EVALUATING THE ENERGY SECURITY RISKS AND BARRIERS TO ELECTRIC VEHICLE ADOPTION IN NOVA SCOTIA

by

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ABSTRACT

As jurisdictions seek to pursue transportation-based emissions reductions, they face the challenge of electrifying the vehicles that operate within them. In this work, jurisdiction-generic methods are defined for analyzing the risks of light duty vehicle electrification from an energy systems perspective. The methodology can be employed by jurisdictions to quantify the risks of electrification in terms of three energy security indicators (3As): availability, affordability, and acceptability. To demonstrate the methods, a case study is conducted to evaluate the three dimensions of energy security in Nova Scotia and identify the barriers to meeting the federal target of 30% EV sales shares by 2030. The results show that although Nova Scotia Power are prepared to accommodate the increase in electricity demand from EV uptake, the high costs of EVs relative to CVs still acts as a significant barrier to achieving increased EV uptake in Nova Scotia.

LIST OF ABBREVIATIONS USED

CV – Conventional Vehicle
EV – Electric Vehicle
ICEV – Internal Combustion Engine Vehicle
HEV – Hybrid Electric Vehicle
BEV – Battery Electric Vehicle
PHEV – Plug-in Hybrid Electric Vehicle
ZEV – Zero-Emission Vehicle
TCO – Total Cost of Ownership and Operation
PV – Present Value
GHG – Greenhouse Gas
IPCC – Intergovernmental Panel on Climate Change
EV30@30 – Clean Energy Ministerial target of 30% electric vehicle sales by 2030
WTT – Well-to-tank
TTW – Tank-to-wheels
WTW – Well-to-wheels
TVPC – total vehicle purchase costs
EVSE – electric vehicle supply equipment
RV – resale value
FC – annual fuel costs
IC – annual insurance costs
MRT – maintenance, repair, and tires
EC – emissions costs
L&R – license and registration
NSP – Nova Scotia Power
IRP – Integrated Resource Plan

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1 INTRODUCTION

In October 2018, the Intergovernmental Panel on Climate Change (IPCC) published a report highlighting the importance of limiting global warming to no more than 1.5°C above pre-industrial levels [1]. If global temperatures are to remain stable below this limit, anthropogenic sources of greenhouse gas (GHG) emissions must reach net zero by 2050 [2]. This will require reducing emissions by approximately 50% relative to 2020 levels along with significant removal of carbon dioxide from the atmosphere by 2030 [2].

To meet these aggressive targets, a revolutionary approach to climate change mitigation must be taken that involves rapid, far-reaching and unprecedented changes to all emissions intensive sectors of society [1]. One specific area of concern is the global transportation sector, since 95% of the world's transportation energy is reliant on emissions-intensive fuels, typically some form of refined liquid petroleum product [3].

In Canada, the transportation sector is the second largest source of energy based GHG emissions, of which road transportation accounts for over 70%, Figure 1. Over half of Canada's road transportation emissions are produced by light duty vehicles [4].

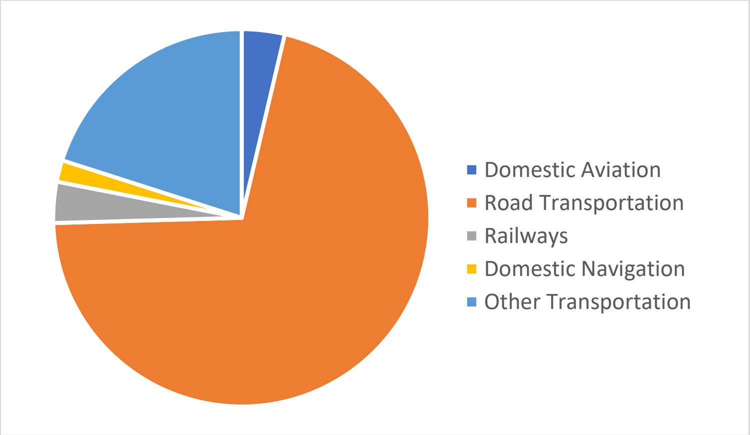

Figure 1: Canada National Inventory Report 2020 - Transportation emissions by subsector [4]

To reduce the GHG emissions from the light-duty vehicle segment, many jurisdictions are setting targets to increase the uptake of zero-emission vehicles (ZEVs) in place of conventional vehicles (CVs) which have historically dominated the light duty vehicle market [5].

Transport Canada defines a ZEV as a vehicle that has the potential to produce no tailpipe emissions [6]. This definition includes both battery electric vehicles (BEVs) which are entirely powered by electricity, and plug-in hybrid electric vehicles (PHEVs) with conventional internal combustion engines (ICEs) that can operate using either the ICE or on-board batteries and electric motor(s) [6]. PHEVs differ from conventional hybrid electric vehicles (HEVs) in that they can be charged from an external source. HEVs cannot be plugged in to charge their on-board batteries and instead rely on charging through regenerative braking and energy from their ICE [6]. The classification of PHEVs as "zero-emissions" is thus somewhat misleading, as PHEVs are simply HEVs that can also be charged from the mains and still produce evaporative and tailpipe emissions associated with their ICE.

The principal benefits of ZEVs come from their ability to use energy in the form of electricity. The exact benefits are dependent on the emissions intensity of upstream electricity generation facilities that a vehicle draws the electricity from. In jurisdictions where electricity is generated primarily from zero-emissions energy sources, such as nuclear, hydroelectricity, solar and wind power, ZEVs are the least emissions intensive to drive. For example, in Quebec, where most electricity comes from hydroelectric sources, the average driver will produce 2 tonnes less annual carbon dioxide when opting to drive a Hyundai Ioniq BEV instead of a conventional Honda Civic [7]. These emissions savings become less significant in provinces with higher electricity generation emissions intensities [7]. A 2019 study found that in Nova Scotia the Hyundai Ioniq EV produced more equivalent annual emissions than the Toyota Prius when driven an equal distance [7].

Despite interprovincial differences in the environmental benefits of ZEVs, Canada has pledged to meet ZEV sales targets established by the Clean Energy Ministerial of 30% ZEV sales by 2030 (EV30@30), and 100% ZEV sales by 2040 [6]. To meet these targets significant changes to Canada's light duty vehicle fleets must take place, considering Electric Mobility Canada found that the EV market share in Canada was just 1.89% in Q1 of 2019 [8]. The low EV market share in Canada can be attributed to many factors, including the high capital costs of EVs, and performance limitations such as range anxiety, winter efficiency losses, and long charge times [9]. As Canada and other jurisdictions strive for increased EV sales, they must consider the risks that consumers incur when transitioning from a CV to a ZEV.

First, are the financial risks that consumers must consider when purchasing a new vehicle. Transportation costs represent the second largest expense for many Canadians, with the average household devoting almost 20 percent of annual expenditure to transportation [10]. For some consumers, a small increase in transportation costs can have a significant impact relative to total annual expenditure. If ZEVs can exist as a cost competitive alternative, consumers can make the transition from a CV to and EV without having to account for additional finances [9].

In their current state, ZEVs benefit from cheaper operating costs than CVs since electricity is typically cheaper than gasoline and electric motors are more efficient [11]. The U.S. Office of Energy Efficiency and Renewable Energy found that on average it costs less than half as much to travel the same distance in an EV than a conventional vehicle [11]. EVs also have maintenance costs that are about 70% below comparable ICE vehicles [12]. This is in part because BEVs have fewer moving parts in their drivetrains and do not require oil changes [12]. However, while the operating costs of EVs are substantially lower, EVs are often significantly more expensive to purchase than their conventional counterparts [11]. In Canada, a new 2020 model ICE car costs $23,955 on average, compared to the average electric car which costs $30,660 [12]. For first time EV buyers, there are also additional capital costs to fund the installation of at-home EV charging infrastructure. Consumers with enough capital to offset this upfront cost difference can recoup some of their expense in operating cost savings over the lifetime of the vehicle.

There are also performance-based risks associated with transitioning from a CV to an EVs. BEVs have limited range compared to most CVs and take significantly longer to recharge [13]. The range limitations of EVs are further exacerbated in cold temperatures and areas with limited access to charging infrastructure. While most EV users are expected to charge their vehicles at home, many jurisdictions believe the deployment of public charging infrastructure is critical for alleviating consumer fear of running out of charge away from home, also known as *range anxiety* [14].

In addition to the risks to consumers, jurisdictions must consider the risks that the electrification of light duty vehicles can have on upstream energy supply chains. As consumers transition to EVs, energy demand from vehicles will shift from petroleum product supply chains to the electricity grid [15]. If electricity suppliers in the jurisdiction are unable to meet this increased demand, it could represent a significant threat to the jurisdiction's energy security.

This thesis proposes an energy systems analysis framework that can be employed to evaluate the socioeconomic and environmental risks to vehicle owners and energy suppliers as a jurisdiction transitions from CVs to EVs [16]. By modelling EV and CV energy processes, and their interaction with upstream energy supply chains and the environment, jurisdictions can develop scenario-based analyses to identify the threats that electrification may pose to the energy security light duty vehicle energy systems [16].

In order to maintain or improve a jurisdiction's energy security, its energy system needs to meet the demands of its energy services with affordable and preferably environmentally acceptable flows of energy [17]. Threats to the energy security of energy systems can be quantified in terms of three energy security indicators (3As): availability, affordability and acceptability [18]. The main objective of this thesis is to develop generic methods for quantifying each of these indicators such that jurisdictions can employ them to understand the threat of electrifying light duty vehicles on energy security.

In this context, availability represents the availability of both the vehicle and the energy needed by the vehicle to allow the driver and any passengers to reach their intended destination in a timely manner [19]. We define methods to quantify availability from two perspectives. First, we consider availability from the consumer-perspective (end-use perspective), which refers to the availability of energy in a vehicle's on-board fuel storage. From this perspective, methods are developed to evaluate the range limitations of EVs compared to traditional CV technology at various temperatures and travel distances. Jurisdictions can employ these methods to understand the risks of EV range limitations at various common commuting distances. From the upstream perspective, availability is considered in terms of the energy suppliers' capacity meet energy requests from downstream vehicle processes. The upstream availability methods are defined to approximate the effect that various EV penetration rates and charging habits can have on the peak load of electricity suppliers in a jurisdiction. The results of these methods can be analyzed in comparison with historical electricity supply data to identify whether suppliers will need to adapt their electricity generation systems to mitigate threats to up-stream availability.

Affordability is quantified as the total cost of ownership and operation (TCO) of conventional and electric vehicles over a 5-year period. To evaluate TCO, a 5-year TCO model is defined to produce detailed cost comparisons that represent the typical ownership costs of conventional and electric vehicles in any generic jurisdiction, including the effects of subsidies and carbon taxation. The TCO model considers the following cost dimensions: depreciation, fuel costs, insurance costs, maintenance and repair, licensing and registration, subsidies, emissions taxes, and at-home charging infrastructure costs. The model also considers the impact that various financing options, such as down payment, and financing periods can have on net TCO. This methodology can be employed by jurisdictions to evaluate differences in the affordability of conventional and electric vehicles based on various vehicle specifications, driving habits, and jurisdiction-specific policies.

Lastly is acceptability, which refers to the greenhouse-gas emissions associated with the operation of conventional and electric vehicles. To quantify differences in the acceptability of EVs and CVs, jurisdiction-specific electricity generation and driving statistics are used to evaluate the equivalent annual fuel-related emissions of various EVs and CVs. The results of this analysis demonstrate the significant impact that a jurisdiction’s electricity consumption emissions intensity can have on the environmental benefits of EVs.

By employing the methodology to evaluate the 3As, jurisdictions can identify risks to the energy security of light duty vehicle processes and upstream energy supply chains. These indicators can be monitored over time, and scenarios can be developed in conjunction with the framework to examine the robustness of energy systems of a jurisdiction in pursuit of electrification targets such as EV30@30 [16].

The remainder of this thesis is structured as follows. First, a brief background is provided on the energy security analysis framework and vehicle types considered. A detailed literature review is then conducted to identify the historical approaches that academics, insurance companies, electricity suppliers and policymakers have taken at quantifying these indicators. Next, the methodology is defined to quantify and compare the 3As for conventional and electric vehicles. Where possible, the methodology will be defined in as generic a fashion as possible such that they can be applied to analyze other Canadian provinces and jurisdictions.

To demonstrate the utility of the proposed methodology, a case study will be conducted to evaluate affordability, availability, and acceptability of electric vehicles in Nova Scotia. The results of the case study can be analyzed to assess the threats to energy security of pursuing the federal electrification targets of 10% EV penetration by 2025 and 30% EV penetration by 2030.

2 LITERATURE REVIEW

In this chapter, the energy systems analysis framework used in this thesis is introduced and its application to conventional and electric vehicles is shown. This is followed by a brief overview of the various vehicle types considered in this thesis. Lastly, a detailed academic literature review is conducted to identify methodology for quantifying the affordability, availability, and acceptability of conventional and electric light duty vehicles. The purpose of this review is to inform the development of generic methods that jurisdictions can employ to monitor and discuss the threats that rapid widespread EV adoption may pose to energy security.

2.1 Energy Systems Analysis Framework

Throughout this thesis, Hughes's generic energy systems analysis framework is used to describe and analyze the energy systems that are associated with conventional and electric vehicles [16]. Within this framework, an energy system is defined as a set of processes organized into chains from an energy source to an energy service. Each process in the energy system attempts to meet a request for energy from a downstream process or service by processing a flow of energy from an upstream process or energy source. Changes to a process's different flows can affect the energy security of the process or the upstream and downstream processes in its chain. The energy consumption of conventional and electric vehicles can be represented as an energy process with the set of flows seen in Figure 2.

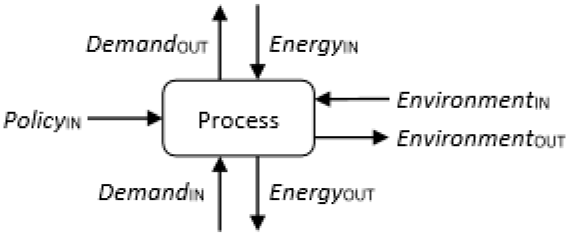

Figure 2: A generic energy process and its flows [16]

For both types of vehicles, the $Demand_{IN}$ flow represents the distance that passengers are requesting to travel in their vehicle. This demand is satisfied by the energy output flow

($\text{Energy}_{\text{OUT}}$), which in both cases, is the energy required by the vehicle process to travel the demanded distance.

CV and EV processes differ in their energy input flows, and the impact they have on the environment. The main energy input flows ($\text{Energy}_{\text{IN}}$) to conventional vehicle processes are petroleum-based fuels, such as gasoline and diesel, used in an internal combustion engine (ICE) that produces kinetic energy output. As a byproduct, this also produces harmful tailpipe emissions that contribute to climate change and air emissions, which are represented by the $\text{Environment}_{\text{OUT}}$ flow.

For the electric vehicle process, the energy input flow represents the amount of electricity necessary for the vehicle's motor to generate the demanded energy output. EV processes have no direct environment output flow because electric motors operate without producing tailpipe emissions. However, it is important to also consider the environmental outputs of the upstream electricity generation processes that provided $\text{Energy}_{\text{IN}}$ to the EV process. The environmental impact of driving an EV corresponds to the emissions intensity of the energy consumed by the vehicle. In Norway, where over 97% of electricity is generated from renewable sources, EVs produce a negligible environmental output [4]. In Canada and other countries across the globe, this is not the case, as almost 65% of total world electricity generation is reliant on fossil fuels [4]. The light duty vehicle fleets in a jurisdiction can be depicted as a series of CV and EV energy consumption processes connected to upstream energy production and supply chains. Figure 3 depicts these processes and their flows.

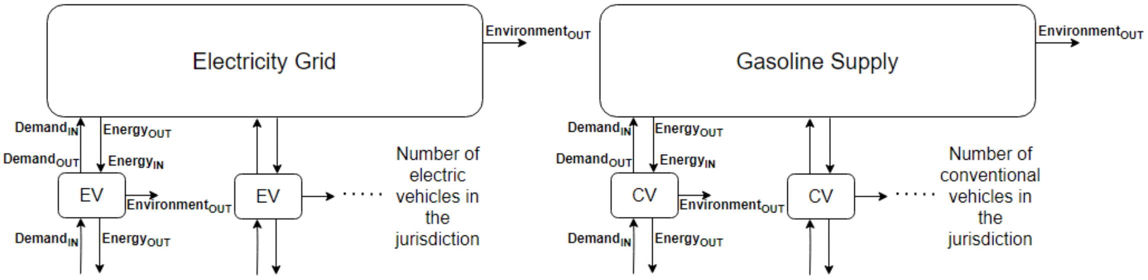

Figure 3: EV and CV processes and upstream energy supply entities in a generic jurisdiction

2.2 Energy Security and Risks to the Energy System

Energy security reflects the level of risk to the entities of an energy system [35]. It can be discussed in terms of three dimensions or indicators: availability, affordability, and acceptability, which are defined in terms of the state of an entity's flows.

For a consuming entity to be considered secure, the volume of its $\text{Energy}_{\text{IN}}$ flows must meet the volume requested in its $\text{Demand}_{\text{OUT}}$ flow and the cost of the energy must be within the entity's energy budget. These two conditions are referred to as *availability* and *affordability*, respectively [20].

To be considered secure, the producing entity must be able to satisfy the requested demand for energy while meeting environmental and production standards (dictated by the regulations specified by the $\text{Policy}_{\text{IN}}$ flow). The conditions required by the regulations are referred to collectively as acceptability [20].

In this thesis, we define a methodology to approximate the state of energy flows from upstream energy suppliers and end use vehicle services in a jurisdiction. The state of these flows can be used to evaluate the three energy-security indicators. Jurisdictions can monitor changes to these indicators over time to discuss the risks of electrifying their transportation [19].

The 3As with respect to a light duty vehicle energy processes can be defined as follows:

Availability: The availability of both the vehicle and the energy needed by the vehicle to allow the driver and any passengers to reach their intended destination in a timely manner.

Affordability: The cost of the energy used by the vehicle, the lifetime cost of owning and operating the vehicle, as well as a variety of societal costs.

Acceptability: The greenhouse-gas emissions associated with the vehicle.

Additional methods can be employed to evaluate threats to the energy security of CV and EV processes and their upstream energy supply entities [20]. Since CVs and EVs demand energy from separate upstream energy processes, the electrification of vehicles will result in a significant shift in demand from refined petroleum product (RPP) systems to the electricity system. Changes to a process's different flows can threaten the energy security of the process or the upstream and downstream processes in its chain [18]. With electrification involving such an extensive change to both the end use transportation service and the energy systems that support them, it is important to consider the potential threats this can pose to a jurisdictions energy security.

The risk associated with increased EV adoption can be evaluated from two perspectives. From an upstream perspective, we can analyze the threat that various EV penetration rates can have on shifts in demand between different energy supply chains. From an end-use perspective, the 3A's can be employed to evaluate the impact on consumers of replacing CVs with EVs [16].

2.3 Vehicle Types

In this section, the vehicle types considered in this thesis are defined in relation to the generic conventional and electric vehicle energy processes.

2.3.1 Conventional Vehicles (CV)

There are two types of conventional vehicles which can be represented by the conventional vehicle energy process in Section 2.1.

Internal combustion engine vehicle (ICEV): ICEVs include vehicles that use an engine to convert the liquid fuel (typically gasoline or diesel) into kinetic energy for its motive power [19].

Hybrid electric vehicle (HEV): There are two main types of HEV. Some HEVs use gasoline or diesel to fuel a generator that charges a battery and/or powers an electric motor that propels a vehicle [6]. Other HEVs use an ICE to propel a vehicle while an electric motor assists during acceleration [6]. Unlike fully electric vehicles, HEVs are only fueled with petroleum and their emissions do not depend on the regional electricity grid [6]. The HEV's battery is charged during "regenerative braking", when brakes convert kinetic energy to electrical energy to slow the vehicle. The batteries can also be charged when the ICE acts as a supplemental generator. Since the effect of the battery on is factored into the vehicles fuel consumption rating, and it only accepts energy in the form of petroleum, the energy use of HEVs can be represented as a conventional vehicle energy process.

2.3.2 Electric Vehicles (EV)

Battery electric vehicle (BEV): BEVs run on an electric motor that is battery powered; the battery is recharged by plugging into an outlet or charging station [21]. The energy consumption of a BEV is entirely electric, and thus, can be represented by a generic electric vehicle energy process.

2.4 Acceptability

The acceptability of EV and CV energy consumption processes and their upstream energy supply systems can be quantified in terms of the GHG emissions they produce. Many researchers employ life cycle analysis (LCA) approaches to quantify and compare the emissions produced by EVs and CVs at a global [22], national [23], and municipal level [24]. The complete life cycle of a vehicle (Figure 4) is the product of two main life cycles: the equipment life cycle, and well-to-wheels (WTW) life cycle [24].

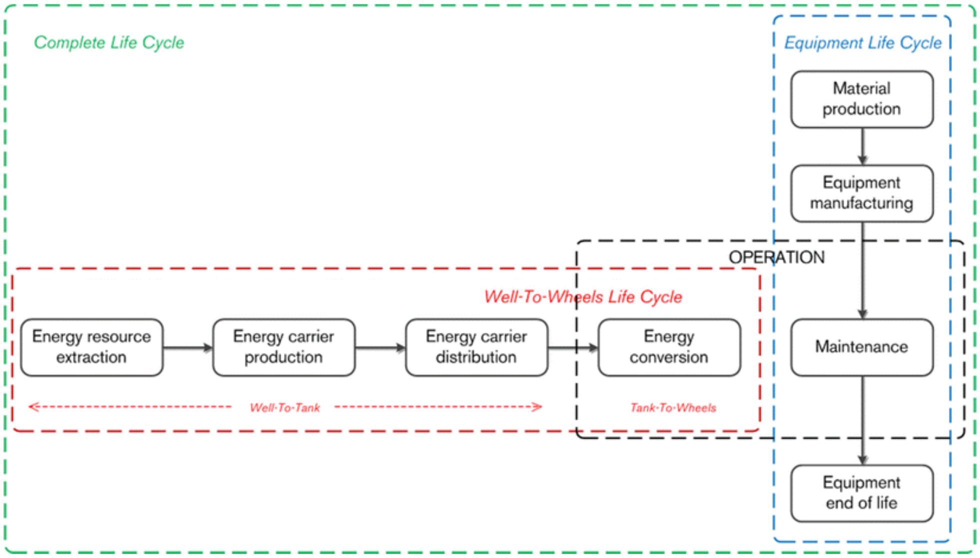

Figure 4: System boundaries for a complete life cycle analysis of vehicles [25]

The vertical flow in Figure 4 represents the equipment life cycle of the vehicle itself from manufacturing to end of life; it is sometimes referred to as the “cradle-to-grave” or “vehicle cycle” [25]. The horizonal WTW cycle focuses on the life cycle of the energy used to propel the vehicle, such as liquid fuel or electricity [25]. Researchers often employ WTW cycle analyses to better understand the impact of the upstream mix of electricity generation technologies on EVs, as well as the impact of different powertrain technologies and fuel sources [26]. The scope of this thesis is constrained to the perspective of vehicle energy systems, and as such, only literature with methods for quantifying GHG emissions from the WTW life cycle are considered.

WTW analyses are often discussed in terms of two major processes [22]. The first is the well-to-tank (WTT) process of mining the energy source, transporting it, and storing the energy in the car, and the other is tank-to-wheel (TTW) process of driving the car using the stored energy [22]. The sum of the emissions factors (measured in gCO_{2eq}/MJ) of each of these processes represents the WTW emissions factor of the energy, which can be multiplied by the ICEVs fuel efficiency to determine its emissions per kilometer [22].

Woo et al. employed this approach to analyze the extent to which the GHG emissions associated with EVs differs among 70 countries in the world, in relation to their domestic electricity generation mix [22]. The results were compared to the GHG emissions from ICEVs and it was found that countries with a high percentage of fossil fuels in their electricity generation mix showed high GHG emissions for EVs [22]. The methods from this study are generic and align with the scope of vehicle technologies and energy systems analyzed in this thesis.

The TTW emissions for both BEVs and CVs are well known and understood. For CVs, the TTW emissions of a gasoline engine are 2.3 $kgCO_2$ per litre of gasoline consumed. For BEVs, since no tailpipe emissions are produced during operation, the total TTW emissions can be calculated as a product of the energy consumed by the vehicle and the electricity consumption emissions intensity of electricity suppliers in the jurisdiction [21]. The electricity consumption emissions intensity of each province in Canada is available from the National Inventory Report published by Environment and Climate Change Canada [4].

Determining the WTT emissions factors is a more difficult process that depends on the energy supply chains specific to the jurisdiction in questions. The emissions factors employed by Woo et al. were sourced from the Well-to-Wheels Report by the Joint Research Centre of the EU Commission (JRC) [27]. The report considers the WTW energy consumption and GHG emissions of a wide range of potential future fuel and powertrain options in the European Union (EU) [27]. The report specifies that its results are only valid for jurisdictions in the EU, and thus, its TTW and WTT emissions factors for gasoline should not be used applied in a case study of vehicles in Canada.

Cai et al. conducted a WTW analysis of the GHG emissions of various Canadian oil sands fuel pathways for end use in the United States [28]. Their analysis produced a range of results for the GHG emissions intensity of gasoline based on different extraction and separation, upgrading and crude transportation pathways [28]. The range of WTW emissions factors for gasoline (97 – 115 gCO_2e/MJ) from this report are used to evaluate the WTW emissions produced by ICEVs, however they explicitly state they should not be directly applied to other jurisdictions [28].

Due to the lack of available and reliable WTT emissions factors that pertain to Nova Scotia, only TTW emissions from fuel consumption during vehicle operation are considered in this thesis. The development of more detailed LCA research specific to Nova Scotia's energy systems is identified as an area for future work.

2.5 Affordability

There are numerous documented transportation system analysis methods for quantifying the affordability of personal vehicles. Certain studies focus on highway cost allocation and investment evaluation, mainly considering: direct market costs, such as road construction and maintenance, travel time, vehicle operating costs, crash damages, and how these vary depending on vehicle type and roadway conditions [29]. Other studies incorporate the cost of environmental impacts, primarily air pollution, but at times also noise and water pollution, and various categories of land use impacts [29]. With such a wide breadth of available information, it is important to concisely define the scope of the vehicle cost factors this study aims to evaluate. This section focuses specifically on reviewing literature with methods to quantify the total cost of ownership and operation (TCO) of conventional and electric vehicles.

The TCO of a personal vehicle encapsulates all expenses associated with ownership and operation of the vehicle. These expenses include both fixed costs (e.g. ownership or time-based), and variable costs (e.g. operating, marginal or incremental) [30]. Variable costs include energy costs (petroleum or electricity), tires, and additional fees such as short-term parking and tolls [31]. Fixed costs include financing, depreciation, registration, and maintenance. Additionally, there are insurance costs, which can behave as a fixed and/or variable cost depending on the specifics of the insurance contract [29].

TCO models to quantify the costs of CVs have existed for several decades. TCO studies that incorporate EV technology have emerged more recently, especially since 2008, when several car manufacturers launched their plans of mass production of electric vehicles [32]. Due to the complexity and scale of modern transportation systems, TCO models for both CVs and EVs must employ several assumptions to establish a set of defined input parameters such that concise cost approximation outputs can be attained to inform consumers and policymakers. The models often employ a series of scenario-based cost-estimations for isolated changes in input parameters, such as different vehicles and driving behaviors, which can be scaled up to represent trends in the jurisdiction. Comparing different TCO studies can become complicated, as analyses can vary greatly in their assumptions, input parameters and research scope [32].

TCO analyses can be divided into two main categories: consumer-oriented studies and society-oriented studies. In consumer-oriented studies, as their name suggests, the costs that are perceived by the consumers are incorporated and different vehicle technologies are compared [32]. Society oriented TCO studies have a broader scope: next to the consumer costs, externalities (such as emissions, noise) and the associated external costs of EVs are included [32]. These studies often focus on national jurisdictions, such as the comprehensive study of U.S. motor vehicle costs from MacKenzie et. al. The cost categories in society oriented studies can include roadway facilities and services, parking, air pollution, oil import costs, congestion, traffic accidents, noise, and land loss [33]. Studies have been employed to evaluate these dimensions of transportation system costs along with several others in European countries [34], Chile [35], New Zealand [36], and a multitude of other national jurisdictions.

In this thesis, a quantitative consumer oriented TCO modelling approach is taken. This approach was chosen since it can be adapted to best illustrate the difference in affordability between CVs and EVs under equal use conditions. A review of academic literature was conducted to determine which state of the art consumer oriented TCO modelling methodologies are best suited for this application.

Hagmen et al. study of personal vehicle TCO and its potential implications for battery electric vehicle diffusion in Sweden [31]. The authors develop a consumer centric total cost of ownership (TCO) model to investigate the possible discrepancy between purchase price and the TCO between internal combustion engine vehicles (ICEVs), hybrid electric vehicles (HEVs) and BEVs. The study concludes that the creation and testing of the TCO model is a complex task which can be challenging for consumers due to bounded access of relevant data and the prediction of future conditions. In their analysis, they focus on the purchase of new Swedish compact vehicles over a short 3-year ownership period. This approach enables them to neglect maintenance and repair costs, as they are often covered by the manufacturer's warranty.

Wu et al. built a probabilistic simulation TCO model broad enough to capture most of a national market [37]. This approach differs from most conventional TCO studies in that it does not produce bottom-up estimates based on scenario models of individual vehicle classes, powertrain technologies, or use cases. Their findings indicate that the comparative cost efficiency of EV increases with the consumer's driving distance and is higher for small than for large vehicles. However, their sensitivity analysis shows that the exact TCO is subject to the development of vehicle and operating costs and thus uncertain. Although this probabilistic model would be ideal for the development of a generic model, lack of available high-resolution data suggests it is not ideal for current TCO applications.

Delucchi et al. approach consumer TCO of electric vehicles from the perspective of lifecycle cost: the annualized initial vehicle cost, plus annual operating and maintenance costs, plus battery replacement costs [38]. Their finding suggest that in order for electric vehicles to be cost-competitive with gasoline ICEVs, batteries must have a lower manufacturing cost, and a longer life, than the best lithium-ion and nickel–metal hydride batteries included in the model. A downside to this modelling approach is that it assumes the vehicle is driven until it is scrapped which does not account for the savings that many consumers incur on the resale of their vehicle [39]. As such, a finite ownership approach that factors in vehicle depreciation was chosen over a lifecycle approach for evaluating TCO in this thesis.

Lebeau et al. define a TCO model for three different car segments to investigate the cost efficiency of electric vehicles compared to conventional vehicles [32]. They include all costs that occur during an expected vehicle ownership of seven years: purchase cost, registration tax, vehicle road tax, maintenance, tires and technical control cost, insurance cost, battery leasing cost, battery replacement cost and fuel or electricity costs [32]. Their results are shown per vehicle segment and illustrate that current electric vehicles are only cost attractive within the premium car segment.

Breetz and Salon analyze the five-year Total Cost of Ownership (TCO) for conventional, hybrid, and electric vehicles in 14 U.S. cities from 2011 to 2015 [40]. The results show spatial variation due to differences in state and local policies, fuel prices, insurance and maintenance costs, depreciation rates, and vehicle miles traveled. In nearly all cities, the costs analysis suggested that the BEV's higher purchase price and rapid depreciation outweighed its fuel savings.

Chatterton et al. consider the financial implications of car ownership and use in a distributional analysis based on observed spatial variance considering income and domestic energy costs [41]. This study is extremely effective at demonstrating the spatial variance of vehicle costs throughout the jurisdiction but fails to consider the full costs of car ownership. Instead, they focus specifically on vehicle excise duty (VED) and fuel cost, which represent around 40% of total car costs and constitute the proportion of costs that national level policy has direct control over.

The TCO analyses in this literature review generally indicate that, without federal support, personal EVs are more expensive than ICEVs, despite from the benefits of significantly cheaper operation costs. The studies also emphasize that EVs are progressively becoming more cost-efficient, and in the future may soon become more economical than CVs. They emphasize the importance of continually re-evaluating and comparing TCO of CVs and EVs over time. However, given the inconsistency of the methodological approaches among these studies, drawing more detailed comparisons between their detailed results can be extremely difficult, and hence prevents a market wide analysis of TCO with respect to varying vehicle models, kilometrage and ownership periods.

For example: some studies assume an ownership period of the entire vehicle lifetime, variously interpreted as 10, 12, 15, or 20 years, while others consider a shorter ownership period of 3–7 years; some studies only include vehicle purchase and fuel costs, while others include many additional operating and maintenance costs; many studies assume no residual value, others assume fixed depreciation schedules across all vehicle types, while a few look at market-based residual value. With such high variance in approaches among TCO studies, it remains unclear whether these financial analyses would come to different conclusions when directly applied to generic Canadian jurisdictions with different driving habits, vehicle models, financing options and government incentives.

The generic TCO approach defined in this thesis consolidates several aspects of the TCO models in the reviewed literature. The model assumes a 5-year ownership and operation period and evaluates purchasing costs based on a variety of financing parameters including: down payment, interest rates, expected depreciation, loan term. A 5-year ownership period was chosen since it is a common ownership term employed throughout the literature and in many TCO analyses from Canadian auto insurance companies [42, 32]. The other TCO cost dimensions considered include fuel costs and emissions taxes, insurance, maintenance and repair, registration, and licensing, and for EVs, the cost of installing at-home charging infrastructure. More details on the specific of TCO methodology, data sources and assumptions are provided in the following chapter.

2.6 Availability

Availability is defined as the ability of a process to meet its energy demands [19]. In this section, we focus specifically on literature containing methods to quantify the availability of energy with respect to electric vehicle processes. From the EV perspective, availability involves a process (i.e., an electric motor) converting an $\text{Energy}_{\text{IN}}$ flow (electricity stored in a battery) into the $\text{Energy}_{\text{OUT}}$ flow (i.e., motive or kinetic energy) required to move the vehicle from the place of origin to the intended destination [19]. If an event occurs that makes the vehicle inoperable or one that limits the $\text{Energy}_{\text{IN}}$ flow, making it difficult or impossible to meet the driver's transportation requirements, then an availability event is said to have occurred [20]. The availability of energy to electric vehicle processes can be quantified from an end-use and upstream perspective.

2.6.1 End-use Availability

First, we consider end-use threats to availability. From this perspective, $\text{Energy}_{\text{IN}}$ is the energy supplied by an energy supplier and stored in a vehicle's battery or fuel tank. Assuming a functional and well-maintained vehicle, availability is threatened when $\text{Demand}_{\text{OUT}}$ exceeds the $\text{Energy}_{\text{IN}}$ of the vehicle process, prior to it being re-fueled with gasoline or charged with electricity. The limited range of electric vehicles, and insufficient access to charging stations throughout many jurisdictions make EVs much more susceptible to exhausting the energy in their batteries before reaching their destination. The consumer uncertainty associated with EV range limitations is referred to as *range anxiety*.

Many researchers use survey data to analyze the driving habits of vehicle owners in a jurisdiction to develop models for evaluating the range limitations of EVs at various trip distances and weather conditions. Mellinger et. al employ an iterative Monte-Carlo approach to simulate the sufficiency of EV range in Switzerland and Finland [43]. Their findings suggest that BEVs in 2017 could already cover 85-90% of trips in both Finland and Switzerland. The model developed in their analysis uses national geo-data to simulate various scenarios in which a user randomly selects a BEV model, makes a trip according to the travel survey and charges at home, work, service areas or other locations. Some drawbacks to the model are that it neglects the impact of temperature on BEV range and assumes that DC fast chargers are available at all fueling stations. It also does not consider the impact of queues at public charging stations.

Yuksei and Mikalek characterize the effect of regional temperature differences on battery electric vehicle (BEV) efficiency, range, and use-phase power plant CO_2 emissions in the United States [44]. Their findings suggest that annual energy consumption of BEVs can increase by an average of 15% in the Upper Midwest or in the Southwest compared to the Pacific Coast due to temperature differences [44]. Greenhouse gas emissions from BEVs were found to vary primarily with marginal regional grid mix, which has three times the GHG intensity in the Upper Midwest as on the Pacific Coast [44]. A drawback to the methods employed in this study is that the temperature performance characteristics of the Nissan Leaf were used as representative of all BEVs.

The temperature-range curve developed by the fleet management solutions company Geotab can be employed to analyze the impact of temperature limitations of any specified BEV's range and efficiency [45]. The curve is the result of an analysis of anonymized data from 5.2 million trips taken by 4,200 EVs representing 102 different make/model/year combinations and analyzed average vehicle trip efficiency by temperature [45]. Their analysis concluded that most EVs follow a similar temperature range curve, regardless of make or model [45]. The Geotab curve can be applied to approximate the temperature adjusted range of an EV as a function of its rated range at various temperatures [45].

In the following chapter, methods are defined which employ this curve to analyze the impact of temperature on real range and efficiency of EVs. The temperature adjusted EV range curves can be compared to various common commuting distances in the jurisdiction to evaluate the potential threat range limitations pose to availability.

2.6.2 Upstream Availability

Availability can also be analyzed from the energy supply-side with methods to approximate the effect that various EV penetration rates and charging habits could have on peak electricity loads in the jurisdiction. The total charging load from EVs can be compared to historical electricity supply data to identify the potential increase in peak load capacity that suppliers must be able to tolerate to mitigate threats to availability.

Researchers have employed a variety of assumptions and methods to develops scenario-based analyses of the impact of EV charging on peak electrical demand. The literature suggests that there are four main charging scenarios which can be used to project the impact of charging on peak electrical loads [46]:

1. Uncoordinated: EV owners charge their vehicles when they come home until fully charged. The peak EV-demand will exacerbate evening peaks in daily demand. Both the business as usual and worst-case scenario.

2. Delayed: Comparable to the uncoordinated scenario, with the difference that charging starts in the end of the evening. This shifts the peak caused by EV-demand so that it does not coincide with the daily peak demand.
3. Off-peak: Charging takes place during the night when the overall electricity demand is low. Local utilities can control charging to employ the electricity generation capacity optimally.
4. Continuous: Uncoordinated scenario in which vehicle owners charge their vehicles whenever possible. Charging takes place at, for example, home and work throughout the day. Continuous charging results in better charged batteries, which enable more trips to be electricity powered. It also requires ubiquitous charging infrastructure.

Van Vliet et al. conduct an analysis which considers the uncoordinated and off-peak patterns to represent best and worst-case charging scenarios [46]. The uncoordinated charging pattern is defined as a normal-distributed electrical load applied at 9:30 in the evening with a standard deviation of 3 hours. The off-peak pattern is dependent on the demand pattern and is defined by fitting a straight demand line between 22:00 and 7:00 so that the total electricity delivered is equal to the sum of total existing demand and demand from EV charging.

In the methods of this thesis, methods are defined to evaluate the impact that uncoordinated and off-peak EV charging scenarios can have on peak loads in electricity generation. The scenarios can be developed for various EV penetration rates to analyze the threat that various increased electrification poses to the availability of electricity in the jurisdiction.

2.7 Summary

In this chapter, the energy systems analysis framework was introduced, and the vehicle types considered in this thesis were defined. A literature review was conducted to identify methods for evaluating the affordability, availability, and acceptability of light-duty conventional and electric vehicles. For acceptability, well-to-wheel analysis research was reviewed and it was determined that TTW will be considered for acceptability in the case study. For affordability, the concept of vehicle TCO was introduced, and different TCO models from the literature were reviewed. Lastly for availability, research on the range limitations of EVs and impact of EV charging on electricity demand were considered. In the following chapter, generic methods are defined to evaluate the affordability, availability, and acceptability of conventional and electric vehicles.

3 METHODS

In this section, methods are defined to evaluate the affordability, availability and acceptability of light-duty conventional and electric vehicles. In the following chapter, this methodology is demonstrated in a case study of Nova Scotia.

3.1 Acceptability

Acceptability refers to the greenhouse gas emissions associated with the fuel consumption of a vehicle. The equivalent annual fuel emissions of a CV can be estimated by multiplying the vehicle's fuel efficiency (L/km) by the emissions intensity of the fuel (kgCO_2e/L) and the average annual distance the vehicle is projected to travel (km), Equation 1.

Equation 1: Equivalent annual CV emissions [47]

$$\begin{aligned} &Equivalent\ Annual\ CV\ Emissions \\ &\quad = Fuel\ Efficiency\ of\ CV \left(\frac{L}{km}\right) * Emissions\ Intensity\ of\ Fuel \left(\frac{kgCO_2e}{L}\right) \\ &\quad * Average\ annual\ distance\ (km) \end{aligned}$$

For EVs, equivalent annual emissions can be estimated as the product of the EV's efficiency (kWh/km), the jurisdiction's electricity consumption emissions intensity (kg CO_2e/kWh), and the annual average distance travelled by a car in that jurisdiction (km) [47], as shown in Equation 2. The consumption emissions intensity of electricity is used as opposed to generation emissions intensity because it considers additional emissions that associated with the transmission and distribution of electricity to the EV.

Equation 2: Equivalent annual EV emissions

$$\begin{aligned} &Equivalent\ Annual\ EV\ Emissions \\ &\quad = EV\ Efficiency \left(\frac{kWh}{km}\right) \\ &\quad * Electricity\ Consumption\ Emissions\ Intensity \left(\frac{kgCO_2e}{kWh}\right) \\ &\quad * Average\ annual\ distance\ (km) \end{aligned}$$

The fuel efficiency of both CVs and EVs can vary depending on whether they are driven in cities or on highways. ICE-based conventional vehicles are more efficient when driven on highways; since over an equal distance less energy is required to maintain a constant speed than to frequently re-accelerate in stop-and-go city environments [48]. The opposite is true for hybrid and electric vehicles, as the energy savings from their regenerative braking systems and motor shutoff when idling result in more fuel-efficient city driving [48]. For the baseline analysis, Natural Resource Canada's (NRCan) combined highway-city fuel efficiency values will be used for all vehicles, which assume a 55:45 city-highway split in projected driving habits [48].

3.2 Affordability

The affordability, or TCO of a vehicle is the sum of the annualized fixed (purchasing) costs and variable costs composed of maintenance, repair, and tires (MRT), and fuel or electricity costs, for a standard distance driven per year. In this section a generic model is defined to evaluate the TCO of BEVs and CVs

The TCO factors considered in this analysis are shown in Equation 3 [31]: [1]

Equation 3: TCO Cost breakdown

$$\begin{aligned} TCO \; = & \; Purchasing\ Costs - Resale\ Value + \ Fuel\ Costs \ + \mathrm{I}nsurance\ Costs \\ & + Maintenance\ and\ Repair + Taxes\ and\ Registration \\ & + Emissions\ Costs + (Charging\ Infrastructure) \end{aligned}$$

To evaluate each of the TCO factors for CVs and BEVs, several input parameters must be defined, including a vehicle buyer profile (VBP) and set of sample vehicles. A VBP contains information to reflect the average consumer in the jurisdiction. This profile is used to estimate insurance costs and must include information regarding the prospective buyer's age, gender, place of residence, and driving history.

Upon determining the VBP and sample vehicles, the following methods can be employed to evaluate the TCO of owning and operating the sample vehicles over a 5-year ownership period. Where possible, the methods are defined to interface with open-access Canadian data to ensure other jurisdictions can easily employ the methodology in comparative studies.

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[1] Charging infrastructure is defined in parenthesis as it is only applicable to BEVs

The net TCO is the sum of the present value of the following cost dimension, Equation 4:

Equation 4: TCO Formula

$$TCO = TVPC - \frac{RV}{(1+r)^n} + PV(r,n,FC) + PV(r,n,IC) + PV(r,n,MRT) + PV(r,n,EC) + PV(r,n,L\&R) + EVSE$$

Where:

TCO – total cost of ownership
TVPC – total vehicle purchase costs
EVSE – cost of installing at-home EVSE
RV – resale value
FC – annual fuel costs
IC – annual insurance costs
MRT – annual maintenance, repair, and tires costs
EC – emissions costs
L&R – license and registration Costs
r – annual real discount rate
n – number of periods (years)

Since there are a multitude of different costs at different points in time over the ownership period of the vehicle, future costs need to be calculated using a discounted formula approximating the time value of money. The present value of a future one-time cash flow can be evaluated with Equation 5; while the present value of annuities, assuming constant payments and a constant interest rate, can be evaluated with Equation 6.

Equation 5: Present value of future one-time cash flow [49]

$$PV = \frac{FV}{(1+r)^{nper}}$$

Equation 6: Present Value of Annuity [49]

$$PV = pmt \times \frac{1 - (\frac{1}{(1+r)^{nper}})}{r}$$

Where:

PV – present value
FV – future value
pmt – the payment made each period
r – the real discount rate per period
nper – the number of periods

Throughout the remainder of the affordability section, the syntax of Microsoft Excel's PV function will be used to as a proxy for the annuity formula and its arguments, as shown below:

PV(r, nper, pmt)

TCO studies typically assume a real annual discount rate in the range of 5–8% [40]. A real annual discount rate of 5% for the baseline analysis.

In the following subsections each of the factors represented in Equation 4 are defined in detail along with methods to evaluate their values.

3.2.1 Total Vehicle Purchase Costs (TVPC)

The total cost that a consumer incurs on a vehicle loan includes the principal amount of the loan and its associated interest, which are determined based on several factors including: the value of the vehicle, the down payment on the vehicle, the loan interest rate and the payment frequency. The principal amount financed on a vehicle loan can be evaluated with Equation 7.

Equation 7: Loan principle equation [50]

$$LP = (MSRP - DP - S) + (MSRP * HST)$$

Where:

LP – loan principle
MSRP – manufacturer suggested retail price of the vehicle
DP – down payment
S – subsidies/purchase rebates
HST – harmonized sales tax

The HST and subsidies applicable in Equation 7 are determined by jurisdiction-specific policies. Sales taxes are applicable to vehicle purchases in Canada, and vary depending on which province the vehicle is purchased in. Electric vehicles are eligible for federal EV purchase incentives of up to $5000 on the purchase of a new EV [7]. Certain provinces, such as Quebec and British Columbia, also offer provincial EV purchase rebates that apply in addition to the federal EV subsidy [7].

Upon determining the principle of the vehicle loan, the weekly, biweekly, or monthly fixed-term loan amortization can be calculated at a defined interest rate, Equation 8.

Equation 8 Loan Amortization Formula [50]

$$PMT = LP\frac{r(1+r)^n}{(1+r)^n - 1}$$

Where:

PMT – the payment per period
LP – loan principle
r – interest rate of the loan per period
n – number of periods over the duration of the loan

The total vehicle purchase cost (TVPC) is the sum of the down payment and the present value of the periodic loan payment annuity less subsidies, Equation 8:

Equation 9: Total Vehicle Purchase Costs equation

$$TVPC \;=\; DP - S \;+\; PV(discount\ rate, n, PMT)$$

In this case, discount rate is the real annual discount rate divided by the number of subperiods (i.e. 12 for monthly, 26 for bi-weekly, 52 for weekly), and n is the number of subperiods over the total financing period.

3.2.2 Resale Value (RV)

A vehicle's resale value (RV) can be approximated with Equation 10, where the depreciation rate (DR) is the percentage of its purchase value lost over a certain time period.

Equation 10: Resale value

$$RV \;=\; MSRP - (DR * MSRP)$$

The depreciation rate of a vehicle is determined by several factors including: vehicle features (colour, equipment), brand perception, fuel prices, maintenance costs, quality scores, government regulations and other less quantifiable values which make it difficult to approximate [31].

A Swedish study found that most TCO models developed by financial institutes for new vehicle purchases include an expected depreciation rate, usually set at approximately 50% after three years of ownership with 45000 km and normal wear and tear [31]. Although this assumption may be accurate for Swedish jurisdictions, it is only viable for a short ownership period and includes mainly European vehicle models.

In Raustad's electric vehicle lifecycle cost analysis [51], Edmunds depreciation data on 16 different models of electric and conventional vehicles was used to calculate the percent depreciation over the first 5 years of vehicle ownership. The estimates were generated with popular American vehicles and an assumed annual driving distance of 12330 miles (19843 km). Their findings indicate that annual depreciation rates are very similar among different vehicle types. The average depreciation of their vehicle sample was extended to project depreciation over a 20-year vehicle life assuming 1.5% of the purchase price remained after 20 years of ownership, Figure 5 depicts the depreciation curve.

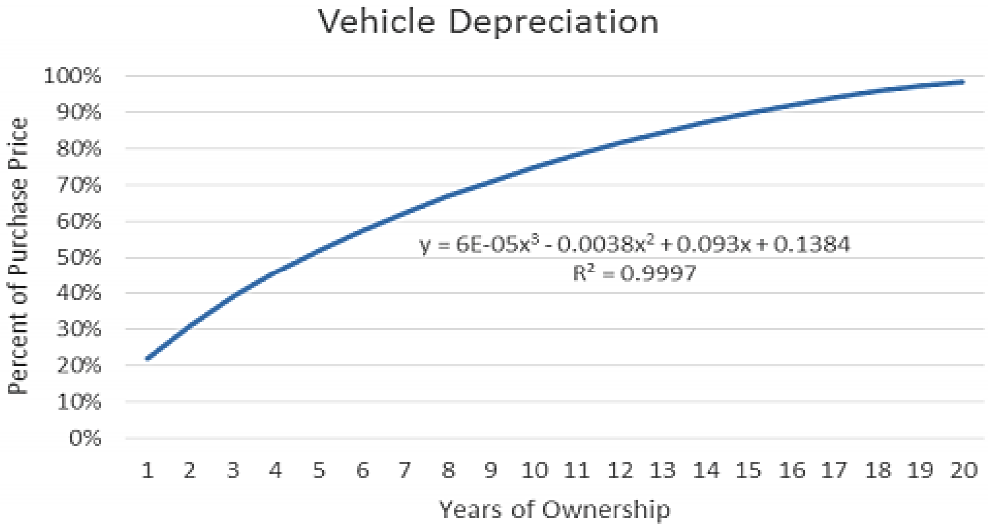

Figure 5: Raustad et al. vehicle depreciation curve [51]

Based on this curve, over a 5-year ownership period the average depreciation rate of a vehicle is 51.6% of its purchase price. This assumption of 51.6% for depreciation rate is used to determine the resale value of each vehicle in the case study.

3.2.3 Emissions Costs (EC)

The net cost of consumer emissions can be determined by multiplying the equivalent annual vehicle emissions (calculated with Equation 1 and Equation 2 from section 3.1 Acceptability) by the ownership period, and the proposed price of carbon, Equation 11.

Equation 11: Annual cost of emissions taxes

$$\begin{aligned} &Annual\ Emissions\ Costs \\ &\quad = Equivalent\ Annual\ Vehicle\ Emissions\ (tonnes\ CO2e) \\ &\quad * Carbon\ Tax\ (\$/tonne\ CO2e) \end{aligned}$$

This method only considers taxes that are directly applicable to consumer fuel purchases.

3.2.4 Fuel Costs (FC)

The most basic approximation for the annual fuel costs of a CV can be determined with Equation 12. The equation uses L to denote energy in the form of liquid petroleum (gasoline or diesel) used by the conventional vehicles.

Equation 12: Annual CV fuel cost

$$\begin{aligned} &Annual\ CV\ \text{Fuel Cost (\$)} \\ &\quad = vehicle\ fuel\ economy\ \left(\frac{\text{L}}{\text{km}}\right) * \text{annual}\ distance\ travelled\ (km) \\ &\quad * liquid\ petroleum\ price\ per\ litre\ (\frac{\$}{L}) \end{aligned}$$

The same equation applies to electric vehicles, but with fuel quantities represented as electricity in kWh.

Equation 13: Annual EV fuel cost

$$\begin{aligned} &Annual\ EV\ \text{Fuel Cost (\$)} \\ &\quad = vehicle\ fuel\ economy\ \left(\frac{kWh}{\text{km}}\right) * \text{annual}\ distance\ travelled\ (km) \\ &\quad * electricity\ price\ per\ kWh\ (\frac{\$}{kWh}) \end{aligned}$$

3.2.5 Insurance Costs (IC)

Vehicle insurance is a significant portion of total vehicle costs; a typical motorist spends almost as much on insurance as on fuel [29]. Individual vehicle insurance rates can vary greatly from person to person and vehicle to vehicle and are determined by a host of different vehicle and owner-specific factors [52].

Vehicle-specific factors: performance, safety ratings, weight, vehicle value and other factors.

Owner-specific factors: number of accident-free years, age, gender, address, and other factors.

The purpose of this study is to evaluate vehicle-specific factors, and as such, the same owner-specific factors will be used when calculating the insurance costs of each vehicle. Using a specific owner profile will not represent all types of owners but can give an indication of the vehicle-specific insurance factors. The parameters defined in the VBP can be used to generate annual insurance cost approximations from TD and CAA online insurance quoting software for each vehicle model [53, 42]. The average of both rates will represent the annual insurance cost (IC) of each sample vehicle.

3.2.6 Maintenance, Repair and Tires (MRT)

Another important consideration is the cost of maintenance and repair of different vehicle drivetrains over a vehicle's lifetime. Many authors believe that maintenance costs are cheaper for electric vehicles since regular oil changes are not necessary. In MIT's *On the Road in 2020* study, Weiss et al assume that all vehicles have the same maintenance and repair costs of $0.036 per kilometer [54]. In the case study (Chapter 5), the average annual cost of maintenance repair and tires for both CVs and BEV are sourced from *Comparing Fuel and Maintenance Costs of Electric and Gas Powered Vehicles in Canada* [55].

3.2.7 Licensing and Registration (L&R)

Registration and Licensing costs are defined by jurisdiction specific policies. For example, all licensing and registration fees applicable to motor vehicles in Nova Scotia are defined by Service Nova Scotia [56]. Nova Scotia's Class 5 license is necessary to drive a private personal vehicle and is a one-time cost of \$80.50 [56]. Vehicle registration costs are applicable every 2-years, and are priced depending on the weight of the personal vehicle [56].

3.2.8 At-home Electric Vehicle Supply Equipment (EVSE)

Many vehicle owners transitioning to electric vehicles will have to install at-home electric vehicle supply equipment (EVSE) to reliably charge their vehicle. The cost of a single port EVSE unit ranges from \$300-\$1,500 for Level 1, \$400-\$6,500 for Level 2, and \$10,000-\$40,000 for DC fast charging. Installation costs vary greatly from site to site with a ballpark cost range of \$0-\$3,000 for Level 1, \$600- \$12,700 for Level 2, and \$4,000-\$51,000 for DC fast charging [57].

In the case study in Chapter 5, a \$4000 cost is included as an estimate of average consumer expenditure on the purchase and installation of an at-home EVSE when first purchasing an EV.

3.3 Availability

Availability of energy with respect to vehicle energy systems can be assessed from two perspectives. First, from the perspective of the vehicle process, methods are defined to evaluate and discuss the range limitations of EVs. Second, availability is analyzed from the energy supply-side with methods to approximate the effect that various EV penetration rates and charging habits could have on peak electricity loads in the jurisdiction. This data can be examined in comparison to historical electricity supply data to identify the potential increase in peak load capacity that suppliers must be able to tolerate to mitigate threats to availability.

3.3.1 End-Use Availability

End-use availability refers to the availability of energy to the vehicle processes while they are in operation. From this perspective, $\text{Energy}_{\text{IN}}$ is met with the energy stored in the vehicle's onboard fuel tank or battery. End-use availability is threatened when a vehicle depletes its energy prior to reaching its destination. The maximum amount of distance a vehicle can travel before having to refuel is referred to as *range*. The range of a BEV the product of its battery capacity and efficiency, Equation 14.

Equation 14: EV Range as a product of battery capacity and efficiency.

$$Range\ (km) = Battery\ Capacity\ (\mathrm{kWh})\ * Efficiency\ (\mathrm{km/kWh})$$

The fear that a vehicle will run out of on-board energy prior to reaching its destination is known as *range anxiety* [58]. If a BEV owner's daily distance requirements can be satisfied within the range of their battery, they can reliably charge their vehicle at-home overnight to maintain end-use availability. However, as a vehicle owner's demand for distance approaches or exceeds EV range, they must consider the feasibility of charging their vehicle at their workplace or at a public charging station in their jurisdiction to maintain availability.

EVs have published range values based on standardized testing performed on a dynamometer in a test facility. This value can vary significantly in real-life conditions depending on terrain, passenger load, speed, driver behavior or outdoor temperature [45].

The fleet management solutions company Geotab conducted an analysis of anonymized data from 5.2 million trips taken by 4,200 EVs representing 102 different make/model/year combinations and analyzed average vehicle trip efficiency by temperature [45]. Their analysis concluded that most EVs follow a similar temperature range curve, regardless of make or model [45]. The curve in Figure 6 depicts their results, which compare the real-world performance of EVs to their rated ranges at various temperatures.

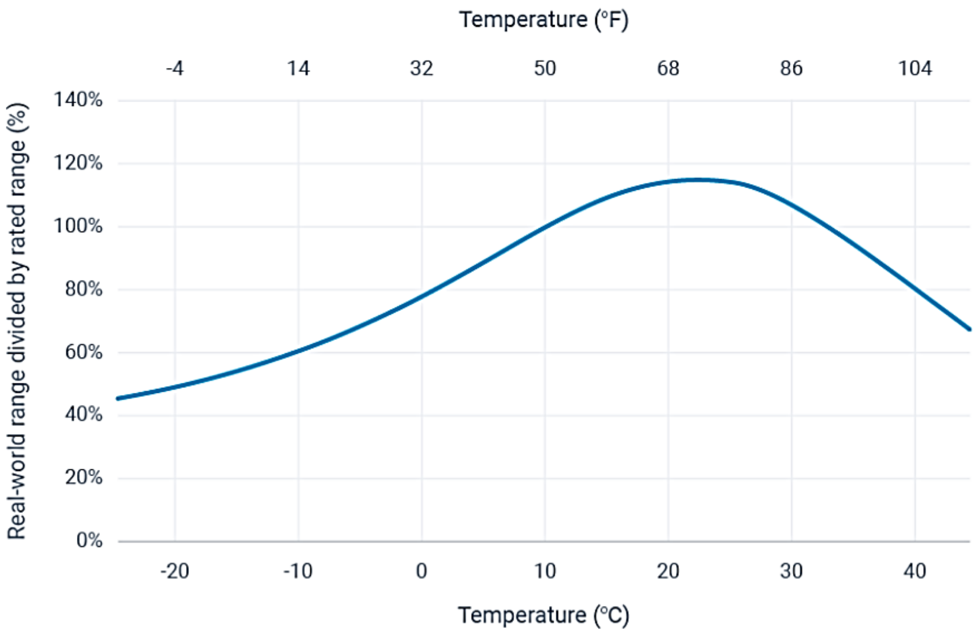

Figure 6: Geotab electric vehicle temperature-range curve. [45]

Using sampled values from this curve, plots can be generated to approximate the impact of temperature on the range of any sample BEV. Table 1 contains the rated range to real range conversion factors at 10°C intervals, which were sampled from the curve using WebPlotDigitizer [59].

Table 1: Geotab EV curve temperature-based range adjustment factors (-20 to 40°C)

Temperature (°C)	**Temperature Factor (Real Range/Rated Range)**
-20	0.492
-10	0.604
0	0.785
10	0.997
20	1.14
30	1.07
40	0.799

Since BEV range is directly proportional to its efficiency, and the capacity of its battery is constant, the temperature factors from Table 1 can also be employed to evaluate a BEV's *real efficiency* at a defined temperature, Equation 15.

Equation 15: Real Efficiency

$$Real\ Efficiency\ = \frac{Rated\ Efficiency}{Temperature\ Factor}$$

The methods in this section can be employed to assess threats to end-use availability by comparing the real range of sample EVs at different temperatures with various common commuting distances in a jurisdiction. The results show the distances and temperatures at which BEV owners are likely to experience range anxiety on their commute if additional charging is not available.

3.3.2 Upstream Availability

Upstream availability considers the energy supplier's ability to provide energy when requested by vehicle processes in the jurisdiction. Availability is threatened from the upstream perspective when energy suppliers must adapt to meet increased demand for energy from the vehicle processes in the jurisdiction. By approximating the daily energy demand of the average EV in a jurisdiction, scenarios can be developed to project the impact that different charging patterns and EV penetration rates can have on peak loads in electricity generation.

The number of EVs in a jurisdiction can be approximated for various EV penetration rates relative to the jurisdiction's vehicle stock, Equation 16.

Equation 16: Approximation of the number of EVs in a jurisdiction

$$Number\ of\ EVs\ =\ EV\ penetration\,\%\ \times\ Jurisdiction\ vehicle\ stock$$

The daily demand for electricity of an EV owner can be approximated as the product of the EV's efficiency and average annual distanced travelled data, Equation 17 [60].

Equation 17: Approximation of the average daily energy demand from an EV

$$\begin{aligned} &Average\ Daily\ Energy\ Demand\ (kWh) \\ &\qquad = EV\ efficiency\ \left(\frac{kWh}{km}\right) \times \frac{Average\ Annual\ Distance\ (km)}{365} \end{aligned}$$

In colder temperatures, EVs operate less efficiently and thus use more energy relative to the same distance travelled at a warmer temperature. The temperature adjusted EV efficiency (Equation 15) can be used in place of rated efficiency to incorporate the impact of temperature on average daily energy demand.

The total daily electricity demand from EVs in a jurisdiction can be approximated with Equation 18, assuming all vehicles in the jurisdiction charge the average daily energy usage.

Equation 18: Total daily demand equation

$$Total\ daily\ demand\ (kWh) = Number\ of\ EVs * Average\ Daily\ EV\ Demand$$

A variety of charging scenarios can be developed to understand the threat that different distributions of this demand can have on upstream electricity suppliers. If the demand from EVs exacerbates peak loads in electricity generation, suppliers may have to adapt their peak load capacity to maintain availability. With the advent of smart meters and coordinated charging, many electricity suppliers believe that scheduling charging requests throughout the nighttime hours can help mitigate peaks caused by increased demand for EV charging.

Charging scenarios can be employed to evaluate the impact of uncoordinated and off-peak EV charging habits relative to their impact on a jurisdiction's daily load curve.

3.3.2.1 Uncoordinated Charging

In the uncoordinated scenario, the total daily demand calculated in Equation 18 is modelled as a normal distribution with a standard deviation of 2 hours, centered at 19h00 so the EVs' load coincides with the evening peak in electricity demand, thus demonstrating the worst-case impact of EV charging on peak load.

3.3.2.2 Off-peak Charging

In the off-peak charging scenario, the best-case scenario is considered, in which energy suppliers have complete coordination of charging the EVs in the jurisdiction. Energy demand in many jurisdictions follows a common profile, with a trough in demand between peaks that occur in the evening and morning. By assuming all charging takes place during this trough in demand, a best-case scenario for the impact of EV charging on peak demand can be determined.

This scenario can be evaluated by solving for the value at which a flat line bounds an area equal to the total EV demand between it and the nighttime trough in the load curve. A representation of the nighttime load trough of in a jurisdiction is depicted in Figure 7.

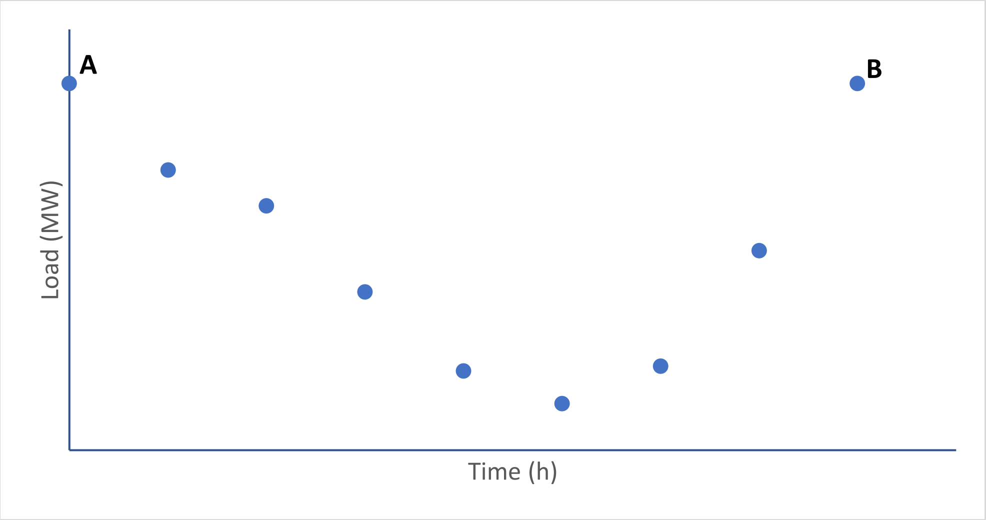

Figure 7: Nighttime trough in generic hourly load data

The maximum amount of energy that can be added to this trough can be determined by calculating the area bound between y_{upper} and y_{lower}, where y_{upper} is maximum load value equal to A_y and B_y (y_{max}), and y_{lower} is the equation of a 6th order polynomial curve fitted to the hourly load data between A and B, Figure 8.

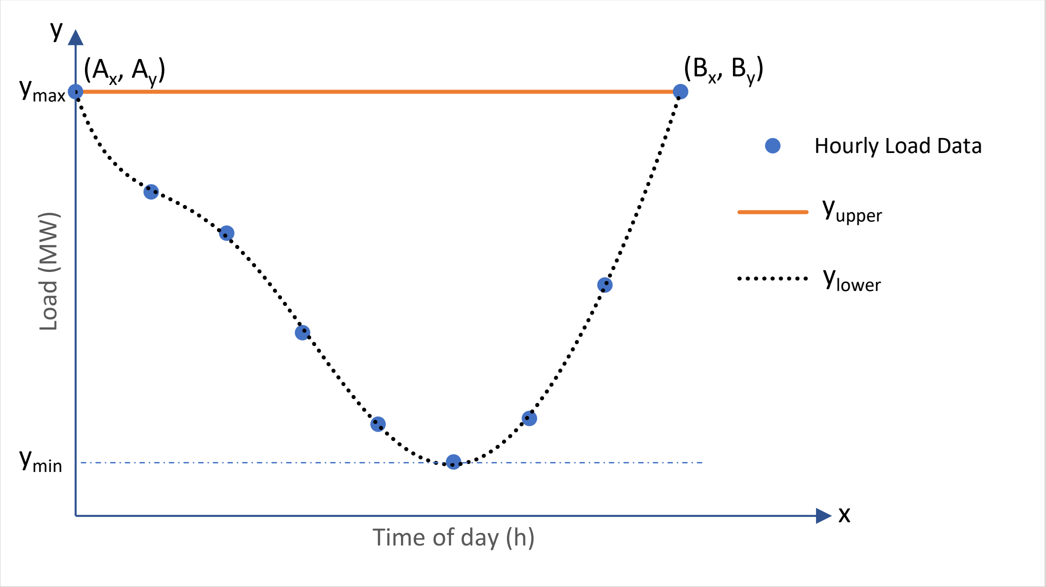

Figure 8: Geometric representation of nighttime trough in demand

This area is calculated as the integral between the curves y_{max} and y_{lower} over the interval from A_x to B_x, Equation 19.

Equation 19: Maximum trough demand

$$Max\ Demand\ (kWh) = \int_{A_x}^{B_x} y_{max} - y_{lower}\ dx$$

An iterative approach can be used to approximate the value of y_{upper} at which the area bound between it and the load curve is equal to the average total daily EV demand. This approach is only valid if the specified demand is less than the max demand of the trough evaluated with Equation 19. If the total daily demand exceeds this limit, the additional demand in the uncoordinated charging scenario will be added as a normal distribution with a standard deviation of 4 hours and a mean centered at 2am.

For each iteration, the following steps are executed:

1. First, the polynomial y_{lower} is shifted by $y_{min} + i$, where i is a counter that is initialized to 0.01 MW. The counter is incremented by 0.01 MW every iteration until a solution is found or it is equal to the difference between y_{max} and y_{min}. The counter increment (0.01) determines the decimal places of precision in the computation.

2. The roots of the shifted polynomial are calculated to determine where the shifted polynomial intercepts with the x-axis. The real roots that exist on the interval from A to B are the limits of integration necessary for evaluating the integral between the shifted y_{lower} and the x-axis.

3. The area bounded between the shifted polynomial and the x-axis is determined by inverting it and evaluating the integral over the interval between the two real roots.

4. If the solved area is less than the required demand value, i is incremented and the steps are repeated. If the area is greater than or equal to the desired area, the approximated solution y_{upper} is equal to the offset ($y_{min} + i$).

In Chapter 5, the coordinated and uncoordinated charging scenarios are evaluated in Matlab and compared to daily load data from Nova Scotia Power (NSP).

3.4 Summary

In this chapter, methods were defined to consider the affordability, availability, and acceptability of conventional and electric vehicles. The acceptability methods show how to calculate the equivalent annual emissions of chosen CVs and BEVs. The affordability methods define a TCO model which can be employed to evaluate the ownership and operating costs of sample CVs and BEVs over a 5-year ownership period. The availability methods consider threats to BEV availability from two-perspectives. From the end-use perspective, the temperature adjusted range of EVs can be calculated and compared to various common commuting distances. From the upstream perspective, methods can be employed to visualize the effect of different charging distributions on peak loads in electricity supply curves. In the following chapter, the methods are applied in a case study evaluating the affordability, availability, and acceptability of light duty vehicle electrification in Nova Scotia.

4 CASE STUDY - NOVA SCOTIA

In this chapter, the methods introduced in Chapter 4 are applied in a case study evaluating the affordability, availability, and acceptability of electrifying light duty vehicles in Nova Scotia. The results of the case study are analyzed to discuss the affordability, availability and acceptability of light duty vehicles in Nova Scotia in the context of the federal electrification targets of 10% ZEVs by 2025 and 30% ZEVs by 2030 (EV30@30). The availability results are first discussed to identify whether the increase in peak demand for electricity from EVs represents a threat to energy security in Nova Scotia. The acceptability and affordability results are then discussed to identify barriers to achieving increased electrification and reductions in light duty vehicle emissions.

4.1 Input Parameters

The following section provides an overview of the input parameters and assumptions used to generate the affordability, availability, and acceptability results for Nova Scotia. These parameters are broken down into the vehicle buyer profile, energy factors, sample vehicles, and financial factors.

4.1.1 Vehicle Buyer Profile

The following assumptions define the vehicle buyer profile used to generate insurance costs in the affordability TCO analysis.

- 5-year ownership period
- Male
- 30 years old
- 10 years of accident-free driving
- Halifax Resident (Postal Code, B3H 4R2)

4.1.2 Energy Factors

Table 2 contains the energy factors used to generate the affordability, availability, and acceptability results.

Table 2 Energy based input parameters for Nova Scotia

Parameter	**Value**	**Source**
Electricity cost ($/kWh)	0.15805	[61]
Gasoline Cost ($/L)	1.03	[62]
Carbon Tax Rate ($/tonne)	N/A	[63] Nova Scotia has an approved cap-and-trade carbon pricing program, this does not involve a direct tax on the emissions from consumer fuel purchases
Annual Distance Travelled (km)	21820	[60]
Electricity Consumption Emissions Intensity (kgCO2e/kWh)	760	[4]
Gasoline Emissions Intensity (kgCO2e/L)	2.3	

4.1.3 Sample Vehicles

To apply the methodology introduced in Chapter 4, a set of sample conventional and electric vehicles must be selected. A detailed breakdown of results will be shown for the 2020 Honda Civic Sedan and 2020 Nissan Leaf which were chosen since they are the most popular CV and BEV in Canada respectively [64, 8]. Additional results will be shown for the vehicles in Table 3 to illustrate the variance in cost and performance within the CV and BEV class. The CV vehicles were chosen to include a compact model (Mitsubishi Mirage), multiple popular multiple mid-size models, an SUV (Honda CR-V) and a light duty pickup truck (Ford F150). The EV models were chosen to include a compact model (Volkswagen eGolf), the four most popular mid-size models, and an SUV (Tesla Model X).

Table 3: Conventional and electric vehicle sample models

Conventional Vehicles	**Electric Vehicles**
2020 Mitsubishi Mirage	2020 Volkswagen e-Golf
2020 Hyundai Elanta	2020 Nissan Leaf
2020 Honda Civic Sedan	2020 Hyundai Ioniq Electric
2020 Toyota Prius	2020 Chevrolet Bolt EV
2020 Honda CR-V	2020 Tesla Model 3 - Standard Range +
2020 Ford F150	2020 Tesla Model X

More detailed specifications for all sample vehicles including fuel consumption, range, curb weight, and trim are defined in Tables A1 and A2 of the Appendix.

4.1.4 Financial Factors

The following data sources and assumptions are used to evaluate the TCO of the sample vehicles in the affordability analysis.

Table 4: Financial data sources and assumptions for Nova Scotia

Parameter	**Value**	**Data Source/Assumption**
Loan Duration (months)	60	It is assumed that the vehicle loan is fully financed over the 5-year ownership period of the vehicle.
Down Payment	20% of MSRP	
Real Annual Discount Rate	5%	
Loan Annual Interest Rate	5%	
Provincial Sales Tax	15%	[65]
Annual CEV M&R Costs	$891	[55]
Annual BEV M&R Costs	$469	[55]
CV Depreciation Rate	51.9%	[51]
EV Depreciation Rate	51.9%	[51]

4.2 Availability

Threats to the availability of energy associated with the electrification of vehicles in Nova Scotia are evaluated from an end-use and upstream perspective.

4.2.1 End-Use Availability

End-use availability threats are considered by comparing the temperature adjusted range of different BEVs to round-trip commuting distances from various population centers to Halifax. The round-trip distances to Halifax from 5 different areas evaluated with Google Maps are listed in Table 5.

Table 5: Round-Trip Distance to and from Halifax

Origin	**Round-Trip Distance (km)**
Bedford	34
Elmsdale	82
Windsor	132
Truro	188
Kentville	210

The temperate adjusted range curves of the sample BEVs from Section 5.1.3 were calculated based on the conversion factors in and the rated range of each BEV. The resulting temperature adjusted range curves of the sample BEVs compared to the round-trip commuting distances can be seen in Figure 9.

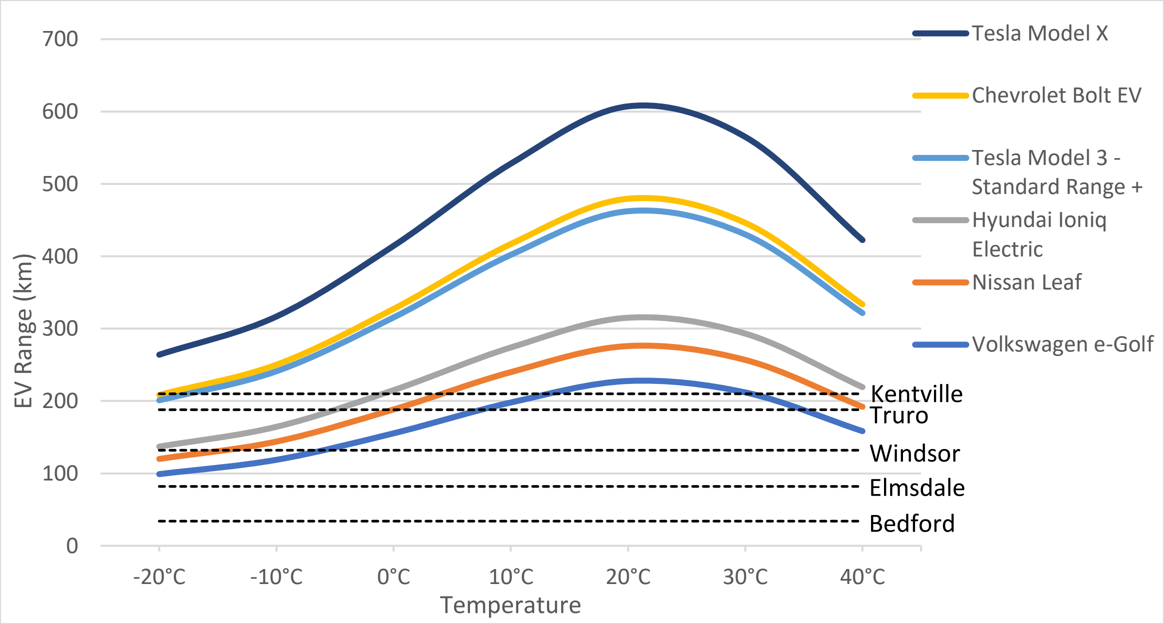

Figure 9: EV Temperature-Range curves of various models compared to round-trip distance to Halifax of several locations.

The end-use availability results indicate that most common BEVs can reliably travel round trip distances of over 100 km regardless of temperature. However, beyond this limit owners driving more range limited EVs as the Volkswagen eGolf and the Nissan Leaf could experience range anxiety.

There are two factors that can help alleviate EV range anxiety. First, vehicle buyers that need to travel longer distances can opt for EVs with large ranges. The Chevrolet Bolt EV and Tesla Model 3 have rated ranges upwards of 400km and can travel well over 200km in -20ºC temperatures. However, increase the range of an EV comes at the cost of a larger on-board battery, which increases cost and can harm the vehicle's efficiency from increased weight.

A second way to mitigate range anxiety is by increasing access to reliable and efficient public charging stations throughout the jurisdiction. In a 2019 survey undertaken by Nova Scotia Power, 65% of respondents stated that they would consider an EV if there were more charging stations available [66]. To address this concern, the Nova Scotia Power have since partnered with Natural Resources Canada to install a more robust network of Level 3 DC-fast charging stations and Level 2 charging stations across the province [67]. Despite these initiatives, access to public charging infrastructure throughout Nova Scotia is still very limited with just over 100 charging stations currently operational throughout the province [66]. Nova Scotia projects that to optimally meet the expected charging demand at 10% electrification, over 2000 electric vehicle charging stations need to be installed throughout the Halifax Regional Municipality alone [66]. Future work should be conducted to evaluate the economic feasibility of expanding public charging station access and its effects on reducing range anxiety.

4.2.2 Upstream Availability

To evaluate threats to upstream availability, four scenarios are developed using the methods from Section 4.3.2 to simulate the changes in peak electricity generation at various temperatures, EV penetration rates, and EV charging distributions. To incorporate seasonal considerations, two average daily load curves were generated with 2020 hourly load data from Nova Scotia Power to represent winter and summer conditions. The winter scenario daily load curve was determined by averaging hourly load data from January to April 2020, while the summer scenarios use the average daily load curve from May to August 2020. Both the summer and winter daily load curves were rearranged to begin at 12:00pm such that the nighttime trough in demand can be analyzed over a continuous interval, Figure 10.

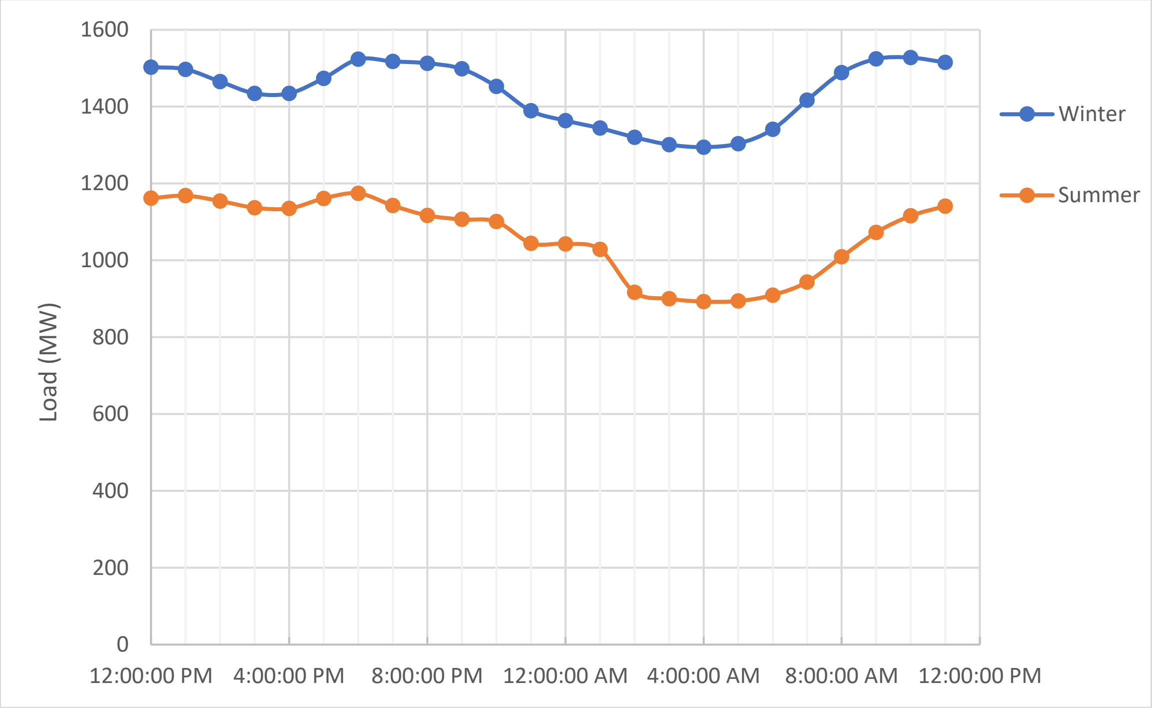

Figure 10: NSP 2020 average hourly total net load curves for summer and winter. [65]

Table 6 provides a summary of the input data for the four scenarios which are named according to the season and the EV penetration rate being simulated (i.e. S10 refers to Summer at 10% EV penetration).

Table 6: Upstream availability scenarios and input data

Scenarios	EV Penetration (%)	Temperature (°C)
S10 (Figure 11)	10%	20
S30 (Figure 12)	30%	20
W10 (Figure 13)	10%	-10
W30 (Figure 14)	30%	-10

For this analysis, it is assumed that the rated efficiency of all EVs in Nova Scotia is 17.96 kWh/100km, which is the average of the efficiencies of the sample BEVs in Section 5.1.3. This baseline efficiency is adjusted to a real efficiency with Equation 15 based on the temperature defined in each scenario. The average daily demand for distance per EV is calculated to be 60 km based on the average annual distance driven of 21820 km [60]. The total vehicle stock in Nova Scotia is 339000 vehicles [60], and is used to determine the number of EVs based on the EV penetration rate defined in each scenario. In the winter scenario, the trough in load is evaluated from 9pm to 9am, while in the summer scenario it exists from 10pm to 10am. Sample calculations are shown for S10, the results for the remaining scenarios employ the same methodology.

S10 – Sample Calculations

Total # EVs = Vehicle Stock * Penetration Rate = 339000 * 0.1 = 33900

Adjusted Daily Demand (kWh)
= Avg daily distance (km)* Avg EV efficiency (kWh/km) / Temp Factor
= 60km * 0.1796 (kWh/km) / 1.14
= 9.45 kWh

Total Daily Demand (MWh) = Total # EVs * Adjusted Daily Demand (kWh) /1000
= 33900 * 9.45/1000
= 320.4 MWh

y_{upper} = 974.2 MW

Uncoordinated Change in Base Load = 0
Uncoordinated Change in Peak Load = 1213 MW – 1174 MW = 38.8 MW

Off-peak Change in Base Load = 974.2 MW – 892.8 MW = 81.4 MW
Off-peak Change in Peak Load = 0

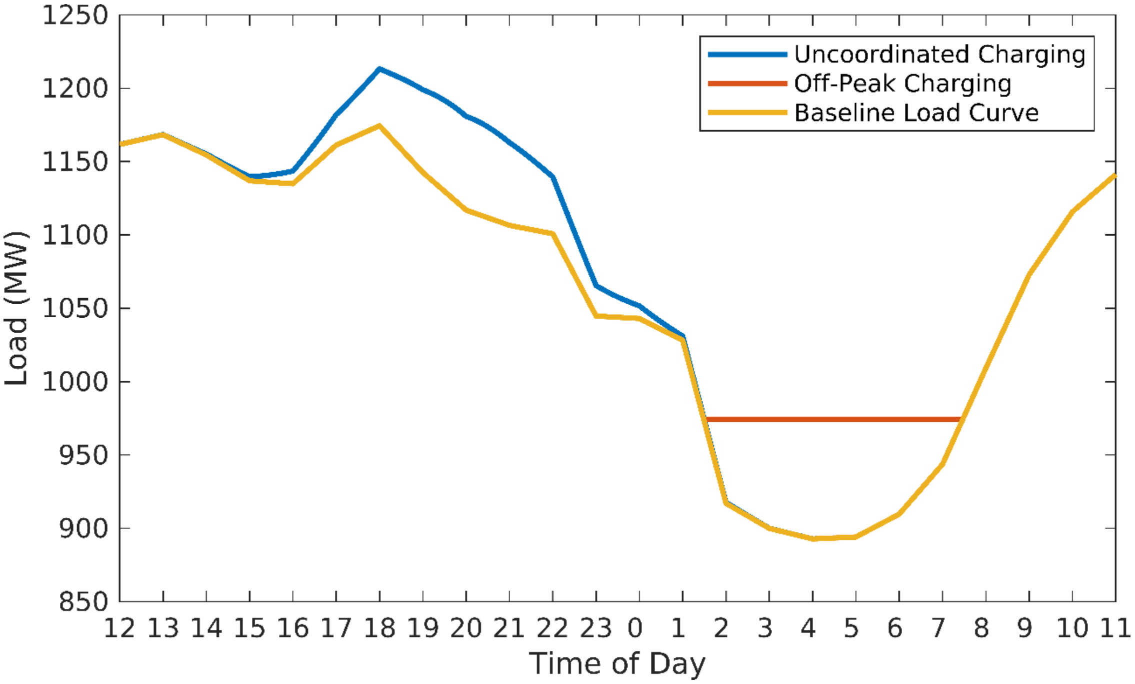

Figure 11: S10 charging scenarios (Summer, 20°C, 10% EV penetration)

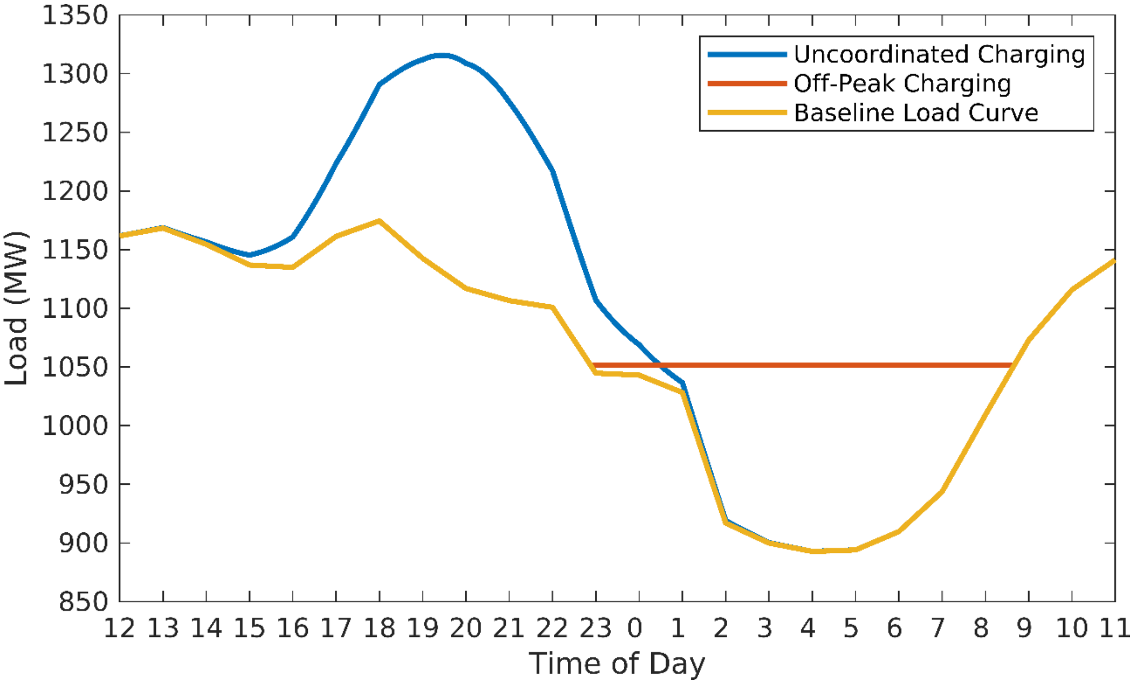

Figure 12: S30 charging scenarios (Summer, 20°C, 30% EV penetration)

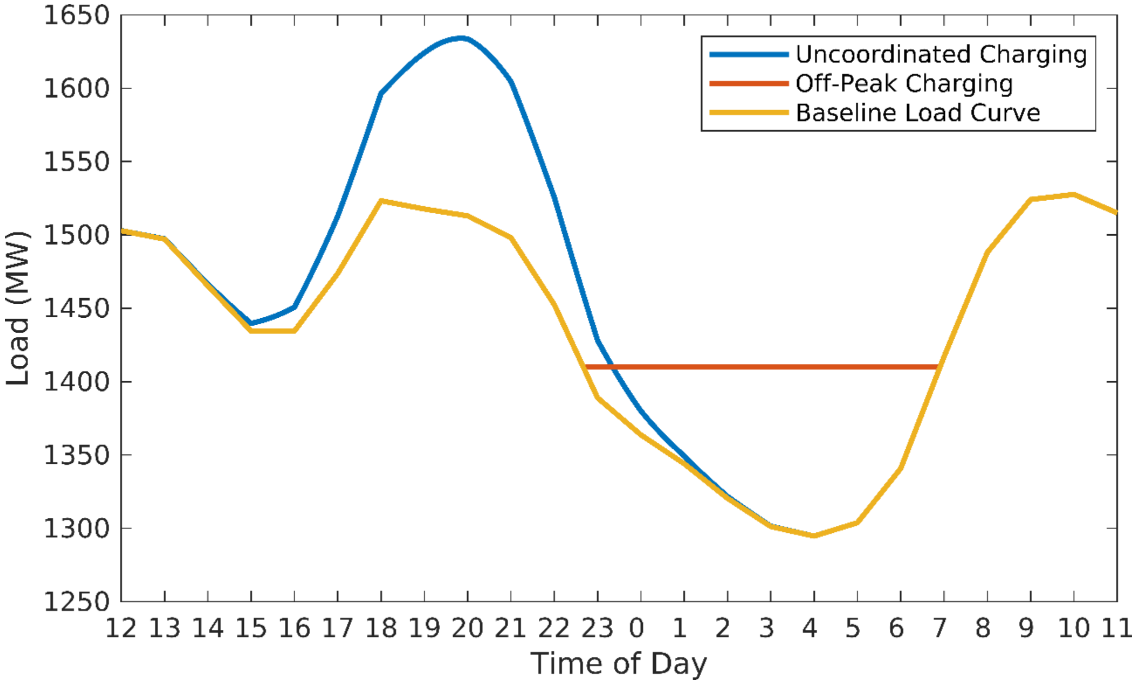

Figure 13: W10 charging scenarios. (Winter, -10°C, 10% EV penetration)

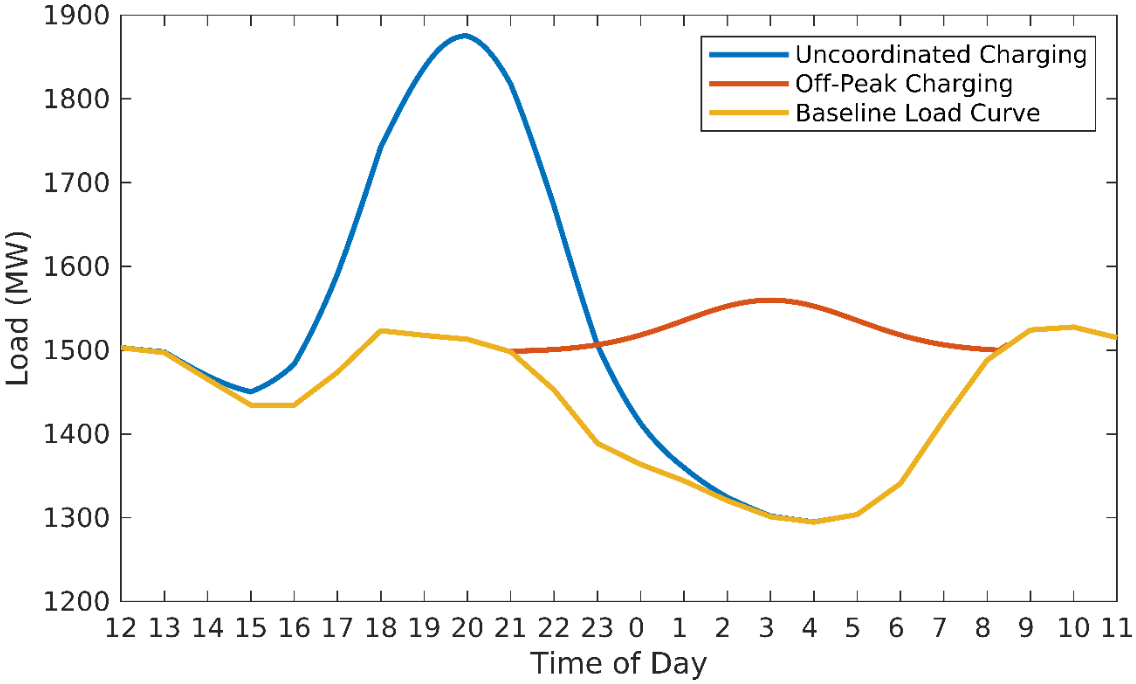

Figure 14: W30 charging scenarios. (Winter, -10°C, 30% EV penetration)

A summary of the results from the four scenarios are provided in Table 7, Table 8, and Table 9. Table 7 includes the temperature adjusted daily demand of the average EV, the total number of EVs, and the total daily demand from all EVs at the penetration rate and temperature defined in the scenario. Table 8 and Table 9 show the impact of the charging scenarios on changes in peak and base load generation in terms of the net change and percentage change respectively.

Table 7: Adjusted daily demand, total number of EVs, total daily demand results

Scenario	Adjusted Daily Demand (kWh)	Total Number of EVs	Total Daily Demand (MWh)
S10 (Figure 11)	9.45	33900	320.4
S30 (Figure 12)	9.45	101700	961.3
W10 (Figure 13)	17.84	33900	604.8
W30 (Figure 14)	17.84	101700	1814

Table 8: Net change in peak and base load

	Uncoordinated		Off-peak	
Scenario	Change in Peak Load (MW)	Change in Base Load (MW)	Change in Peak Load (MW)	Change in Base Load (MW)
S10 (Figure 11)	38.8	0	0	81.4
S30 (Figure 12)	141.2	0	0	158.8
W10 (Figure 13)	106.4	0	0	115.2
W30 (Figure 14)	347.4	0	61.6	203.4

Table 9: Percent change in peak and base load

	Uncoordinated		Off-peak	
Scenario	Change in Peak Load (%)	Change in Base Load (%)	Change in Peak Load (%)	Change in Base Load (%)
S10 (Figure 11)	3.3	0	0	9.1
S30 (Figure 12)	12	0	0	18
W10 (Figure 13)	7.0	0	0	8.9
W30 (Figure 14)	23	0	2.1	15.7

The upstream availability results show the impact of different temperatures, EV penetration rates and EV charging patterns on the summer and winter average daily load curves in Nova Scotia. The results are analyzed to determine the worst-case scenario impact of EV charging on peak loads in electricity generation and whether NSP have sufficient planned capacity to maintain availability in this case.

4.2.2.1 Summer vs. Winter

There are two important factors that differentiate the impact of EV charging demand on average daily load in the winter months compared to the summer months. First, the winter average daily load curve peak of 1527 MW is 30% greater than the average summer peak of 1174 MW. This difference is the result of the large winter demand for electric heating and comparatively small summer demand for air conditioning [68].

Second, due to colder temperatures EVs operate less efficiently in the winter months and thus consume more energy over an equivalent distance driven. The efficiency factor of the average EV is 0.604, compared to 1.14 at 20°C. This resulted in average daily loads that were 89% greater in the winter scenarios which equates to an 853 MWh difference in the total average daily demand from EVs at 30% EV penetration.

Due to higher winter peak loads and EV efficiency losses in cold temperatures, Nova Scotia is most vulnerable to the threat of EV load exceeding NSP's peak capacity in the winter.

4.2.2.2 Uncoordinated vs. Off-peak Charging

The uncoordinated and off-peak charging scenarios illustrate the benefits of improved demand side management (DSM) and smart grid technologies with respect to the impact of EV charging on peak load.

During the uncoordinated scenarios, the greatest change in peak load is applied at 1900h and coincides with the evening peak in the daily load curve. In the W30 scenario, this resulted in a 23% increase in peak load, with no change in the base load. In contrast, the off-peak charging scenarios depict a best-case scenario in which local utilities can control charging to employ the electricity generation capacity optimally. In the off-peak W30 scenario, load is distributed throughout the trough in nighttime demand such that it prioritizes changes in base load, resulting in a 15.7% increase in base load and only a 2.1% change in peak demand. The results suggest that improved DSM to incentivize off-peak EV charging could almost entirely mitigate the impact of EV charging on peak load at 30% penetration and would allow NSP to meet the demand from EVs with more affordable and reliable base load generation.

4.2.2.3 Threat of EV30@30

To evaluate the threat to availability of achieving 30% electric vehicles by 2030, the results from the W30 scenario can be compared to projected 2030 capacity from NSP.

Capacity projections are available from Nova Scotia Power's 2020 Integrated Resource Plan (IRP), which provides an analysis of their energy system transition to 2045 including multiple scenarios forecasting annual peak capacity, energy demand, and changes to the electricity generation mix [69]. Based on the IRP's 1.0A scenario, a baseline scenario which assumes low electrification and base demand side management, NSP are planning to have 2.97 GW of installed capacity (ICAP) by 2030 [69]. To factor for the variability of renewable sources, the net operating capacity of each generation source is scaled based on its effective load carrying capacity (ELCC) to determine the system's total unforced firm peak capacity (UCAP) of 2.21 GW [69]. Comparing the 2.21GW of UCAP firm capacity to the 1.9 GW peak load from the worst-case charging scenario (W30 uncoordinated) equates to a 16.3% planning reserve margin (PRM),[2] which refers to the quantity of planning reserves that should be held above the forecast annual firm peak, calculated as a percentage of annual firm peak load [69]. The planning reserve margin of 16.3% is slightly below NSP's target PRM of 17.8% [69]. Despite being lower than desired, a PRM of 16.3% suggests that Nova Scotia are prepared to accommodate uncontrolled EV charging at penetration rates close to 30% [69]. The risk of any threat to availability is low considering EV penetration is currently less than 1% in Nova Scotia, and 30% EV penetration is unlikely to occur by 2030.

4.3 Acceptability

The equivalent annual emissions results for Nova Scotia based on the input parameters defined in section 5.1 are displayed in Figure 15.

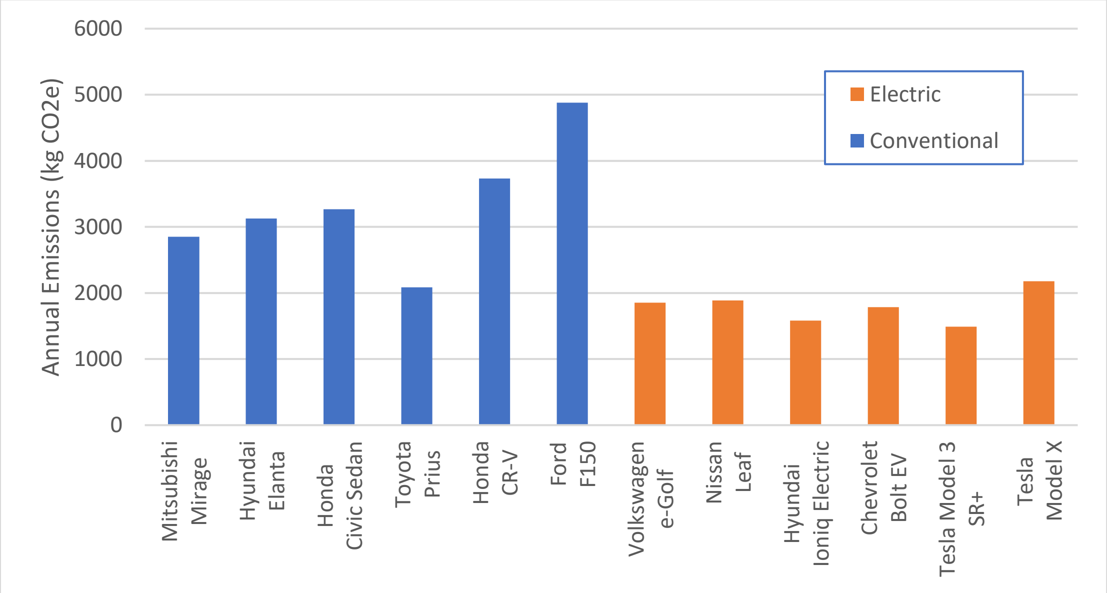

Figure 15: Equivalent annual emissions of travelling 21820 km annually. Nova Scotia, 2020

The results in Figure 15 show how the equivalent annual emissions of the most popular CVs and BEVs in Canada compare over an equal annual distance driven in Nova Scotia.

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[2] Planned Reserve Margin is calculated here as the percentage of total capacity that exceeds the peak from the W30 generation scenario. Different jurisdictions use slight variations on this calculation, such as whether total capacity is measured as installed capacity (ICAP) or unforced capacity (UCAP), or whether the median peak load or maximum peak load is used.

The sample BEVs were on average more acceptable than the CVs, with the average CV (3324 kg CO_2) producing 85% more annual emissions than the average BEV (1796 kg CO_2). The CVs varied more significantly than the BEVs in emissions output within each sample set; the standard deviation within the CV sample was 936 kg CO_2 compared to only 244 kg CO_2 for the EV sample. The Ford F150 was the least efficient CV and produced 134% more annual emissions than the most efficient CV, the Toyota Prius. The annual emissions of the Toyota Prius rivaled the emissions of the BEVs, producing only 16% more annual emissions than the average BEV.

The results show that there are two main avenues through which the acceptability of light duty vehicle fleets in Nova Scotia can be improved: improving the efficiency of CVs in the vehicle stock and increasing EV adoption.

Significant annual emission reductions can be achieved if vehicle owners in Nova Scotia opt for more efficient conventional vehicles. An individual transitioning from a Ford F150 to a Toyota Prius will reduce their annual emissions greater than an individual switching from a compact CV to an EV. A major issue with this option is that to achieve significant efficiency gains it would require end-users to transition from SUVs and light duty trucks to more efficiency compact and mid-size vehicle models. In Canada, consumers have shown a preference for larger vehicles. Prior to 2010, cars and trucks had an approximately equal market share of about 50% each. Since then, a gap has emerged with a record 73% of new vehicle sales being trucks in December 2017 [70].

Nova Scotia can further improve the acceptability of BEVs by reducing the emission intensity of their electricity generation. Nova Scotia Power's baseline IRP scenario 1.0A projects that electricity will be generated with an emissions intensity of 360 gCO_2/kWh by 2030 [69]. This would reduce the annual emissions produced by BEVs by 50% relative to NSP's 2018 electricity generation emissions intensity of 720 gCO2/kWh.

4.4 Affordability

A detailed breakdown of the 5-year TCO of the 2020 Honda Civic and the 2020 Nissan Leaf is displayed in Table 10.

Table 10: 5-year TCO breakdown of the 2020 Honda Civic and the 2020 Nissan Leaf

	2020 Honda Civic Sedan	**2020 Nissan Leaf**
Down Payment	$4,598.00	$8,859.60
Purchase Subsidy	$0	-$5,000.00
Amount Financed	$21,840.50	$37,083.10
Resale Value	-$9,006.63	-$17,354.32
Fuel	$7,713.41	$2,820.44
Insurance	$5,797.56	$5,334.26
Maintenance	$3,857.56	$2,030.52
Emissions ($0/tonne)	$0	$0
License & Registration	$463.44	$560.42
EVSE	$0	$4,000.00
TCO	**$35,263.84**	**$38,334.03**

Figure 16 displays the TCO model results for all sample vehicles based on the input parameters defined in Section 5.1.

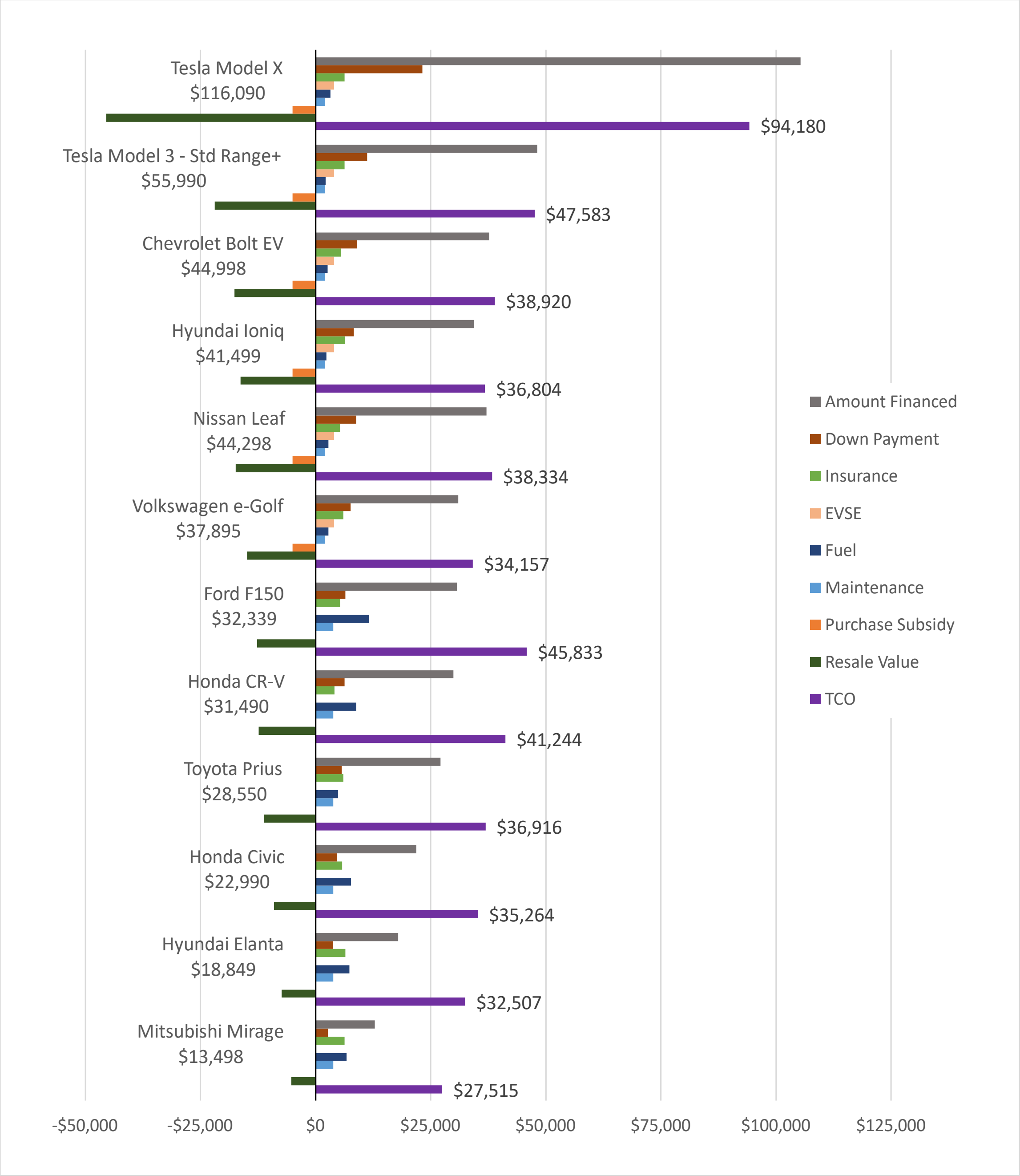

Figure 16: TCO results. The MSRP of each vehicle is listed below its model name.

The results in Figure 16 reveal several trends regarding the affordability of the most popular CVs and BEVs in Nova Scotia. These factors can be discussed to identify significant discrepancies between the affordability of CVs and BEVs, and the feasibility of subsidies to incentive the purchase of BEVs.

4.4.1 Vehicle Class

Vehicle class is a significant factor that contributed to the TCO of both the CV and BEV samples. Vehicle TCO tends to increase with size. The compact vehicles were the most affordable, with the CV (Mitsubishi Mirage, TCO of $27,515) having a TCO nearly 20% less than that of the BEV (Volkswagen e-Golf, TCO of $34,157). BEVs were most cost competitive with CVs in the mid-size class; the average CV TCO ($34,896) was only 13.6% less than that of the average BEV. The TCO discrepancy between CVs and BEVs is most significant among the light duty trucks and SUVs, with the Honda CR-V having a TCO over 56% less than that of the Tesla Model X.

The large difference in TCO between conventional and battery electric light duty trucks and SUVs could significantly limit electrification in Nova Scotia, as their sales outpace that of cars. A major reason for the significant cost discrepancy is that there are only two fully electric SUVs currently available for sale in Canada, the Tesla Model X (MSRP $116,090) and the Audi e-Tron (MSRP $90,000) [71]. To make matters worse, both vehicles far exceed the maximum base model price of $45,000 necessary to qualify for the $5000 purchase rebate through the Canadian federal ZEV incentive program [72].

In terms of light duty trucks, the difference in affordability between electric and conventional models cannot be assessed as there are currently no fully electric alternatives currently available for purchase in Canada [71]. This represents a significant barrier to light duty vehicles emissions reductions since light duty trucks are extremely popular among Canadians and are the least fuel-efficient vehicle class. Ford F-series trucks were the best-selling vehicle in Canada in Q1 of 2020, with full-size pickup trucks representing 22% of total new vehicle sales [73].

Several car companies have announced plans to sell electric pickups in the upcoming years, including an electric Ford F150 and the Tesla Cybertruck. Although there is limited projected pricing information available, most of these vehicles will suffer from the same affordability issues as SUVs. The Rivian R1T is projected to be the first market available EV truck, with a projected base model price of over $90,000 [74].

4.4.2 Capital Costs vs Operational Costs

The TCO results show that certain BEVs (especially mid-size models) can be quite close in cost to CVs, but it is important to also consider the how costs are distributed over the ownership period of the vehicle. For example, although the TCO of as the Honda Civic and Nissan Leaf differ by less than 10%, the BEV will have a much larger upfront capital cost. Even when factoring in a $5000 purchase subsidy, a 20% down payment on the purchase of the Nissan Leaf is 93% more than that of the Honda Civic. For wealthier individuals this may be less of a concern since the BEV will incur operational savings relative to a CV over its lifetime through cheaper fuel and maintenance costs. However, for individuals with limited savings, the difference in capital costs could be what prevents them from opting for a BEV, despite equivalent TCOs.

4.4.3 Subsidies

Many jurisdictions have implemented EV subsidy programs to reduce the capital cost of EVs to incentivize increased EV adoption. In the TCO results, the $5000 federal purchase incentive was included, yet despite this rebate and operational savings on fuel and maintenance, the TCO of most EVs was greater than equivalent CVs. The Nissan Leaf has a TCO over $3000 greater than that of the Honda Civic and its 20% down payment is over $4500 greater. These cost differences are a major barrier to EV adoption in Nova Scotia, where EVs currently represent less than 1% of new vehicle sales [66].

If Nova Scotia want to improve EV adoption rates, they may consider implementing a provincial subsidy program to further reduce the cost of EVs. The cost effectiveness of an EV subsidy is commonly assessed by the cost per tonne of emissions that are reduced when an individual opts for an EV over its conventional alternative [19, 75, 7]. Table 11 shows the price of emissions reductions at different provincial subsidy rates when considering the replacement of the Honda Civic with a Nissan Leaf. The cost per tonne reduced emissions was evaluated with Nova Scotia Power's 2018 emissions intensity and their projected 2030 emissions intensity to show the impact of decarbonizing electricity generation on the cost effectiveness of subsidies.

Table 11: Cost per tonne emissions reduction of subsidizing the replacement of the Honda Civic with the Nissan Leaf

		Cost per tonne emissions reduced ($/tonne)		
Year	Emissions Intensity of Electricity Generation (gCO_2e/kWh)	$1000 Subsidy	$3000 Subsidy	$5000 Subsidy
2018 ($/tonne)	720	145	436	726
2030 ($/tonne)	360	73	218	363

The cost per tonne emissions reduced by EV subsidies becomes more affordable with decreases in emissions intensity and subsidy rate. However, as subsidy rate decreases, the subsidy becomes less effective at reducing cost and incentivizing the purchase of EVs. A $1000 subsidy relative to the TCO of the Nissan Leaf is only a 3% reduction in cost. If the Nova Scotia government wants to consider offering provincial subsidies that are significant enough to incentive greater EV adoption, they should first wait for NSP improve their emissions intensity such that they can maximize the emissions reduced per dollar invested in each subsidy.

5 CONCLUSION

This thesis was developed to address the problem of reducing transportation sector emissions produced by conventional light duty passenger vehicles, which are the dominant light duty vehicle technology in most jurisdictions across the globe. Although it is widely agreed upon in the literature that transitioning the conventional vehicles in a jurisdiction to electric vehicles is the most promising solution to decarbonizing this subsector, it can be difficult to quantify the risks to consumers and energy suppliers of pursuing this transition. Many studies have employed jurisdiction specific methodologies to quantify the risks of electrifying light duty vehicles, but due to the complexity of this issue and cross-study differences in approach, it is difficult to make comparisons between the results from different jurisdictions.

The thesis addressed this problem by employing an energy systems analysis framework to model the energy processes and flows in the light duty conventional and electric vehicle systems of generic jurisdictions. The state of these flows can be used to evaluate three energy-security indicators which reflect the level of risk to the entities of an energy system: affordability, availability, and acceptability. The affordability methods consist of a consumer-oriented total cost of ownership and operation (TCO) model that accepts jurisdiction specific input parameters to approximate the average 5-year total cost of ownership and operation of a number of sample conventional and battery electric vehicles. The availability methods consider threats to the availability of energy from an upstream and end-use perspective. The upstream availability methods can be employed to assess the risk of various EV charging scenarios to the availability of electricity in the jurisdiction. The end-use availability methods consider the risk of exceeding EV range at different temperatures and trip distances. Lastly, the acceptability methods can be used to develop comparison between the equivalent annual emissions of various CVs and EVs based on the average distance travelled and electricity emissions intensity in the jurisdiction. To demonstrate the utility of this approach, the methods were applied in a case study of Nova Scotia to evaluate the three energy security indicators. These results of these indicators were discussed to identify the barriers to achieving EV adoption targets in Nova Scotia and evaluate the risk of rapid EV adoption to upstream energy availability.

The affordability results showed that despite federal EV purchase incentives and efforts to reduce the cost of BEVs, CVs are still comparably the more affordable option in Nova Scotia. The high capital costs of BEVs relative to CVs and the lack of cost-competitive SUVs and light duty trucks are significant barriers to achieving increased BEV adoption in Nova Scotia. The Nova Scotia government could attempt to reduce the TCO and high capital costs of EVs by implementing provincial EV subsidies, but they should consider that due to Nova Scotia Power's existing high emissions intensity, EV subsidies are currently less cost-efficient than other investments in emissions reduction. However, despite the cost differences identified in the results of this thesis, many researchers are hopeful that EVs could reach cost parity with ICE vehicles by as early as 2025, based on cost trajectories including battery-cost and efficiency improvements, power-electronics scale economies, and indirect cost reduction based on increased volume production. As the EV market continues to evolve and Nova Scotia Power decarbonizes its electricity generation, the Nova Scotia government should continue to employ the TCO methodology to track changes in the affordability of EVs and CVs to identify whether provincial subsidies cost effective investment in increasing EV adoption rates.

The upstream availability results showed the impact of various EV penetration rates, temperatures and charging distributions on the summer and winter 2020 load curve from Nova Scotia Power. Due to higher winter peak loads and EV efficiency losses in cold temperatures, Nova Scotia was found to be most vulnerable to the threat of EV load exceeding NSP's peak capacity in the winter. Despite these factors, when comparing the winter charging load from EVs at 30% penetration to Nova Scotia Power's projected 2030 capacity it did not represent a significant risk to availability in either the uncoordinated or off-peak charging scenario. Although the risk of uncoordinated charging at 30% penetration is minimal, the results depicted the significant benefits of the off-peak charging pattern, which mitigated changes in peak-load in exchange for cheaper and more reliable base load generation.

The end-use availability results depicted the significant effect that temperature and battery size can have on EV range. It was found that Nova Scotian's with commute distances greater than 100 km, such as from Kentville to Halifax, would be unable to complete their commute in certain EV models without access to public charging infrastructure. Since the more range limited EV models tend to be the most affordable, range anxiety could act as a significant barrier to EV adoption for individuals with long daily trip distances seeking EVs at a cost-competitive price point.

Lastly, the acceptability results for Nova Scotia showed that EVs are currently the more acceptable option but can be greatly improved as Nova Scotia Power decarbonize their electricity generation systems. It was also found that significant emissions reductions can achieved by encouraging the purchase of more efficient conventional vehicles. Consumers opting to transition from light-duty trucks to more efficient mid-size CVs or HEVs will reduce an equivalent amount of emissions to individuals transitioning from a mid-size CV to a mid-size EV.

5.1 Limitations and Future Work

In future work, the methodology from this thesis can be expanded to assess the three dimensions of energy security in more detail.

For affordability, due to limitation in the scope of this thesis and the breadth of factors that contribute to CV and EV TCO, there are improvements that can be made to the accuracy of the TCO methodology. In the case study, several assumptions had to be made including approximations of depreciation rate, EVSE costs, maintenance and repair costs and financing parameters. In future work, the TCO model should be expanded to limit the amount of input assumptions and a sensitivity analysis should be conducted to identify the input parameters with the most significant impact on CV and EV TCO.

The upstream availability methods defined to assess the threat of EVs charging to the availability of electricity were successful in generating high level approximations of the benefit of different charging distributions. However, with additional data sources the methods could be modified to improve accuracy. First, the approximation of average daily demand from EVs assumes all EVs have the same average efficiency and travel the same distance. With more detailed information and data on how individuals within Nova

Scotia travel and charge their EVs, more accurate demand approximations can be generated. Another limitation of this methods is that the demand distributions are not directly based on real EV charging data but are instead approximated distributions to demonstrate a worst- and best-case scenario representation of the effects of coordinated and off-peak EV charging. With additional hourly datasets on end-use EV charging, these distributions could be modified to represent differences in the charging habits of individuals throughout the jurisdiction.

In terms of end-use availability, the methods generate effective approximations of the effects of temperature on EV range for rapid comparison to various trip lengths in the jurisdiction. In future work, these methods should be expanded to interface with data on various common commute distances throughout the jurisdiction to determine what percentage of vehicle owners would require at-work charging infrastructure to make their commute without range anxiety. In the Statistics Canada 2016 Census there is provincial data on the number of individuals commuting between counties, but it does not provide detailed information on the distances that consumers are travelling. The collection of higher resolution data on the daily distance travelled by individuals in the jurisdiction would greatly expand the scope of analysis.

Lastly, the acceptability methods were effective in comparing the equivalent annual emissions of various CVs and EVs based on the average distance travelled and electricity emissions intensity in the jurisdiction. The results of the case study on Nova Scotia showed that EVs are currently the more acceptable option but can be greatly improved as Nova Scotia Power decarbonizes its electricity generation system. In future work, these methods should be expanded to include a complete life cycle analysis of the emissions associated with conventional and electric vehicles.

5.2 Summary

Together, the results of the affordability, availability and acceptability methods represent the three dimensions of the energy security of light duty vehicle systems in a jurisdiction. By evaluating these indicators, policymakers can identify the economic forces that support or impede EV adoption, the changes in electricity demand necessary to meet increased EV adoption, and the reductions in greenhouse emissions that are attainable through a transition to EVs. Jurisdictions can also help influence the cost of EVs through subsidy programs and emissions taxes, but they must ultimately decide whether the reductions in greenhouse emissions from increased EV adoption outweigh the impact it will have on the affordability and performance of consumer vehicles and increased electricity generation requirements of electricity suppliers. As EV technology continues to evolve, jurisdictions can apply the generic methods from this thesis to assess the trade-off between these indicators and pursue more acceptable light duty vehicles systems without threatening energy security.

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APPENDIX

A1: Conventional vehicle sample specifications [48]

				Fuel Consumption (L_e/100km)		
Vehicle Name	**Trim**	**Class**	**Curb Weight (kg)**	**City**	**Hwy**	**Comb**
Mitsubishi Mirage	ES CVT	Compact	920	6.6	5.6	6.2
Hyundai Elantra	Essential IVT	Mid-size	1360	7.8	5.6	6.8
Honda Civic Sedan	LX CVT	Mid-size	1252	7.9	6.1	7.1
Toyota Prius	FWD	Mid-size	1380	4.4	4.7	4.5
Honda CR-V	LX AWD	SUV	1513	8.7	7.4	8.1
Ford F150	XL 2WD Reg Cab 6.5' Box	Pickup	2207	12	8.9	10.6

A2: Battery electric vehicle sample specifications [48]

Vehicle Name	Trim	Class	Curb Weight (kg)	Range (km)	Fuel Consumption (kWh/100km)		
					City	Hwy	Comb
Volkswagen e-Golf	Comfortline 4-Door	Compact	1615	198	17.4	19.9	18.5
Nissan Leaf	SV HB	Mid-size	1604	240	17	21.2	18.9
Hyundai Ioniq Electric	Pref HB	Mid-size	1529	274	14.5	17.4	15.8
Chevrolet Bolt EV	5dr Wgn LT	Mid-size	1616	417	16.5	19.5	17.9
Tesla Model 3 - Standard Range +	Standard Range Plus RWD	Mid-size	1612	402	14.1	15.9	14.9
Tesla Model X	Long Range AWD	SUV	2459	528	21.2	22.5	21.8