capability of all EVs connected to the IIS. Power system stability analysis could be performed on many different scenarios to determine the best switching scheme.
10. Conduct economic analysis to determine if the widespread implementation and subsidization of V2G chargers is a cost effective approach for utilities to defer future capacity upgrades or improve system reliability.
11. Investigate and quantify the benefits of using EVs as a form of energy storage to increase the penetration of renewable energy on the NL grid.
12. Perform more detailed power system stability analysis to assess the advantages of EVs following the loss of other transmission elements.

References

[1] P. Valdes-Dapena and I. Sherman, "Electric cars have been around since before the US Civil War," CNN, 10 October 2019. [Online]. Available: https://www.cnn.com/interactive/2019/07/business/electric-car-timeline/index.html. [Accessed 31 October 2019].

[2] F. Alizon, B. S. Shooter and T. W. Simpson, "Henry Ford and the Model T: lessons for product platforming and mass customization," *Design Studies,* vol. 30, no. 5, pp. 588-605, September 2009.

[3] C. Paine, Director, *Who Killed the Electric Car?.* [Film]. USA: Electric Entertainment, 2006.

[4] J. Cook, N. Oreskes, P. Doran, W. Anderegg, B. Verheggen, E. Maibach, J. Carlton, S. Lewandowsky, A. Skuce, S. Green, D. Nuccitelli, P. Jacobs, M. Richardson, B. Winkler, R. Painting and Ri, "Consensus on consensus: a synthesis of consensus estimates on human-caused global warming," *Environmental Research Letters,* vol. 11, no. 4, pp. 1-7, 2015.

[5] National Aeronautics and Space Administration (NASA), "2018 fourth warmest year in continued warming trend, according to NASA, NOAA," NASA, 6 February 2019. [Online]. Available: https://climate.nasa.gov/news/2841/2018-fourth-warmest-year-in-continued-warming-trend-according-to-nasa-noaa/. [Accessed 11 November 2019].

[6] M. Franchini and P. M. Mannucci, "Impact on human health of climate changes," *European Journal of Internal Medicine,* vol. 26, no. 1, pp. 1-5, 2015.

[7] International Energy Agency (IEA), "Global EV Outlook 2019: Scaling-up the transition," International Energy Agency (IEA), Paris, France, 2019.

[8] International Energy Agency (IEA), "CO_2 EMISSIONS FROM FUEL COMBUSTION: OVERVIEW (2019 edition)," International Energy Agency (IEA), Paris, France, 2019.

[9] O. v. Vliet, A. S. Brouwer, T. Kuramochi, M. v. d. Broek and A. Faaij, "Energy use, cost and CO2 emissions of electric cars," *Journal of Power Sources,* vol. 196, no. 4, pp. 2298-2310, 2011.

[10] G. Wu, A. Inderbitzin and C. Bening, "Total cost of ownership of electric vehicles compared to conventional vehicles: A probabilistic analysis and projection across market segmants," *Energy Policy,* vol. 80, pp. 196-214, 2015.

[11] PLUG'N DRIVE, "Electrify Your Ride," PLUG'N DRIVE, North York, ON, 2019.

[12] "TRAX," Chevrolet, 2019. [Online]. Available: https://www.chevrolet.ca/en/suvs/previous-year-trax. [Accessed 19 November 2019].

[13] BC Hydro, "How much does owning an electric vehicle cost?," BC Hydro, 2019. [Online]. Available: https://electricvehicles.bchydro.com/learn/costs-of-electric-vehicles. [Accessed 17 November 2019].

[14] Canadian Automobile Association (CAA), "Canadians Unclear About the True Cost of Owning a Vehicle," Canadian Automobile Association (CAA), 24 May 2018. [Online]. Available: https://www.caa.ca/canadians-unclear-about-the-true-cost-of-owning-a-vehicle/. [Accessed 17 November 2019].

[15] Government of Canada, "List of eligible vehicles under the iZEV Program," Government of Canada, 6 November 2019. [Online]. Available: https://www.tc.gc.ca/en/services/road/innovative-technologies/list-eligible-vehicles-under-izev-program.html. [Accessed 17 November 2019].

[16] K. M. Tan, V. K. Ramachandaramurthy and J. Y. Yong, "Integration of electric vehicles in smart grid: A review on vehicle to grid technologies and optimization techniques," *Renewable and Sustainable Energy Reviews,* vol. 53, pp. 720-732, 2016.

[17] H. L. Breetz and D. Salonb, "Do electric vehicles need subsidies? Ownership costs for conventional, hybrid, and electric vehicles in 14 U.S. cities," *Energy Policy,* vol. 120, pp. 238-249, 2018.

[18] Z. Wang and S. Wang, "Grid Power Peak Shaving and Valley Filling Using Vehicle-to-Grid Systems," *IEEE Transactions on Power Delivery,* vol. 28, no. 3, pp. 1822-1829, July 2013.

[19] J. Campillo and G. Carli, Technologies and Applications for Smart Charging of Electric and Plug-in Hybrid Vehicles, O. Veneri, Ed., Cham: Springer, 2017, pp. 23, 114.

[20] J. Neubauer and E. Wood, "The impact of range anxiety and home, workplace, and public charging infrastructure on simulated battery electric vehicle lifetime utility," *Journal of Power Sources,* vol. 257, pp. 12-20, 2014.

[21] J. R. M. D. Reyes, R. V. Parsons and R. Hoemsen, "Winter Happens: The Effect of Ambient Temperature on the Travel Range of Electric Vehicles," *IEEE Transactions on Vehicular Technology,* vol. 65, no. 6, pp. 4016-4022, 2016.

[22] D. Shukman, "Electric car future may depend on deep sea mining," BBC News, 13 November 2019. [Online]. Available: https://www.bbc.com/news/science-environment-49759626. [Accessed 18 November 2019].

[23] International Economic Analysis Department - Bank of Canada, "Outlook for Electric Vehicles and Implications for the Oil Market," Bank of Canada, Ottawa, CA, 2019.

[24] Electric Mobility Canada, "Electric Vehicle Sales in Canada in 2018: A phenomenal record-breaking year," Electric Mobility Canada, Ile des Sœurs, QC , 2019.

[25] Government of Canada, "Zero-emission vehicles," Government of Canada, 14 August 2019. [Online]. Available: https://www.tc.gc.ca/en/services/road/innovative-technologies/zero-emission-vehicles.html. [Accessed 25 November 2019].

[26] Canada Energy Regulator , "Market Snapshot: Growing electric vehicle incentives in Canada," Government of Canada, 28 August 2019. [Online]. Available: https://www.cer-rec.gc.ca/nrg/ntgrtd/mrkt/snpsht/2018/01-03lctrcvhclncntvs-eng.html. [Accessed 25 November 2019].

[27] Newfoundland and Labrador Hydro, *Presentation: Electric Vehicle Charging - Regulatory and Program Considerations (Internal Document),* St. John's: Newfoundland and Labrador Hydro, 2019.

[28] L. Bird, "Electric-vehicle charging network planned for N.L. in 2020," CBC, 26 October 2019. [Online]. Available: https://www.cbc.ca/news/canada/newfoundland-labrador/electric-vehicle-charging-network-newfoundland-1.5334972. [Accessed 5 December 2019].

[29] Newfoundland Power, "Plugging in on the Rock - Electric Vehicle Market Assessment," Newfoundland Power, St. John's, NL, 2018.

[30] Bruce Power; Plug'N Drive; University of Waterloo; Pollution Probe, "Accelerating the Deployment of Plug-In Electric Vehicles in Canada and Ontario," Bruce Power; Plug'N Drive; University of Waterloo; Pollution Probe, 2016.

[31] Dunsky Energy Consulting, "Conservation Potential Study - Final Report (Volume 1 - Results)," Dunsky Energy Consulting, Montreal, QC, 2019.

[32] Newfoundland and Labrador Hydro, "Reliability and Resource Adequacy Study," Newfoundland and Labrador Hydro, St. John's, 2018.

[33] "About Hydro," 2018. [Online]. Available: https://nlhydro.com/about-hydro/. [Accessed 18 July 2018].

[34] Newfoundland and Labrador System Operator (NLSO), *System Data - Retrieved from NLSO SCADA system,* St. John's, NL: Newfoundland and Labrador System Operator (NLSO), 2020.

[35] Nalcor Energy, "In the Know: Newfoundland and Labrador System Operator (NLSO)," Nalcor Energy, 2019. [Online]. Available: https://nlhydro.com/wp-content/uploads/2018/01/Hydro-InTheKnow-NLSO_FINAL.pdf . [Accessed 10 February 2019].

[36] Newfoundland and Labardor System Operator (NLSO), "NLSO Standard - Transmission Planning

Criteria," NLSO, 11 5 2018. [Online]. Available: http://www.oasis.oati.com/woa/docs/NLSO/NLSOdocs/TP-S-007_Transmission_Planning_Criteria_UPDATED_05112018.pdf. [Accessed 10 February 2019].

[37] Power Advisory (LLC), "Review of the Newfoundland and Labrador," St. John's, 2015.

[38] "Transmission," 2018. [Online]. Available: http://www.poweryourknowledge.com/pdf/TR2.pdf. [Accessed 22 July 2018].

[39] "Service Territory," 2018. [Online]. Available: https://www.newfoundlandpower.com/en/About-Us/About-Newfoundland-Power/Service-Territory.

[40] "Map-Service-Areas," Newfoundland and Labrador Hydro: A Nalcor Energy Company, 2018. [Online]. Available: https://nlhydro.com/winter/power-restoration/map-service-areas/. [Accessed 3 Febuary 2019].

[41] Newfoundland and Labrador Hydro, "Thermal Generation," Newfoundland and Labrador Hydro, 2019. [Online]. Available: https://nlhydro.com/operations/thermal-generation/. [Accessed 17 February 2019].

[42] "Churchill Falls: At a Glance," 22 July 2018. [Online]. Available: https://nalcorenergy.com/nalcor-operations/churchill-falls/at-a-glance/.

[43] P. Kundur, Power System Stability and Control, J. N. Balu and G. M. Lauby, Eds., McGraw-Hill, Inc, 1994.

[44] A. Rahman, L. C. Saikia and N. Sinha, "Automatic generation control of an interconnected two-area hybrid thermal system considering dish-stirling solar thermal and wind turbine system," *Renewable Energy,* pp. 41-54, May 2017.

[45] Nalcor Energy, "Lower Churchill Project - At a Glance," Nalcor Energy, 2019. [Online]. Available: https://nalcorenergy.com/nalcor-operations/lower-churchill-project/at-a-glance/. [Accessed 28 February 2019].

[46] Nalcor Energy, *Integrated Project Schedule (Internal Document),* St. John's: Nalcor Energy, 2020.

[47] Emera Inc., "Project Overview - Maritime Link," Emera Inc., September 2016. [Online]. Available: http://www.emeranl.com/site/media/emeranl/Documents/01242014ML%20Overview.pdf. [Accessed 7 March 2019].

[48] Newfoundland and Labrador Provincal Government, "Why not develop Gull Island first?," Newfoundland and Labrador Provincal Government, St. John's, 2012.

[49] H. Mckenzie Sutter, "Transmission link between Labrador and Newfoundland energized as Muskrat Falls project nears completion," The Globe and Mail, 27 June 2018. [Online]. Available: https://www.theglobeandmail.com/business/industry-news/energy-and-resources/article-transmission-link-between-labrador-and-newfoundland-energized-as/. [Accessed 6 March 2019].

[50] E. O. Oni, K. I. Mbangula and I. E. Davidson, "A review of LCC-HVDC and VSC-HVDC technologies and applications," in *2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, Florence Italy, 2016.

[51] Y. Xue and X.-P. Zhang, "Reactive Power and AC Voltage Control of LCC HVDC System With Controllable Capacitors," *IEEE Transactions on Power Systems,* vol. 32, no. 1, pp. 753-764, 2017.

[52] P. Thomas, *HVdc Systems Overview (Internal Document - Presentation),* St. John's, NL: NL Hydro, 2017.

[53] Newfoundland and Labrador System Operator (NLSO), "Newfoundland and Labrador Power System Restoration Plan (Internal Document)," Newfoundland and Labrador System Operator (NLSO), St. John's, NL, 2019.

[54] E. Rakhshani, D. Remon, A. M. Cantarellas and J. M. Garcia, "Virtual Synchronous Power Strategy for Multiple HVDC Interconnections of Multi-Area AGC Power Systems," *IEEE Transactions on*

Power Systems, vol. 32, no. 3, pp. 1665 - 1677 , 2017.

[55] M. Yilmaz and P. T. Krein, "Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles," *IEEE TRANSACTIONS ON POWER ELECTRONICS,* vol. 28, no. 5, pp. 2151-2169, 2013.

[56] "AC Motor VS. DC Motor: Which One Is Better for EVs?," 22 March 2018. [Online]. Available: https://www.boldbusiness.com/transportation/ac-motor-vs-dc-motor-one-better-evs/. [Accessed 9 July 2018].

[57] "ecoTECHNOLOGY for Vehicles," 2018. [Online]. Available: http://publications.gc.ca/collections/collection_2011/tc/T22-193-2010-eng.pdf. [Accessed 9 July 2018].

[58] IONITY, "Technology," IONITY - The Power of 350 kW, 2019. [Online]. Available: https://ionity.eu/en/design-and-tech.html. [Accessed 17 October 2019].

[59] Canadian Electricity Assocation (CEA), "The Smart Grid: A Pragmatic Approach," 2010.

[60] S. (. Letendre, P. (. Denholm and P. (. Lilienthal, "Electric & Hybrid Cars: New Load, or New Resource?," Public Utilities Fortnightly (PUF), December 2006. [Online]. Available: https://www.fortnightly.com/fortnightly/2006/12/electric-hybrid-cars-new-load-or-new-resource. [Accessed 16 December 2019].

[61] Nova Scotia Power - An Emera Company, "Time-of-Day Rates," Nova Scotia Power - An Emera Company, 2019. [Online]. Available: https://www.nspower.ca/en/home/for-my-home/heating-solutions/electric-thermal-storage/tod-rates/default.aspx. [Accessed 4 October 2019].

[62] OVO Energy, "Your Vehicle-to-Grid Charger," OVO Energy, Bristol, 2019.

[63] M. A. Ortega-Vazquez, "Optimal scheduling of electric vehicle charging and vehicle-to-grid services at household level including battery degradation and price uncertainty," *IET Generation, Transmission & Distribution ,* vol. 8, no. 6, pp. 1007-1016 , 2014.

[64] K. Uddin, T. Jackson, W. D. Widanage, G. Chouchelamane, P. A. Jennings and J. Marco, "On the possibility of extending the lifetime of lithium-ion batteries through optimal V2G facilitated by an integrated vehicle and smart-grid system," *Energy,* vol. 133, pp. 710-722, 2017.

[65] P. K. Detwiler, "Electric Cars and the Power Grid: How Are They Coming Together?," 28 January 2013. [Online]. Available: https://www.forbes.com/sites/peterdetwiler/2013/01/28/electric-cars-and-the-power-grid-how-are-they-coming-together/#7007b6c51976. [Accessed 9 July 2018].

[66] K. Clement-Nyns, E. Haesen and J. Driesen, "The Impact of Charging Plug-In Hybrid Electric Vehicles on a Residential Distribution Grid," *IEEE TRANSACTIONS ON POWER SYSTEMS,* vol. 25, no. 1, pp. 371-380, Feburary 2010.

[67] "Power System Harmonics," April 2001. [Online]. Available: http://literature.rockwellautomation.com/idc/groups/literature/documents/wp/mvb-wp011_-en-p.pdf. [Accessed 10 July 2018].

[68] A. Lucas, F. Bonavitacola, E. Kotsakis and G. Fulli, "Grid harmonic impact of multiple electric vehicle fast charging," *Electric Power Systems Research,* vol. 127, pp. 13-21, October 2015.

[69] "Peak Shaving," 2018. [Online]. Available: https://new.abb.com/distributed-energy-microgrids/applications/energy-storage-applications/peak-shaving.

[70] A. Gajduk, M. Todorovski, J. Kurths and L. Kocarev, "Improving power grid transient stability by plug-in electric vehicles," *New Journal of Physics,* November 2014.

[71] M. C. Kisacikoglu, B. Ozpineci and L. M. Tolbert, "EV/PHEV Bidirectional Charger Assessment for V2G Reactive Power Operation," *IEEE TRANSACTIONS ON POWER ELECTRONICS,* vol. 28, no. 12, pp. 5717-5727, 2013.

[72] Siemens PTI, "PSS®E," Siemens PTI, 2019. [Online]. Available:

https://www.siemens.com/global/en/home/products/energy/services/transmission-distribution-smart-grid/consulting-and-planning/pss-software/pss-e.html. [Accessed 12 December 2019].

[73] Newfoundland and Labrador System Operator (NLSO), "2019 Annual Planning Assessment," NLSO, St. John's, NL, 2019.

[74] P. Stratton, Interviewee, *Senior Market Analyst.* [Interview]. 7 March 2019.

[75] Newfoundland and Labrador Hydro - Market Analysis Department, *Forecasted EV Demand (Internal Document),* Newfoundland and Labrador Hydro, 2019.

[76] Newfoundland and Labrador System Operator (NLSO), "Transmission Planning Criteria," NLSO, St. John's, 2018.

[77] TransGrid Solutions, "Operational Studies - LIL Bipole: Transition to High Power Operation (Stage 4D) (Internal Document)," TransGrid Solutions, Winnipeg, MB, 2019.

[78] J. D. Glover, S. M. Sarma and T. J. Overbye, Power System Analysis and Design, 5 ed., Stamford, CT: Cengage Learning, 2012.

[79] Newfoundland and Labrador System Operator (NLSO), "Transmission Facilities Rating Guide," Newfoundland and Labrador System Operator (NLSO), St. John's, NL, 2017.

[80] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. V. Cutsem and V. Vittal, "Definition and Classification of Power System Stability," *IEEE TRANSACTIONS ON POWER SYSTEMS,* vol. 19, no. 2, pp. 1387-1401, 2004.

[81] M. J. Basler and R. C. Schaefer, "Understanding Power-System Stability," *IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS,* vol. 44, no. 2, pp. 463-473, 2008.

[82] J. J. Grainger and W. D. Stevenson, Jr, "Power System Stability," in *Power System Analysis*, Singapore, McGraw-Hill, Inc, 1994, pp. 695-746.

[83] D. L. H. Aik, "A General-Order System Frequency Response Model Incorporating Load Shedding: Analytic Modeling and Applications," *IEEE Transactions on Power Systems,* vol. 21, no. 2, pp. 709-716, 2006.

[84] "Spinning Reserve," Energy Storage Association (ESA), 2018. [Online]. Available: http://energystorage.org/energy-storage/technology-applications/spinning-reserve. [Accessed 2 October 2018].

[85] "Proposed Definition of “Special Protection System”," NERC - North American Electric Relilabity Corporation, November 2015. [Online]. Available: https://www.nerc.com. [Accessed October 2 2018].

[86] H. Bevrani, T. Ise and Y. Miura, "Virtual synchronous generators: A survey and new perspectives," *International Journal of Electrical Power & Energy Systems,* vol. 54, pp. 244-254, 2014.

[87] P. Tielens and D. VanHertem, "The relevance of inertia in power systems," *Renewable and Sustainable Energy Reviews,* vol. 55, p. 999–1009, 2016.

[88] Government of NL (Finance), "Statistics - Transportation," Government of NL (Finance), 2019. [Online]. Available: https://www.stats.gov.nl.ca/Statistics/Statistics.aspx?Topic=transportation. [Accessed 2 December 2019].

[89] "Transportation Electrification," 2018. [Online]. Available: http://www.hydroquebec.com/transportation-electrification/electric-vehicles/charging.html. [Accessed 9 July 2018].

[90] H. Bevrani, T. Ise and Y. Miura, "Virtual synchronous generators: A survey and new perspectives," *Electrical Power and Energy Systems,* vol. 54, pp. 244-254, 2014.

Appendix A – EV vs. ICEV Cost Benefit Analysis

EV vs ICEV
ICEV - 2019 Chevrolet TRAX

Note: Costs are shown as positive values; Benefits as negative values

Current Year	**2019**
Present Worth Year	2019
Number of Years in Study	10
Discount Rate	6.5%
Total In-service Project Cost	$ 25,700
In-service Year	2020
Other Project Cost ***after*** In-service (if applicable)	
Other Project Year (if applicable)	
Replacement Cost (if applicable)	$ -
Replacement Year (if applicable)	
Project cost in Ending (**E**) or Beginning (**B**) Year $$	B
O&M costs - Escalation based on mixture of Materials & Labour	More Material Less Labour

A	B	C	D	E	F	G	H	I	J	K	L
Year		Annual O&M Cost $	Annual Fuel Price (if applicable)	Annual Fuel Cost $	Other Cost $	Total Costs $	Benefit 1 (specify) $	Benefit 2 (specify) $	NET $	P.W. January 2019	Cumulative Present Worth
0	2019	-		-	-	-	-	-	-	-	-
1	2020	717		2,236	-	28,653	-	-	28,653	26,735	26,735
2	2021	733		2,236	-	2,969	-	-	2,969	2,458	29,193
3	2022	750		2,236	-	2,986	-	-	2,986	2,321	31,514
4	2023	767		2,236	-	3,003	-	-	3,003	2,192	33,705
5	2024	784		2,236	-	3,020	-	-	3,020	2,070	35,775
6	2025	802		2,236	-	3,038	-	-	3,038	1,955	37,730
7	2026	820		2,236	-	3,056	-	-	3,056	1,846	39,576
8	2027	838		2,236	-	3,074	-	-	3,074	1,744	41,320
9	2028	857		2,236	-	3,093	-	-	3,093	1,648	42,968
10	2029	876		2,236	-	3,112	-	-	3,112	1,557	44,525

EV vs ICEV
EV - 2019 Chevrolet BOLT

Note: Costs are shown as positive values; Benefits as negative values

Current Year	**2019**
Present Worth Year	2019
Number of Years in Study	10
Discount Rate	6.5%
Total In-service Project Cost	$ 44,800
In-service Year	2020
Other Project Cost ***after*** In-service (if applicable)	
Other Project Year (if applicable)	
Replacement Cost (if applicable)	$ -
Replacement Year (if applicable)	
Project cost in Ending (**E**) or Beginning (**B**) Year $$	B
O&M costs - Escalation based on mixture of Materials & Labour	More Material Less Labour

A	B	C	D	E	F	G	H	I	J	K	L
Year		Annual O&M Cost $	Annual Fuel Price (if applicable)	Annual Fuel Cost $	Other Cost $	Total Costs $	Benefit 1 (specify) $	Benefit 2 (specify) $	NET $	P.W. January 2019	Cumulative Present Worth
0	2019	-		-	-	-	-	-	-	-	-
1	2020	102		528	-	45,430	(5,000)	-	40,430	38,213	38,213
2	2021	105		528	-	633	-	-	633	524	38,737
3	2022	107		528	-	635	-	-	635	494	39,231
4	2023	110		528	-	638	-	-	638	465	39,696
5	2024	112		528	-	640	-	-	640	439	40,134
6	2025	115		528	-	643	-	-	643	413	40,548
7	2026	117		528	-	645	-	-	645	390	40,938
8	2027	120		528	-	648	-	-	648	367	41,305
9	2028	122		528	-	650	-	-	650	347	41,652
10	2029	125		528	-	653	-	-	653	327	41,978

Appendix B – DMV Statistics

New Motor Vehicle Sales, Newfoundland and Labrador – Units Sold (2010-2019) [87]

Month	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
January	1,545	1,546	1,700	1,659	1,653	1,632	1,627	1,574	1,609	1,599
February	1,693	1,684	1,851	1,959	1,622	1,688	1,864	1,784	1,652	1,730
March	2,822	2,897	2,961	3,172	2,909	2,369	2,820	2,935	2,604	2,590
April	3,161	3,105	3,293	3,663	3,871	3,810	3,833	3,530	3,083	2,823
May	3,456	3,155	3,850	4,033	4,018	4,040	3,804	3,895	3,461	3,414
June	3,797	3,276	3,730	3,690	3,254	3,571	4,023	3,629	3,205	3,235
July	3,327	2,889	3,212	3,544	3,620	3,663	2,725	3,087	3,023	3,014
August	2,854	2,890	3,340	3,488	3,536	3,383	2,829	3,112	3,030	3,253
September	2,601	2,621	2,920	3,207	3,387	3,406	3,193	3,301	2,855	
October	2,467	2,431	2,692	2,894	2,799	3,040	2,492	2,629	2,558	
November	2,078	2,357	2,329	2,286	2,457	2,535	2,642	2,383	1,899	
December	1,868	1,965	1,728	1,844	2,314	1,882	1,835	1,392	1,275	
Total	31,669	30,816	33,606	35,439	35,440	35,019	33,687	33,251	30,266	
Source: Statistics Canada Table 20-10-0001-01 (formerly CANSIM 079-0003)										

Number of Road Motor Vehicle Registrations– By (2010-2018) [87]

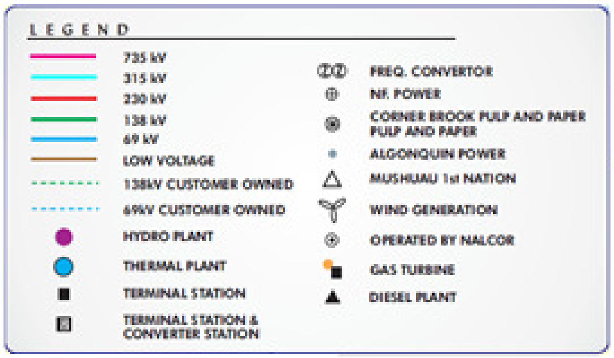
Type of vehicle	2010	2011	2012	2013	2014	2015	2016	2017	2018
Total, vehicle registrations	556,154	591,644	608,946	628,651	651,010	670,686	689,129	698,669	691,966
Total, road motor vehicle registrations	334,912	356,294	362,191	369,264	377,539	383,841	390,574	391,934	381,271
Vehicles weighing less than 4,500 kilograms	311,393	330,263	335,359	341,745	349,436	354,811	361,096	362,839	353,735
Vehicles weighing 4,500 kilograms to 14,999 kilograms	5,239	5,740	6,044	6,274	6,486	6,885	7,045	7,105	6,721
Vehicles weighing 15,000 kilograms or more	4,485	4,946	5,076	5,115	5,146	5,340	5,411	5,437	5,274
Buses	1,291	1,394	1,343	1,370	1,395	1,427	1,468	1,425	1,387
Motorcycles and mopeds	12,504	13,951	14,369	14,760	15,076	15,378	15,554	15,128	14,154
Trailers	46,785	52,605	54,978	58,123	61,212	63,471	64,350	63,411	59,300
Off-road, construction, farm vehicles	174,457	182,745	191,777	201,264	212,259	223,374	234,205	243,324	251,395
Source: Statistics Canada, Table 23-10-0067-01 (formerly CANSIM 405-0004) – June 14, 2019									

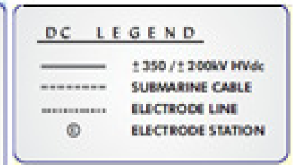
Electric and Hybrid Vehicle Penetration [87]

Registered Active Passenger Vehicles						
Year	2012	2013	2014	2015	2016	2017
Electric	36	31	34	37	43	63
Hybrid	164	202	239	279	316	364
Gross Vehicle Weight Rating of 4,500 kg and above electric vehicles are excluded) Source: Compiled by the Community Accounts Unit based on information provided by the provincial Motor Registration Division. Date: 1/14/2019						

Appendix C – Newfoundland and Labrador Grid Map

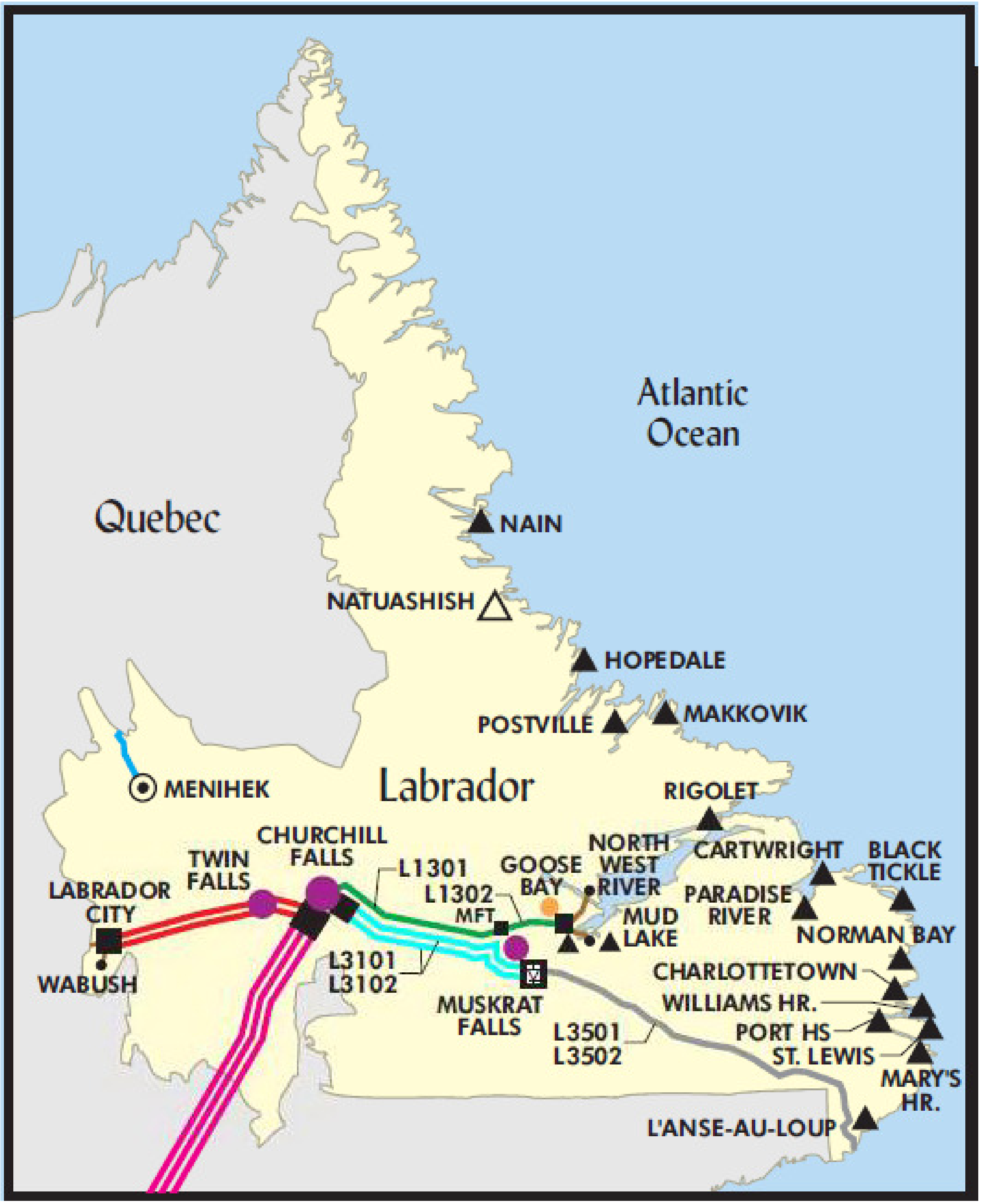
(Courtesy of NL Hydro)





Island Interconnected System (IIS)

Labrador Interconnected System (LIS)



Appendix D – NL Hydro Operating Load Forecasts

(Courtesy of NL Hydro)

Peak Demand Forecast (P90)
Island Interconnected System
(60 Hz MW)

	2019/20	2020/21	2021/22	2022/23	2023/24	2024/25	2025/26	2026/27	2027/28	2028/29
Non-coincident Customer Requirements										
Newfoundland Power System	1464.5	1466.3	1467.0	1477.1	1486.5	1494.2	1503.1	1514.8	1523.8	1533.9
Hydro Rural System	100.5	99.6	98.5	98.4	99.2	99.8	100.0	100.1	100.1	100.2
Industrial Customers										
Corner Brook Pulp & Paper	107.0	107.0	107.0	107.0	107.0	107.0	107.0	107.0	107.0	107.0
North Atlantic Refining	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5	31.5
Teck - Duck Pond	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0
Vale - Long Harbour	46.0	52.0	54.0	54.0	54.0	54.0	54.0	54.0	54.0	54.0
Praxair - Long Harbour	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
Coincident Customer Requirements										
Newfoundland Power System	1449.9	1451.6	1452.3	1462.3	1471.6	1479.3	1488.1	1499.7	1508.6	1518.6
Hydro Rural System	93.6	92.8	91.8	91.7	92.4	93.0	93.2	93.3	93.3	93.3
Industrial Customers										
Corner Brook Pulp & Paper	97.0	97.0	97.0	97.0	97.0	97.0	97.0	97.0	97.0	97.0
North Atlantic Refining	28.6	28.6	28.6	28.6	28.6	28.6	28.6	28.6	28.6	28.6
Teck - Duck Pond	0.5	0.5	0.5	0.5	0.5	0.5	0.0	0.0	0.0	0.0
Vale - Long Harbour	41.7	47.2	49.0	49.0	49.0	49.0	49.0	49.0	49.0	49.0
Praxair - Long Harbour	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
Sum of Island Coincident Customer Demands	1717.1	1723.5	1724.9	1734.8	1744.9	1753.1	1761.6	1773.3	1782.2	1792.3

Notes:
1. P-90 demand forecast reflects increased demand requirements associated with P90 weather conditions.
2. Newfoundland Power System non-coincident peak demand forecast sourced to NLH Planning Load Forecast, Base Case, Summer 2019.
3. Hydro Rural System non-coincident peak demand sourced to NLH Planning Load Forecast, Base Case, Summer 2019.
5. Industrial customer non-coincident power requirements reflect assessed industrial power requirements as of November 22, 2019.
6. Forecast coincident customer requirements reflects historical median or average coincidence factor values.
7. The sum of Island coincident customer demands does not include system transmission losses or station service load requirements.

Source: Market Analysis Section, Resource and Transmission Planning Department

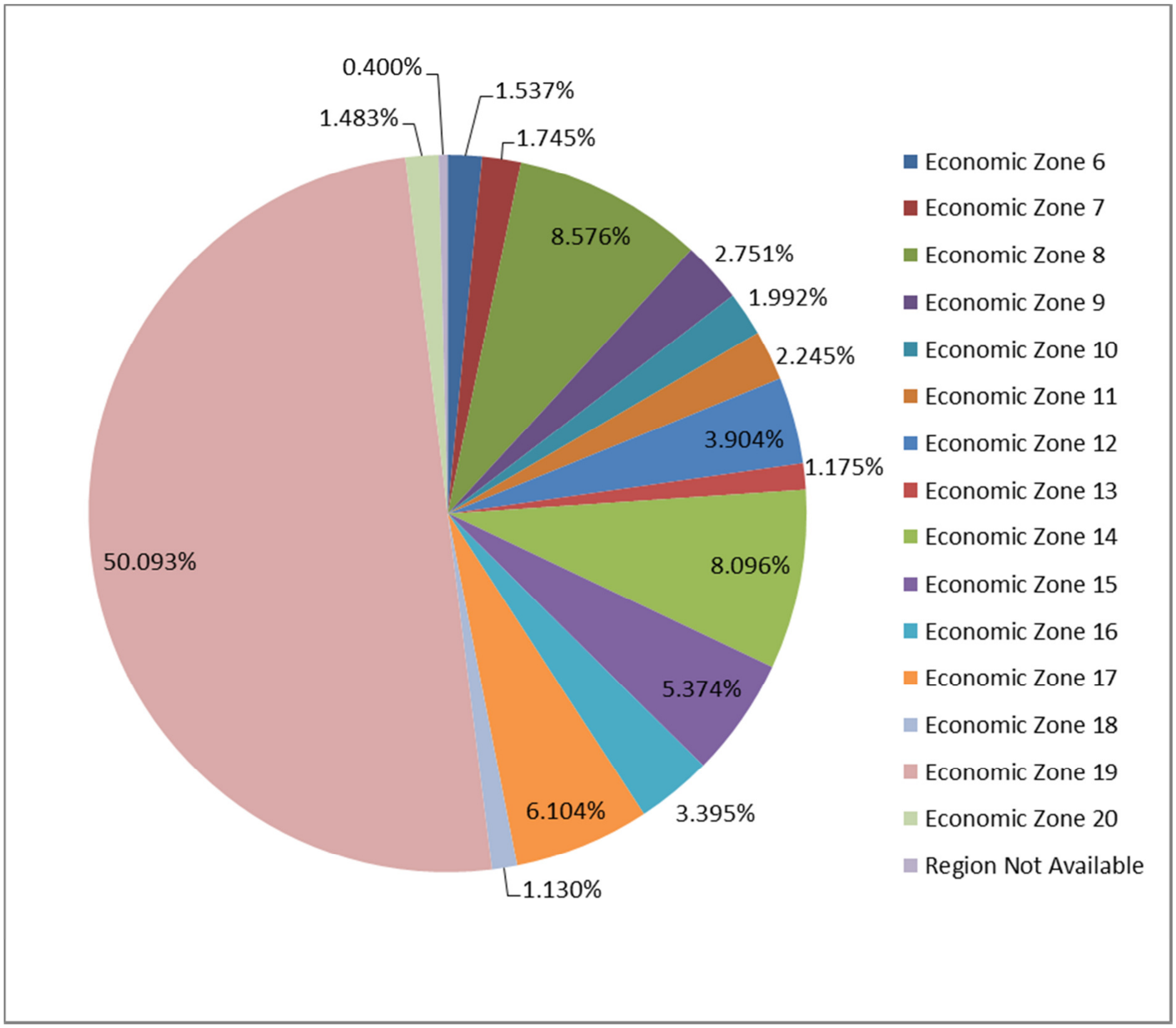
Date: 25-Nov-19

Appendix E – EV Distribution by Zone

(Courtesy of the Government of NL) [87]

Newfoundland & Labrador Economic Zones [87]

EV Breakout by Economic Zone



Economic Zone: Economic zones are geographic areas defined by the 1995 Federal/Provincial Task Force on Community Economic Development to facilitate regional economic planning and development. There are currently 20 economic zones in the province. Each zone has a Regional Economic Development Board (REDB) whose job is to facilitate the development of business and economic opportunities in its area.

Appendix F – Power System Stability Simulation Results

Island Demand (MW)	Island Generation (MW)	Spinning Reserve (MW)	HVdc			Frequency Controller Enabled?	Generation Added (MW)	Results	
			LIL (MW)	ML (MW)	Net DC (MW)			Lowest Frequency (Hz)	EV Transient Contributions (MW)
2,023	1,695	206	900	500	400	No	535	59.02	275
1,750	1,425	207.5	900	500	400	No	265	58.99	279
1,485	1,159	209	900	500	400	No	140	59.01	262
1,250	922	211	900	500	400	No	0	59.02	251
877	549	208.3	900	500	400	No	0	59.02	251
2,003	1,476	208	900	300	600	No	315	59.01	506
1,730	1,248	206	900	300	600	No	45	59.00	539
1,518	991	206.5	900	300	600	No	0	59.02	519
1,247	719	208.5	900	300	600	No	0	59.00	494
1,003	474	206	900	300	600	No	0	58.99	479
1,998	1,328	211.5	900	158	742	No	175	59.00	661
1,736	1,065	206	900	158	742	No	0	58.99	660
1,578	908	209	900	158	742	No	0	59.00	667
1,346	676	212.3	900	158	742	No	0	59.00	644
1,179	509	233.7	900	158	742	No	0	59.01	639
2,004	1,176	205.5	900	0	900	Yes	65	59.02	721
1,825	996	206.5	900	0	900	Yes	0	59.01	723
1,650	822	206	900	0	900	Yes	0	59.00	702
1,475	647	221.7	900	0	900	Yes	0	58.99	690
1,295	467	209.5	900	0	900	Yes	0	59.00	675