Electric vehicle implications of disaster induced power outages

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We acknowledge and respect the lək̓ʷəŋən peoples on whose traditional territory the university stands and the Songhees, Esquimalt and W̱SÁNEĆ peoples whose historical relationships with the land continue to this day.

Supervisory Committee

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Abstract

The increasing electrification of the transport sector will create an increased vulnerability to power outages caused by disasters. This thesis provides two contributions in this area by offering suggestions for increasing earthquake grid resilience and modeling the use of electric vehicles (EVs) providing aid during a disaster induced outage.

In British Columbia, Canada, the Lower Mainland and the Greater Victoria area on Vancouver Island have seen the largest adoption of EVs in the province and are located in an area of high seismic hazard, so it is crucial for the region to understand and plan for the impact of a large earthquake on the power system. This thesis compiles lessons learned from past large earthquakes in Chile, Japan, and New Zealand and applies them to increasing the power system resilience of the Lower Mainland and Vancouver Island. These suggestions are also compared with how fuel infrastructure resilience could be increased in the region of study.

When used in conjunction with microgrids, EVs can potentially remain functional for the duration of a power outage. This thesis uses an agent-based model to study the behaviour of a fleet of EVs providing disaster relief during a power outage. EVs are tasked with donating energy to a shelter (Task 1), delivering critical supplies (Task 2), and providing transport for personnel or performing inspections (Task 3). Using a six EV fleet with two of each EV type, it was found that the 250, 350, and 450 kWh storage sizes could provide for outages of 0.5 to 1 day, 1 to 1.5 days, and 2 to 4 days, respectively. The rate of energy donated to the shelter was found to be 350 kWh/day, while the Type 1, 2, and 3 EVs, used energy at the microgrid at a rate of about 200 kWh/day, 100 kWh/day, and 50 kWh/day, respectively. Increasing battery storage size reduced the variation in the average daily energy use of the EVs and creating a six EV population with only Type 2 and 3 EVs was found to reduce variation even further and substantially increased the length of outage that the various microgrid storage sizes could provide for with 250 kWh storage now providing for outages of 2 to 4 days, while 350 and 450 kWh storage sizes routinely accommodated the EVs operating for a full two weeks (the time horizon of the model).

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Chapter 1. Introduction

1.1. Electric Vehicle Adoption Benefits and Outlook

The adoption of electric vehicles (EVs) has the potential to help address such issues as urban air pollution, climate change, and fossil fuel resource depletion [1]. On a global scale, the transport sector accounts for about 16% of emissions [2]. Relative to internal combustion engine (ICE) vehicles, EVs also offer benefits such as noise reduction, better performance, lower maintenance requirements, and economic savings over the vehicle lifetime [3].

Despite supply chain issues, 2021 global EV sales reached a high of 6.6 million which was nearly double the amount sold in 2020 [2]. In Canada, it has been forecasted that EVs will reach a 22% market share by 2026 [4]. In British Columbia (BC), the Province passed the Zero-Emission Vehicle Act, requiring automakers to meet an increasing annual percentage of new light-duty zero-emission vehicle (ZEV) sales and leases. The goals of the act are to reach 10%, 30%, and 100% of light-duty sales by 2025, 2030, and 2040, respectively [5]. At the federal level, the Government of Canada has published proposed regulations that will require 100% of new vehicles sold in Canada to be ZEVs by 2035 [6]. This serves to signal that the electrification of the transportation sector in Canada is likely to continue to increase. In addition to the transport space, there is a growing dependency on electricity for such critical services as health care, communications, education, and emergency response, among others [7].

1.2. Power Outages of the Electrical Grid

The importance of the electrical grid cannot be overstated in modern life. In Asia and the Pacific, for example, electricity demand is predicted to increase by 3.4% in each year by 2030. To accommodate this increase in demand, it is important to have a power supply that is efficient and reliable [8]. Even though grid outages are low-probability events, they can still result in harsh socioeconomic impacts. In 2015, electricity outages cost consumers in the United States (US) about $44 billion [9].

Power grid outages can stem from accidental threats (damage occurring due to an insider with no malicious intent), natural threats caused by environmental or natural phenomenon, and malicious, intentional threats to disrupt the operation of the power system [10]. Examples from recent years of blackouts caused by natural disasters are the 2012 Hurricane Sandy, the 2011 Japan earthquake, and the 2005 Hurricane Katrina [10]. Close to 58% of the outages in the US between 2003 and 2012 were caused by weather related events, and the growing severity of wildfires and extreme weather events has been a large contributor to the increasing frequency and duration of outages [10] [11].

1.3. Thesis Objectives and Contributions

The continued adoption of EVs will increase the electrification of the transport space. This increased electrification will lead to an even greater dependence on the electrical grid. With an increased dependence on the electrical grid, society will be even more vulnerable to the effects of power outages. There are also potential benefits of EVs in grid outage situations, particularly if self-generating microgrids and bidirectional charging infrastructure are effectively utilized.

The objective of this thesis is to explore the implications of EV adoption on natural disaster induced power outages. In pursuing this objective, this thesis offers two separate contributions:

1. A study into how the earthquake resilience of the electrical grid on the Lower Mainland and Vancouver Island in British Columbia can be increased to be able to minimize or avoid outages completely, with the aim of keeping EVs able to charge. This study is accomplished by reviewing past earthquakes in Chile, Japan, and New Zealand and compiling a list of lessons learned which considers both the successes and failures experienced during those earthquakes. The lessons learned are applied to the Lower Mainland and Vancouver Island and are compared with how the fuel resilience may be increased in both regions as well. The idea being that the transportation sector is still in a transitional point between relying on conventional fuels and electricity, and it is important to consider the

resilience of both. Suggestions are also provided for what level of government or private business may make changes to increase the earthquake resilience of the electric grid or fuel infrastructure.

2. An investigation into the use of EVs in the aftermath of a disaster induced outage to understand how EVs can remain charged in that situation and what their energy requirements may look like. This is undertaken using the framework of an agent-based model (ABM) where the EVs act as individual agents in the model. The EVs are provided access to a microgrid composed of solar panels and various sizes of battery storage. In simulating the post-disaster behaviour of a fleet of EVs, their energy requirements are calculated, along with how long the microgrid could facilitate the fleet operating in absence of the larger grid.

1.4. Thesis Outline

This thesis is formatted as a manuscript-based thesis that is composed of papers that have been or will be submitted to academic journals. The thesis is separated into four chapters. Chapters 2 and 3 are derived from journal papers for which the student was the main author of. To clarify the contribution of the various authors, a preface is added to each of these chapters. These chapters each follow the conventional layout of an academic paper and contain their own introduction, methods, results, discussion, and conclusions.

Following this introductory chapter, the thesis is organized as follows:

Chapter 2 – Earthquake Resiliency Implications of Electric Vehicle Adoption in British Columbia

This chapter focuses on the following:

- A review of past earthquakes in Chile, Japan, and New Zealand and their impact on the electrical grid

- A compilation of lessons learned from these past earthquakes which are applied to the electrical grid on the Lower Mainland and Vancouver Island in British Columbia, Canada
- Suggestions for increasing the fuel infrastructure resilience of both regions
- Policy recommendations at various level of government and private business to increase the resilience of the electrical grid and fuel infrastructure

Chapter 3 – Using Electric Vehicles to Enhance Power Outage Resilience – An Agent-based Study

This chapter focuses on the following:

- A description of the agent-based model that was constructed to study the behaviour of a fleet of EVs that are provided access to a still-functional microgrid, following a disaster induced outage
- A collection of results for the length of outage that the microgrid could provide energy to EVs for, the daily energy donated to a shelter by EVs, and the daily energy used at the microgrid by the various EV types
- A discussion on the implications of the model results with respect to scheduled charging of EVs after a disaster, microgrid design, and post-disaster EV fleet management in absence of a microgrid

Chapter 4 – Conclusions and Future Work

This chapters compiles the key findings that were derived from the previous chapters and offers opportunities for future work that could be accomplished in this area.

Chapter 2. Earthquake Resiliency Implications of Electric Vehicle Adoption in British Columbia

This chapter is based on a publication that was submitted in March 2023 to Springer's *Natural Hazards* journal. The submitted publication uses the same title as this chapter. The paper was authored by M. Churchill, Dr. D. Bristow, and Dr. C Crawford. M. Churchill was responsible for the background research, compiling the lessons learned, and the preparation of the manuscript. M. Churchill and D. Bristow collaborated on the methodology. D. Bristow and C. Crawford were responsible for supervision of the work as well as reviewing and editing the manuscript.

2.1. Introduction

The adoption of electric vehicles (EVs) can offer a host of benefits compared to internal combustion engine (ICE) vehicles, such as reduced greenhouse gas (GHG) emissions, better energy efficiency, and economic savings over the vehicle lifetime [12] [13]. EVs also offer the potential to transfer power from EV batteries to the grid or a building which allows better integration of renewable energy, controlled charging, and the ability to use EVs as mobile energy storage [12] [14] [15] .

EV adoption has seen rapid growth during the last decade, even during the economic turmoil caused by the COVID-19 pandemic. In fact, worldwide EV registrations increased by 41% in 2020 [16]. The resilience of EV sales to the COVID-19 pandemic can be attributed to many countries strengthening emissions standards and zero-emission vehicle (ZEV) sales mandates, along with the expanding number of available EVs and falling battery costs [16]. By 2040, EVs could represent 12 – 28% of the global fleet, depending on factors such as battery cost reduction and the amount of government subsidies [17].

In British Columbia (BC), close to 95% of electricity comes from renewable sources (hydro, wind, biomass), and about 90% of the province's installed generating capacity is renewable energy [18]. This means that operating and charging an EV in BC has very little associated GHG emissions. It has been predicted that full electrification of the road fleet would reduce total transport and electricity emissions by 38% between 2015 and 2055, relative to business as usual [19].

Compared to other Canadian provinces, BC has been ahead of the curve for EV adoption, and 2020 saw BC with the highest uptake of ZEVs in North America, with ZEV sales averaging 9.4% of new vehicle sales for the year [20]. The greatest adoption of EVs in BC continues to be in major urban centers where public charging is more readily available. In particular, the largest concentrations of EVs in BC can be found in the Metro Vancouver (mainland) and Greater Victoria (on Vancouver Island) areas [21]. Unfortunately, EV adoption has been slower in rural areas of BC, in part due to longer driving distances in these areas and the range anxiety that stems from a lack of available charging infrastructure.

Both the Metro Vancouver and Greater Victoria areas are located in southwestern BC which coincides with the portion of the province that would be most affected by a Cascadia Subduction Zone (CSZ) earthquake. The CSZ is a region extending from northern California to central Vancouver Island, where the Juan De Fuca, Explorer, and Gorda plates are driven beneath the North American plate in a subduction process [22]. The subduction zone is locked and slowly accumulating strain. When the strain is released, a massive “megathrust” earthquake is produced. This type of great subduction zone earthquake is the largest in the world and the only type capable of earthquake magnitudes in excess of 8.5 M [23]. Geologic evidence from buried soils, tsunami deposits, and liquefaction features have provided the understanding that many great earthquakes have occurred in this region over the last several thousand years, with the most recent being a 9.5 M earthquake in 1700 AD [24]. Estimates of the probability of another earthquake of this magnitude occurring over the next 50 years range from 7-15% for an earthquake that affects the entire Pacific Northwest to about 37% for an earthquake that affects southern Oregon and northern California [22] [23] [25].

Earthquakes mainly cause damage through ground shaking and secondary effects, such as liquefaction, landslides, and tsunamis. Liquefaction is a phenomenon where an earthquake increases pore-water pressure in sediment and reduces grain-to-grain contact forces. The sediment then loses strength and behaves as a fluid [24]. Large earthquakes can also cause damage through aftershocks which can bring down already weakened structures. Following the 2010 earthquake in Chile, 19 aftershocks larger than 6.0 M were experienced in the first month [22]. The economic impacts of a Cascadia earthquake would be staggering, with losses estimated at upwards of $70 billion USD for Washington, Oregon, and California [22].

Following a large scale disaster, such as an earthquake, vehicles play crucial roles during the early stages of response and recovery. In the hours or days following a disaster, vehicles are needed for search and rescue efforts and provide assistance by transporting people in medical need, along with critical supplies, such as food, water, and medicine. In medium to long term recovery, vehicles resume their pre-disaster functions as permanent physical and social structures begin to be restored [26].

Through disaster response and recovery, conventionally fueled vehicles rely on the resilience of the fuel infrastructure, and these vehicles are only able to provide disaster relief for as long as fuel supplies last. For example, at normal rates of use, the city of Toronto had less than six days of gasoline storage in 2010, with a majority of that storage distributed in vehicle tanks [27]. In November 2021, the Trans Mountain Pipeline, a crucial source of fuel for BC, was brought offline during extreme flooding in the region. This led to the Province requesting that drivers limit their fuel purchasing to allow an available supply of fuel for emergency services [28]. Natural disasters can impact the fuel infrastructure in a multitude of ways. Loss of power can lead to interruptions at refineries and at the pumps that move oil and gas through pipelines. Pipelines themselves can be damaged by high winds, flooding, and earthquake induced stresses. Additionally, natural disasters can impact fuel supply by blocking or destroying transportation networks such as roadways, bridges, and ports [29]. Interdependencies among infrastructures lead to an increase in the damaging effects of a disaster [30]. Figure 2-1 shows a simple example of some interdependencies between the fuel, power, and transportation infrastructure.

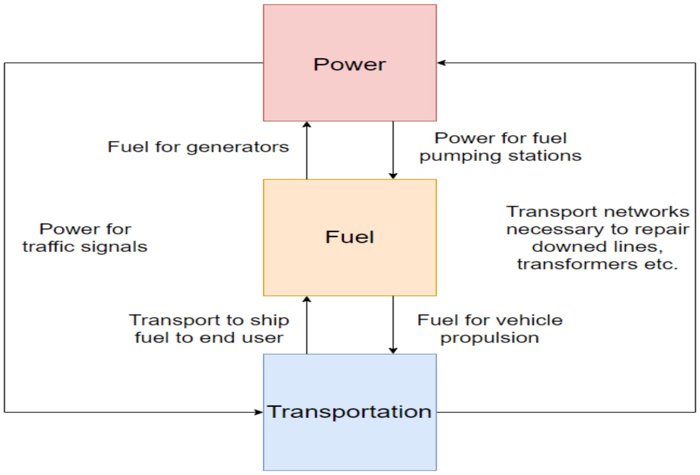


Figure 2-1 - Interdependencies between fuel, power, and transportation infrastructure

Fuel infrastructure resilience can be increased in many ways. Redundancy can be added by increasing the number of fuel sources and the number of modes by which fuel reaches its final destination. During the extreme flooding of BC in November 2021, additional fuel was barged in from Washington state to help maintain supply [31]. The government also looked into sourcing fuel from as far away as Oregon and California [32]. These options may not be available following a CSZ earthquake. Fuel resilience can also be increased by adding more storage to help maintain fuel supply when the source is cut off. Designing cities with a walkable urban form can also help to reduce fuel necessity. Additionally, increasing vehicle efficiency means that the most work possible can be done for a given amount of fuel [33] [34].

While the fuel infrastructure will remain critical for the foreseeable future, increased adoption of EVs will mean that supplying energy for vehicles after a disaster will start to depend more heavily on the resilience of the electrical system. As a CSZ earthquake is a worst-case natural disaster for southwestern BC, it will be the focus of this paper. To study the impacts of this scale of earthquake on the power system, past earthquakes in Chile, Japan, and New Zealand are examined. Lessons from these earthquakes are compiled and applied to the lower mainland of BC and Vancouver Island. These suggestions are compared with how fuel resiliency might be improved in these areas. To the authors' knowledge, no other papers have examined how the BC electrical grid could improve its earthquake resilience to maintain the use of EVs after an earthquake event and how those improvements compare with increasing fuel resilience.

2.2. Past Earthquake Impacts on the Power System

2.2.1. Chile 2010 Earthquake

Chile is located at a point of convergence between the Nazca and South American plates which can generate earthquakes of great magnitude approximately every 100-200 years [35] [36]. On February 27th, 2010, an 8.8 M earthquake struck the central region of Chile, affecting over 8 million people [37]. 521 people were killed, and the economic impact was valued at $30 billion US dollars [38]. The earthquake resulted in a rupture 500 km long by 100 km wide and produced a tsunami that damaged 500 km of coastline. Highways, railroads, ports, and airports all saw damage due to ground shaking and liquefaction [37]. The earthquake caused a blackout that affected 4.5 million people and took days in some areas, and weeks in others, to recover the full supply [38].

The Chilean Central Interconnected System (SIC) provides power to over 93% of the population [39]. Following the earthquake, a blackout took place for a load of 4522 MW. 693 MW of the existing generation plants were affected and removed from service for repairs, while 950 MW of plants that were still being built were put on hold to conduct assessment [40]. In previous years, Chile had seen growing investment in power plants, so the missing plants did risk the general supply of energy [38]. Generation equipment is generally built to high standards which contributed to its good performance during the earthquake.

Chile's transmission network has limited route dispersion and redundancy since it follows the long and narrow layout of the country [37]. The electrical grid in Chile is designed using the N-1 security criteria. This means that the system is designed to be able to withstand the loss of one component without risking the general supply of electricity [41]. After the earthquake, the central part of the country was separated from the south, and a two-island scheme was used for operation [40]. The transmission network was able to provide power within 24 hours and the islands were connected within two days. The fast recovery of the transmission service was attributed to quality infrastructure construction and the fast and competent response of the repair staff. Damage was observed in 500 kV bushings, and 25 failures were reported in pantograph disconnect switches and candlestick live-tank circuit breakers [37] [42]. Emergency plans had counted on the availability of cranes and spare parts which were unavailable in the early days due to the earthquake's disruption of the transportation infrastructure [38].

While restoring supply at the generation and transmission levels was quick, restoring the supply to the end consumer was a longer process. Several parts of the distribution network were severely damaged, and there were coastal regions where the distribution network was completely destroyed by falling houses or washed away by the tsunami [40]. The 220 kV system had been designed to appropriate seismic standards and performed well. In coastal regions, the lower voltage sub-transmission system suffered sporadic damage from high levels of shaking. After two weeks, distribution system service was brought back online [37].

Commercial power outages and loss of reserve power in distributed network facilities led to telecommunication being overwhelmed [37]. Problems with the communication network led to difficulty assessing the damage and safety of the distribution network and reporting points of failure between low level voltages lines and buildings [37] [40]. Private communication systems remained functional as they used repeaters that fed through still operational low voltages lines, batteries, and photovoltaic (PV) panels. While these networks collapsed when the batteries had lost their capacity, they still offered enough use to facilitate the initial energy restoration activities [38].

The distribution companies did not have the resources available for the huge number of repairs and relied heavily on imported human and technical resources from other parts of the country and subsidiaries in neighboring countries [38]. Damage to the distribution network was due to collapsing walls, landslides, and tsunamis and not due to design or construction failures. Investigators in the incident have encouraged Chile to use a decentralized, local focus on distribution dispatch during system recovery to improve operation reaction speed and adapt to local realities [38]. Mobile generators in the 100 to 250 kW range were found to be most effective in supporting recovery in isolated areas and tsunami affected towns. Units in the 1 to 10 kW range were helpful in supplying electricity to critical loads such as hospitals, firehalls, gas stations, and communication and antennas. Unfortunately, fuel supplies were extremely limited due to the behavior of the population, damaged roads, and fallen bridges. Emergency trucks were still able to be refueled by using the army’s strategic fuel reserves [38].

2.2.2. Japan 2011 Earthquake

On March 11th, 2011, a large earthquake occurred off the coast of Tohoku, Japan. The earthquake was 9.0 M, caused intense shaking for 120 – 190 s, and triggered a tsunami that reached heights of 9.3 m along the coastline of the Fukushima prefecture [43]. The earthquake resulted 15,984 confirmed deaths, with more than 2,000 people unaccounted for, and caused an estimated $15 billion (US) worth of damage [44]. Roughly 92.4% of the deaths were attributed to the tsunami which inundated over 400 km^2 of land [45] [46]. Most of the earthquake damage was in the Tohuku region, served by the Tohuko Electric Power Company (ToPo), and the northern part of the Kanto region, served by the Tokyo Electric Power Company (TEPCO). The earthquake interrupted electricity for 8.7 million customers [43]. After two days, 1.5 million were still without power, and after three days, 300,000 remained without electricity [44].

14,000 MW of generation plants were impacted, mainly by the tsunami and some shaking damage [47]. Significant damage was caused to thermal power stations. Three thermal stations (generation capacity of 3.4 GW) were flooded by the tsunami and required one to two years to fully recover [43]. Renewable energy generation capacity generally performed well, and no major damage was reported on wind farms, both inland and off-shore. PV capacity outside of the affected region was undamaged but was unavailable due to grid-tied inverters that disconnected during the outage. There was some landslide damage to penstocks and headraces at small hydroelectric power facilities [47].

In February 2011, nuclear power supplied roughly 31% of Japan’s electricity. It was the country’s baseload electricity source and represented 40% of TEPCO’s output [48]. The greatest damage inflicted by the earthquake took place at the Fukushima Daiichi Nuclear Power Station. The plant had a total generation capacity of 4.7 GW and consisted of six reactors, three of which were in operation when the earthquake struck [43]. The earthquake caused the loss of the plant’s external power supply, and, while the emergency generators started successfully, they were located underground and were flooded by the tsunami [49]. The loss of power led to core melt in reactors 1, 2, and 3, releasing a massive amount of radioactive material. Within a few days, hydrogen had leaked from the reactor pressure vessels into the building and caused the explosion of reactors 1, 3, and 4 [49]. A fatal flaw in the design of the plant was the 5.7 m height of the tsunami wall. A historical study had revealed that a tsunami much larger than 5.7 m had occurred around 869 AD, and a recommendation was made in 2006 to increase the height of the wall but was ignored [49]. Due to their proximity to the line from the Fukushima plant, TEPCO and ToPo were greatly affected by the earthquake, and the large scale outage was caused in part by the imbalance between the electricity supply and load levels [50].

High voltage transmission lines saw damage from shaking and floating debris and high voltage substations were damaged by shaking [47]. 43 154/500 kV transformers were damaged from shaking and 23 were damaged by the tsunami [51]. For more than two decades before the disaster, Japanese power utilities had been installing high voltage substations that met seismic qualification guidelines. Quite a number of components at these substations still failed which was likely caused by older, non-qualified equipment encountering higher than assumed ground motions [47].

The tsunami caused some damage to medium voltage substations (66 kV) and extreme damage to the low voltage distribution system [47]. It was noted that an important substation in Hachinohe City stayed intact due to being elevated above tsunami height [43]. Some inland substations suffered short circuits and ground faults from seismic damage. Substations also saw damage to circuit breakers and disconnectors as well as oil leaking from transformer bushings [43]. Coastal areas served by ToPo saw tsunami damage to 24,000 distribution poles and more than 7000 pole-mounted transformers [51]. End users experienced building damage to lighting systems, power receiving systems, electrical panels, and cables [43].

Following the earthquake, TEPCO's electrical capacity decreased from 52 million kW to 31 million kW [48]. To combat the power shortage, each electric power company took measures to restore their older fossil fuel-based generation facilities. This led to thermal power accounting for 90% of ToPo and TEPCO's generating capacity [50]. The disaster also caused the operation of many nuclear power plants to be postponed, dropping nuclear plant operation to 15% by the end of 2011 [50]. To continue meeting customer demand after the earthquake, TEPCO implemented rolling blackouts, allowing groups of two to three million customers to receive power for a three-hour window every 24 hours. TEPCO and ToPo both targeted reductions in customer power use by 15% and achieved this by having large factories shifting operation to off-peak hours and installing onsite generation, the commercial sector reducing the use of lighting and air conditioning, and households reducing consumption through any means possible [43].

Japan uses mainly above ground low voltage lines and relatively few buried high voltage or distribution power lines. This design style helped to minimize liquefaction damage to buried power lines [47]. Mobile transformers were an effective measure to quickly restore power to small substations that were damaged [47]. Following the earthquake, a review of power system damage determined that the electrical system policies implemented after the Kobe earthquake were mostly appropriate. As complete tsunami protection would be challenging to achieve, Japan was encouraged to add more grid redundancy to ensure fast restoration times [43]. A study by the American Society of

Civil Engineers (ASCE) noted that distributed generation resources could reduce the risk associated with extensive power outages after a disaster [21]. The earthquake also showcased the role EVs could play in disasters when 65 Nissan Leafs were made available to local authorities in Sendai to deliver goods and medical supplies while the fuel infrastructure continued to be unavailable [52].

Analysis of the earthquake brought attention to the exceptional performance of microgrids in the aftermath. The Sendai microgrid at the Tohoku Fukushi University in Sendai was developed by NTT Facilities and consists of several distributed energy resources (DERs). Under normal conditions, the microgrid is connected to the ToPo grid and can be disconnected in times of power outage. While the gas engines initially stopped function due to abnormal voltage detection, the PV and battery storage systems remained able to supply critical loads during the outage. The following day, the gas engines were able to be restarted and provided power to important loads until full service was returned [43]. Another microgrid is used to provide energy for Japan’s Roppongi Hills complex in central Tokyo which is a complex of offices, restaurants, and residential space. The microgrid consists of natural gas and steam turbine generators, absorption chillers, steam boilers, and exhaust heat boilers. The system was able to meet all energy demands of the complex after the earthquake and was even able to provide excess electricity to TEPCO [43].

2.2.3. New Zealand 2011 Earthquake

The South Island of New Zealand is located at a zone of convergence between the Pacific and Australian tectonic plates which generate subduction earthquakes at an interval of 200 – 300 years [53]. On September 4th, 2010, a 7.1 M earthquake occurred near the Canterbury region of New Zealand. Due to its distance from urban areas, the earthquake only injured approximately 100 people and caused no fatalities. This earthquake initiated an aftershock sequence which led to a 6.3 M earthquake beneath Christchurch, New Zealand on February 22nd, 2011 [53]. This earthquake was substantially more damaging due to extreme ground shaking, with recorded accelerations of up to 2.2 g, and resulted in 185 fatalities and 7,171 people injured [53]. Although it was relatively small in magnitude, the position of the epicentre, depth, acceleration experienced, and ground conditions combined to create an extremely devastating event [54]. The repair cost of the earthquake sequence was estimated at around $27 billion US dollars [55].

The earthquake caused significant changes to the environment through liquefaction, lateral spreading near waterways, land level changes, and landslides. Liquefaction caused large amounts of damage to the built environment of Christchurch, with much of the damage experienced by unreinforced masonry buildings [53]. The earthquake left 80% of the Christchurch area without power, amounting to an outage of 629 million customer-minutes [38]. The initial effects on the power grid were primarily due to liquefaction, even though strong ground shaking was observed. Although landslides and rock falls occurred, they were primarily in regions without dense power infrastructure deployment [56]. It took 10 days to get 90% of the power back on [54]. As electric power is generated south of Christchurch and was not in the area affected by the Canterbury earthquake sequence, the earthquakes had no impact on power generation. The event caused a temporary increase in the South Island’s power grid frequency which was dealt with by transferring additional power to the North Island.

The electric power system in Christchurch is served by Transpower and Orion. Transpower operates the country-wide transmission system, and Orion is the local power distribution company [57]. The impacts of both Canterbury earthquakes on the transmission grid were negligible. The Christchurch earthquake caused power to the Christchurch City feeders and substations to be unavailable for 4.5 hours to facilitate safety checks and minor repairs. Following the safety checks, the supply at the grid exit points was restored to full capacity and N-1 security, excluding the Bromley substation which had supply restored to an N security level [57]. Damage at the Bromley substation was due to liquefaction and was inflicted on a 220 kV capacitor voltage transformer and two 66 kV transformer bushings. The minimal damage to the transmission grid can be credited to the implementation of lessons learned after the 1987 Edgecrumbe earthquake which demonstrated the need to seismically restrain heavier equipment on substations [57]. Transpower’s equipment for 220 kV lines were also well installed to IEEE 693 (high zone) standards and were well anchored [56].

While most of Transpower’s power lines are overhead, Orion’s lines are mostly buried underground. The difference in performance between the transmission and distribution networks can be attributed to buried infrastructure being more vulnerable to the effects of liquefaction [56]. 4 of 314 substations were severely damaged: one due to liquefaction, one from shaking, one from a boulder, and one from its infill wall failing [54]. The lack of damage to the above ground distribution network was credited to work Orion had performed in the previous decade, such as the reinforcement of unreinforced masonry substation buildings [56]. Orion was able to restore power to 50% of households on the day of the event, 75% after two days, 90% within ten days, and 98% after two weeks [57].

Earthquake liquefaction led to damage of 50% of the 66 kV and 10% of the 11 kV buried cables which led to widespread power outage [58]. In the 66 kV lines, the cables that were damaged beyond repair were oil-filled. Oil-filled cables in the run from Bromley GXP to the New Brighton and Dallington substations were deemed unrepairable and replaced by temporary 66 kV overhead lines [54]. A total of more than 1,000 faults were identified in the 11 kV cables and occurred in either aluminum or copper core cables [57]. 66 and 11 kV cable failures generally occurred in places that experienced substantial permanent ground displacement (5 cm to 50 cm) [56]. A large amount of the damage occurred in the PILCA (paper-insulated, lead-covered, armoured) 11 kV cables due to joints pulling apart.

The successful performance of the New Zealand infrastructure came from a combination of risk planning for likely earthquake events, seismic strengthening of the substations, improvement to key bridge approaches, and improvements in design standards [54]. After the mid-1990s, Orion contributed over $6 million on seismic protection work and a further $35 million to build resilience into their network. It is likely that Orion's $70 million earthquake repair costs would have more than doubled without this work [57]. Following the earthquake, a long-term recommendation was made for Orion and other power utilities to re-assess the seismic weakness of buried power cables. Use of these cables could be mitigated by using overhead transmission and distribution lines through liquefaction zones [56].

The findings on the impacts on the power system from past earthquakes are summarized in the following section of this paper.

2.3. Discussion

2.3.1. Lessons Learned from Past Earthquakes

Table 2-1 summarizes the fundamental information about each earthquake and what factors contributed to failure or slow recovery for generation, transmission, distribution, and supporting services.

Table 2-1 - Fundamental information and factors in failure or slow recovery for Chile, Japan, and New Zealand earthquakes

Earthquake Location and Year	**Chile (2010)**	**Japan (2011)**	**New Zealand (2011)**
Earthquake Magnitude	8.8 M	9.0 M	7.1 M (Sept. 4th, 2010) 6.3 M (Feb. 22nd, 2011)
Tsunami	Yes – damaged 500 km of coastline	Yes – reached heights of 9.3 M along Fukushima prefecture coastline	No
Extent and Duration of Power Outage	Blackout for 4.5 million people with full service returned after two weeks	Electricity interrupted for 8.7 million customers, only 300,000 without electricity after three days	80% of the Christchurch area lost power (equating to 629 million customer-minutes), two weeks to restore 98% of power
Contributors to Failure or Slow Recovery of Generation Capacity	Damage to 693 MW of existing plants, 950 MW of plants that were being built were brought offline to conduct assessments	14,000 MW of plants damaged mainly by tsunami and some shaking, low height of tsunami wall led to catastrophic failure at Fukushima plant	N/A, as earthquake did not impact power generation
Contributors to Failure or Slow Recovery of Transmission System	Some damage to components, cranes and spare parts were unavailable in early days due to transport infrastructure damage	Shaking and floating debris damaged high voltage substations, non-qualified substations likely failed from higher than assumed ground motions	Christchurch City feeders and substations unavailable for 4.5 hours to conduct safety checks and repairs, some liquefaction damage to 220 kV transformer

Contributors to Failure or Slow Recovery of Distribution System	Distribution network in coastal regions was destroyed by tsunami and falling houses, resources were unavailable for the huge number of repairs	Tsunami caused some damage to 66 kV substations and extreme damage to the low voltage system, coastal regions saw damage to 24,000 distribution poles and 7,000 pole-mounted transformers	4 of 314 substations damaged from liquefaction, shaking, and being crushed, incredible liquefaction damage to 50% of the 66 kV and 10 % of the 11 kV buried cables which resulted in the widespread outage
Contributors to Failure or Slow Recovery of Supporting Services or Infrastructure	Telecommunication was overwhelmed which led to difficulty assessing and reporting the damage to the distribution network, fuel supplies were extremely limited	Earthquakes greater than 8.0 M were found to break down early warning systems, tsunami risk had also been underestimated [59]	Orion head office administration building and control center suffered substantial damage and were unusable, a standby control site was available [54]

In Table 2-2, information is gathered for factors that made each country resilient to earthquake induced failures or enabled a quick recovery.

Table 2-2 - Factors in failure resilience or quick recovery for Chile, Japan, and New Zealand earthquakes

Earthquake Location and Year	**Chile (2010)**	**Japan (2011)**	**New Zealand (2011)**
Contributors to Failure Resilience or Quick Recovery of Generation Capacity	Substantial power plant investment in previous years meant that missing plants did not risk general supply of electricity	Older fossil fuel plants were brought back online to combat power shortage, customer demand was met by utilizing rolling blackouts and targeting reductions in customer power use	Power generation was not interrupted due to location outside of the zone of earthquake impact, temporary increase in power grid frequency was dealt with by transferring power from the South to the North Island
Contributors to Failure Resilience or Quick Recovery of Transmission System	N-1 design criteria meant system was able to withstand component loss, ability to island different grid portions enabled quick recovery	Japan had installed high voltage substations that met seismic qualifications for previous two decades	Heavier equipment was seismically restrained on substations, 220 kV lines were well installed to IEEE 693 High Zone standards

Contributors to Failure Resilience or Quick Recovery of Distribution System	Imported human and technical resources to aid recovery, 100-250 kW generators for recovery in isolated areas, 1-10 kW generators for supplying power to hospitals, firehalls, gas stations	Elevating an important substation above tsunami height prevented damage, minimal buried components minimized liquefaction damage	Orion had made improvements to the above ground distribution network, including reinforcing masonry buildings, temporary overhead 66 kV lines replaced damaged buried cables
Contributors to Failure Resilience or Quick Recovery of Supporting Services or Infrastructure	Private communication stations remained functional due to using repeaters, low voltage lines, batteries, and PV panels that were still operable	Due to power being available before conventional fuel, EVs could be used to deliver goods and medical supplies, microgrids were found to perform exceptionally well in the aftermath	Key bridge approaches were improved, previous planning for a standby control site allowed Orion to continue managing the system after the earthquake

Considering the strengths and weaknesses in the performance of each country's power system, a list of lessons learned for increasing earthquake resilience are compiled in Table 2-3.

Table 2-3 - Lessons learned to increase power system earthquake resilience

Lessons Learned to Increase Power System Earthquake Resilience
Available excess generation capacity enables quick recovery
Electrical grid design with N-1 criteria prevents cascading failure
Use grid design that allows the ability to island different portions of electrical grid
Have available resources to perform grid repairs and plan for aid agreements with surrounding areas
Where possible, move distribution equipment away from seismically vulnerable buildings, landslide areas, and coastal regions in tsunami zones
Reinforce unreinforced masonry buildings that contain, or could collapse on, grid components

If transformers cannot be moved out of tsunami inundation areas, they can be elevated to above flooding height
Mobile generators and transformers are effective for restoring power in isolated areas or for critical services, such as hospitals
Telecommunication systems are crucial after an earthquake but can be overwhelmed or unavailable due to lack of power, better to use private forms of communication
Fuel supply is often scarce following an earthquake
All three countries had improved seismic resilience and were able to restore power to the vast majority of consumers within a week to two weeks
Utilizing above ground components can prevent liquefaction damage – if buried components must be used, locate them out of liquefaction zones where possible
There is risk involved in locating generation capacity in tsunami zones or locating too much generation capacity in a single location that could sustain damage – opt instead for a distributed layout
Rolling blackouts paired with customers reducing demand can be an effective recovery tool if available generation capacity will not meet demand
Microgrids can remain functional during grid outages and allow power to still be supplied to critical loads
EVs can provide mobile energy storage in the aftermath of an earthquake
Seismic strengthening of existing substations is effective at improving resilience
Building resilience is less costly than repairing or replacing damaged components after an earthquake

2.3.2. Applying Lessons Learned to the Lower Mainland and Vancouver Island

Regional Background

The term “Lower Mainland” is generally used to refer to the area of BC that is west of Hope and south of Whistler, roughly aligning with the regional districts of Metro Vancouver and the Fraser Valley [60]. As of the 2016 Canadian Census, the Lower

Mainland is home to 2.83 million people (approximately 60% of the province’s population) [61].

Located near the boundary of the North American and Juan de Fuca plates, the Lower Mainland can experience shallow crustal, deep intraslab, and megathrust earthquakes. The friction between the plates causes great strain and deformation and ongoing earthquake activity. As earthquakes that occur inland or just offshore are much closer to the populated urban areas, and happen with much greater frequency than megathrust earthquakes, they may be the greatest earthquake hazard for the Lower Mainland [62].

Vancouver Island (VI) is located in the northeastern Pacific Ocean. The island trends northwest-southeast and is located about 50 km off the southwest coast of mainland BC. VI is separated from the Lower Mainland by the Salish Sea. The island extends 460 km from northwest to southeast, and is up to 80 km in width [63]. In 2016, VI was home to a population of close to 800,000, with about half of that number living in the metropolitan area of Greater Victoria [64].

VI is located where the eastward moving Juan De Fuca plate is moving beneath the western portion of the North American plate in a subduction process. This tectonic environment predisposes VI to earthquakes of the shallow crustal, deeper sub-crustal, and great inter-plate (subduction zone) variety [63].

Electrical Grid

The British Columbia Hydro and Power Authority (BC Hydro) is the main electricity distributor in the province of BC and generates 43,000 GWh of electricity annually to supply more than 1.9 million residential, commercial, and industrial customers [65]. BC Hydro predicts roughly 350,000 EVs will be on BC’s roads by 2030. This increase is estimated to add an additional 1,050 GWh of electricity load per year [66]. BC Hydro operates 13 hydroelectric facilities in the Lower Mainland and a thermal plant that was decommissioned in 2016. These Lower Mainland facilities represent 1,104 MW of capacity (9.3% of BC Hydro’s total capacity) and generate an average of 4,700 GWh a year [67].

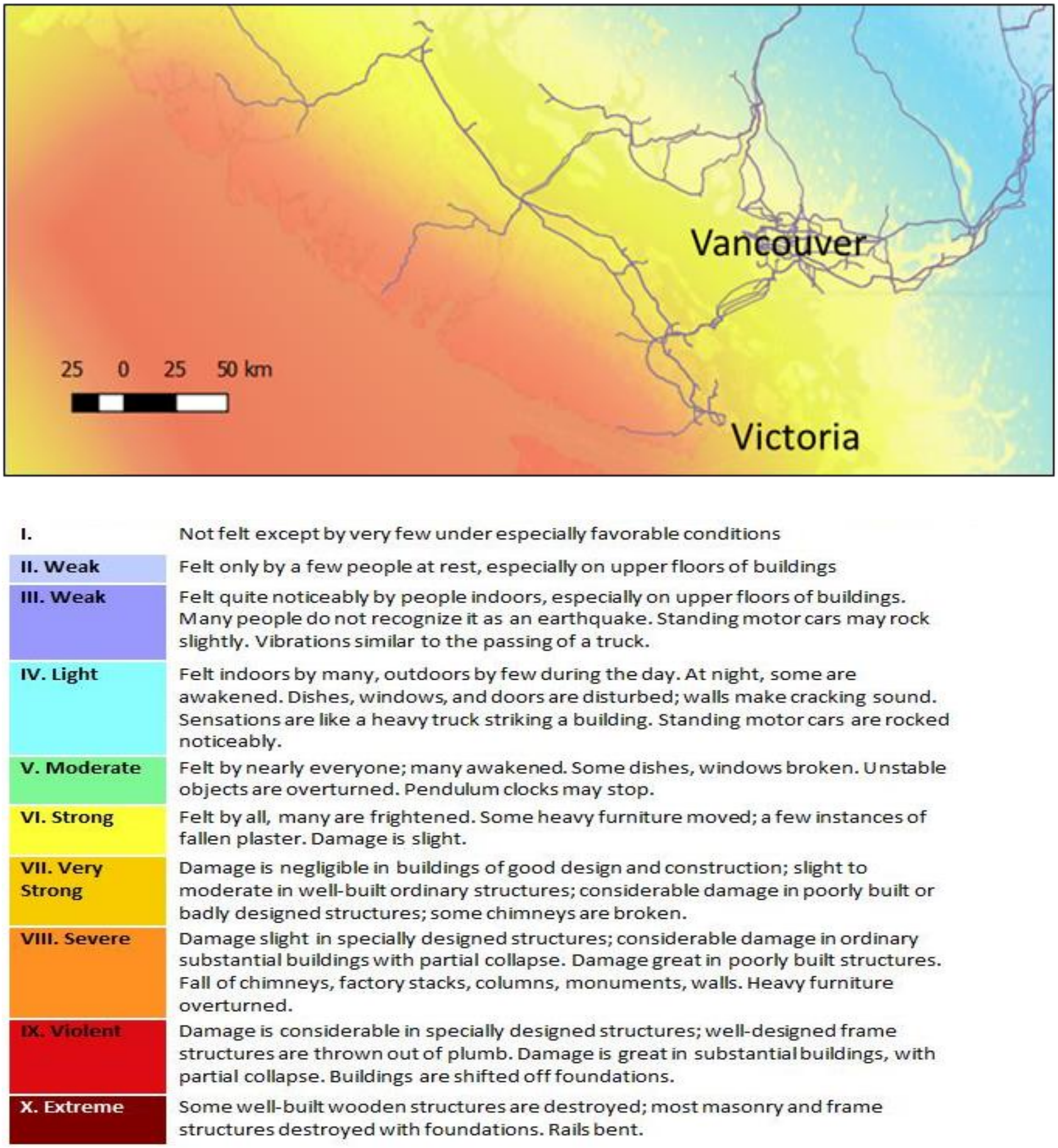
The Lower Mainland receives the bulk of its power through 500 kV transmission lines from large hydroelectric systems in the northeastern and southeastern portions of the province. These dam systems are located far enough away from the CSZ to remain unharmed by a subduction zone earthquake. It is also likely that the 500 kV transmission network connecting the Lower Mainland to these systems would be relatively unscathed by a large earthquake. Damage at the distribution level would be the main concern for the region, particularly the high voltage substations. As the region has substantial redundancy built into the network, an earthquake event may only cause outages that last for a couple weeks. Fires, a secondary earthquake effect, could be a concern for the densely populated urban areas of the Lower Mainland.

On VI, BC Hydro runs four hydroelectric systems, with six generating stations and a total capacity of 471 MW. These facilities are supported by transmission infrastructure and additional facilities on the mainland and represent 4% of BC Hydro’s total capacity [68].

BC Hydro’s on-island generating facilities are only able to meet about 20% of VI’s total demand, with about 80% of the electricity coming from the mainland through underwater cables [69]. Similar to the Lower Mainland, the bulk of this electricity would have its origins in the large hydroelectric facilities in the northeast and southeast regions of the province [70]. VI is also home to several independent power producers (IPPs). These include biogas facilities, a wind farm, run of river hydro projects, a natural gas generation station (contract agreement with BC Hydro ends April 2022 [71]), and a solar energy project [70].

VI’s power grid is connected to the mainland by AC and DC submarine and overhead cables. Two parallel HVAC 525 kV circuits connect the mainland to mid-VI via two submarine and three overhead sections, with a reactor station midway. There is one 138 kV and one 230 kV AC line that connects the mainland to southeast VI via two submarine and three overhead sections. There are also two legacy HVDC links in this region that are considered obsolete and less reliable.

Figure 2-2 uses the Modified Mercalli intensity scale to illustrate the relative earthquake intensity that would be experienced in the region of study. The lines on the figure represent transmission lines.



I.	Not felt except by very few under especially favorable conditions
II. Weak	Felt only by a few people at rest, especially on upper floors of buildings
III. Weak	Felt quite noticeably by people indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck.
IV. Light	Felt indoors by many, outdoors by few during the day. At night, some are awakened. Dishes, windows, and doors are disturbed; walls make cracking sound. Sensations are like a heavy truck striking a building. Standing motor cars are rocked noticeably.
V. Moderate	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects are overturned. Pendulum clocks may stop.
VI. Strong	Felt by all, many are frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage is slight.
VII. Very Strong	Damage is negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys are broken.
VIII. Severe	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX. Violent	Damage is considerable in specially designed structures; well-designed frame structures are thrown out of plumb. Damage is great in substantial buildings, with partial collapse. Buildings are shifted off foundations.
X. Extreme	Some well-built wooden structures are destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

Figure 2-2 - 9.0 M Cascadia Subduction Zone earthquake scenario from the Geologic Survey of Canada, overlaid using the Modified Mercalli intensity scale on the region of study and transmission lines

Damage from a CSZ event could be severe for the power system [72]. Damage to the mid-Island or southern lines connecting with the mainland would lead to outages on VI, and the extent of damage would determine the outage length. The length of the outage could extend anywhere from days to months, depending on the severity of the earthquake. BC Hydro's modelling of CSZ events suggest that, in the worst case, large-scale outages of weeks to months are possible with partial restoration following that. After the event, the timeline could extend to years to get back to full functionality. All of the generation plants on VI can run disconnected from the mainland but would not be able to serve the full load. A partial load would be created by temporarily cutting service to industrial customers and by utilizing rolling blackouts (blackouts could range from 1 hour on/off to 12 hours or more). It is also likely that the load will be reduced due to damage in the distribution system and would lower demand. It was noted that seismic design is not used on system elements past the substations since those portions are commodity designed.

BC Hydro is in the process of upgrading dams and water passage systems to align with the necessary seismic standards. If there were to be a major earthquake (over 1 in 1000-year event) before the upgrades are completed, the dams on VI would be at risk of failure. The John Hart dam provides 50% of power generation on the island and has received seismic upgrading. Two upstream upgrades for the John Hart are to be completed by the 2030s, along with a power tunnel replacing the aging penstocks. As it stands, power generation from BC Hydro's VI facilities would not be dependable following an especially damaging CSZ event.

BC Hydro is currently looking into replacing one of the links connecting VI to the mainland. The older portion of the southern line (138 kV) cable has the highest risk of failure and, as of 2021, is not in the ten-year plan for replacement. The newer (2010/2011) 230 kV line is engineered for a 1 in 2475 earthquake event and is built on deep piles or caissons where it crosses liquefaction zones. The mid-VI crossing lines are engineered for a 1 in 475 event and are less at risk to submarine hazards, but they are oil-filled and could be impacted by earthquake damage to their pumping stations which would take weeks to months to fix. In fact, during the June 2021 heatwave, one of the oil-filled cables was found to be bulging and leaking oil which resulted in it being temporarily removed from service [73]. It is likely that the damage to the cable was caused by a combination of the heat and the increased electrical load from air conditioning on VI. A full replacement of any of these cables would take years but BC Hydro does maintain enough back up cable stock to perform splices or section replacements. The overhead sections of the 500 kV lines are at risk from landslides, and the reactor station connecting the 500 kV lines could be at risk from peak ground acceleration (PGA) or prolonged shaking. Damages at the reactor station could also result in fires.

Options for Increasing the Resilience of the Electric Grid

A CSZ event could cause outages in the range of weeks for the Lower Mainland and months for VI. Both regions can draw from the lessons learned in Chile, Japan, and New Zealand, and apply them to increase the earthquake resilience of the electrical grid. The goal would be to make changes that would hopefully reduce overall outage time and allow EVs to remain usable following the disaster.

While adding more generation capacity to the Lower Mainland would increase resilience for the region, it is unlikely that a CSZ event would sever the Lower Mainland from the transmission lines connecting it and the large dam systems in the province. VI, on the other hand, does not have enough generation capacity to meet its peak demand, assuming that the links connecting VI and the Lower Mainland were damaged. Adding more generation capacity to VI would allow faster recovery in the aftermath of an earthquake, assuming that it has a high seismic design. This new generation should be added in a distributed fashion as much possible. Distributed generation means that the technologies used for generating electricity are placed as close to the end users as possible. This new generation should also be located outside of tsunami zones. The Greater Victoria area is population dense but has relatively little nearby generating capacity. Building new generating capacity will mean that it is constructed with modern seismic standards and will be able to help meet the increasing electrical load expected from EVs.

The electrical grid in both regions should be designed with N-1 criteria in mind and be able to island different portions after an earthquake. The grid should be examined thoroughly, and, where possible, vulnerable system elements should be relocated away from seismically unfit buildings (many of the older buildings in downtown Victoria are masonry and about half of those are unreinforced [74]) and landslide areas. VI has areas with substantial tsunami run up potential. In the Greater Victoria area, a CSZ event could cause tsunami heights that range from 3.5 to 8.5 m [75]. Where possible, grid elements should be relocated from these areas or elevated to above flooding height. In both VI and the Lower Mainland, liquefaction maps can be used to determine where buried system elements cross liquefaction zones and whether the system elements could be relocated above ground. Both regions could also take inspiration from New Zealand and conduct a program to seismically reinforce substations and unreinforced masonry buildings.

Establishing microgrids in both regions can help to ensure that power will still be supplied to critical loads during an outage. After a disaster, BC Hydro temporarily disconnects net metering customers, since they are considered a danger until site-checks can be conducted. Microgrids that are established “behind the meter” would still allow generated power to be used after a disaster. Microgrids in the Lower Mainland would hopefully be able to provide power for an outage lasting a week or two. On VI, microgrids would need substantial attached generation capacity and or storage to remain a viable source of energy in an outage lasting for months.

Both regions could also increase earthquake resiliency by planning for the event. The regions should plan to have resources available to perform grid repairs and establish agreements with surrounding areas to provide aid following an earthquake. VI should have an available supply of mobile generators and transformers on hand to aid recovery in more remote areas. Private telecommunication systems should also be established for use during a disaster. To avoid fuel scarcity for generators, the regions should plan to have enough fuel stock on hand to provide for remaining ICE vehicles in fleets and back-up generators. As VI is likely to have marine transport affected by an earthquake, it should plan to have a robust back up supply of fuel.

During the earthquake recovery process, rolling blackouts could be paired with asking customers to reduce demand if available generation cannot meet demand. Available EVs could also be utilized as mobile energy storage and use their battery power to support critical loads.

Table 2-4 collects the options for increasing electrical grid resilience in the Lower Mainland and on VI.

Table 2-4 - Options for increasing electrical grid resilience on the Lower Mainland and Vancouver Island

Location	Both the Lower Mainland and Vancouver Island	Vancouver Island
Actions to Increase Earthquake Resilience of Generation Capacity	Adding more generation capacity would increase the earthquake resilience of both regions but may not be necessary for the Lower Mainland, establishing microgrids can provide electricity generation during a temporary outage	More generation capacity on VI will help to ensure that it could meet the power needs of the area if disconnected from the mainland, new generation capacity should be built to modern seismic standards, use a distributed layout, and be located outside of tsunami zones
Actions to Increase Earthquake Resilience of the Transmission System	Use the N-1 criteria for grid design and provide the ability to island different portions of the grid, relocate vulnerable system elements away from seismically unfit buildings, anchor high voltage substations	Seismic upgrades to the high voltage transmission lines connecting to the mainland will benefit VI as the area is heavily reliant on power from the mainland
Actions to Increase Earthquake Resilience of the Distribution System	Use liquefaction maps to determine where buried system elements cross liquefaction zones and relocate elements above ground (if possible), grid elements in tsunami zones should be relocated or elevated above flooding height, plan to have resources available for grid repairs	Access to mobile generators and transformers will aid recovery in remote areas, unreinforced masonry buildings in Victoria should be reinforced if there is a possibility that they may collapse on grid components
Supporting Services that Can Increase General Earthquake Resilience	Plan for the event and establish aid agreements with surrounding areas, establish private communication systems, stockpile enough fuel to provide for back-up generators, utilize EVs for mobile energy storage	It is crucial for VI to plan on how much fuel it would require for back-up generators as it will likely be cut off from fuel supply in the aftermath of an earthquake

Fuel Infrastructure

BC receives crude and refined oil from Alberta, eastern Canada, and Washington State. Fuel arrives in the Lower Mainland by the Trans Mountain Pipeline (TMPL), marine tankers, rail, and truck. These modes of transport bring fuel to several large storage and distribution facilities in the region. Almost all fuel imports arrive refined, but some crude oil is refined locally at Chevron’s Burnaby refinery. A third of BC’s transportation fuel is produced at Chevron Burnaby which receives the majority of its crude oil by pipeline, with supplemental deliveries by rail and truck. More than 50% of Vancouver's fuel demand comes via the TMPL and almost 30% of the TMPL's daily oil arrivals are transported from the Westridge Terminal to California, the Gulf Coast, and China. Supplementary fuel supply for the region is imported from Washington State refineries. Marine fuel transport arrives in the Port Metro Vancouver or one of the four petroleum terminals within it. Transportation from distribution centers to end-users is done through trucks, pipelines, storage tanks, and barges. The airport receives its fuel via a 41 km jet fuel pipeline that connects the airport to Chevron Burnaby and the Westridge Marine Terminal [34].

The majority of fuel that arrives on VI is delivered via the TMPL to the Lower Mainland and then by marine transport to VI. Fuel is transported from the Lower Mainland by barge or marine vessel across the Strait of Georgia to various ports along the east coast of VI. Some ports receive fuel every other week, while others see deliveries as frequently as two to three times per week. VI has tank farms near Nanaimo, Cobble Hill, and Chemainus which receive fuel through pipelines from nearby marine terminals. After arriving at a port, fuel can be pumped directly into storage where trucks collect and deliver fuel to depots and end-users. Fuel can also be transported in the "roll-on roll-off" fashion, where trucks drop their load on to a departing marine vessel and the load is picked up by another truck after the vessel docks. Additionally, some of the fuel transport on VI is done via rail, and the region also receives supplementary fuel from Washington State.

Options for Increasing the Resilience of the Fuel Infrastructure

It bears mention that, as VI gets much of its fuel from the Lower Mainland, VI is directly dependent on the resilience of the Lower Mainland fuel infrastructure as well as depending heavily on marine transport and infrastructure. During the November 2021 flooding, additional fuel was received from the US via barges [31].

The federal government should ensure that the sections of the TMPL that run through potential earthquake damaged areas are built to current seismic standards or are retrofit. TMPL pumping stations should have back up power available to deal with the likely power outage that will follow an earthquake. A study should be conducted to look at locations that receive fuel in the Lower Mainland and how seismically vulnerable they are. Ports in liquefaction areas can improve resiliency through retrofitting or by hardening liquefaction prone soils. The region could also develop an alternate location for a fuel delivery hub that is outside of liquefaction zones [76]. As it is a crucial facility for the region, it should be ensured that the Chevron Burnaby location is seismically robust. Planning should be done with respect to how fuel will be prioritized following an earthquake. There may be temporary measures after an earthquake to stop fuel deliveries to other parts of the world and possibly Vancouver Airport, assuming flights are temporarily grounded.

Since VI depends so heavily on ports to receive fuel, it should be a top priority for the region to study how the current port structures are likely to weather an earthquake event. Other than retrofitting existing ports, VI could add additional port locations or capacity, emergency berth structures, alternate landings with roll-on-roll-off capabilities, floating tank farms, and ships equipped with cranes to transfer cargo to land [34]. A study of the marine transport earthquake resilience of VI found that berth and ramp recovery were the limiting factors in terminal recovery, so it may be wise to focus on increasing the resilience of those elements [77]. As VI receives fuel using a “just in time” model that allows 3 days-worth of “business as usual” fuel at any given time, resiliency can be increased by adding additional fuel storage to the region. VI should also coordinate planning with the Lower Mainland for how fuel will be prioritized after an earthquake and how much of a decrease in supply from the Lower Mainland could be expected. It may be that regions of the US are less affected by the earthquake and are able to supplement fuel deliveries from the Lower Mainland.

At the municipal level, organizations should plan ahead for the amount of fuel they would expect use after a disaster and develop adequate storage capabilities. The planning process would involve looking at the amount of fleet vehicles and back-up generators that would be expected to operate after an earthquake. Looking at fleet composition, an increase in the use of EVs would help to lower the volume of necessary fuel reserves. Also, as new fleet vehicles are purchased, increasing vehicle fuel efficiency will help to optimize the use of fuel reserves. In the case of VI, fleets that utilize hydrogen vehicles should be aware that hydrogen fuel would have some of the same issues with transport as conventional liquid fuels. Municipalities would also be wise to understand what sort of transport routes may be damaged following an earthquake and how that would affect their access to fuel. For example, the highway connecting mid-VI to the Greater Victoria area could be blocked due to the landslides, so the area may be temporarily limited to receiving fuel via ports in the southern portion of VI or by air transport. Access to private communication networks will also help municipalities to coordinate with one another and adopt to the post-disaster realities.

The November 2021 flooding in BC taught several lessons on the importance of fuel infrastructure resilience. During the flood, the population had to be encouraged to ration fuel supplies as damage to critical highways, as well as the TMPL, left the region with a limited access to fuel [78]. To deal with this, fuel was sourced from other areas in the US [32]. In the case of an earthquake, there is little warning time for populations close to the epicenter, so any panic buying of fuel would likely occur in the aftermath as people may attempt to leave the affected area. This behavior could be partially negated if there are temporary “shelter in place” orders following the earthquake. One positive aspect of the flooding was that it helped to generate a new interest in EV adoption as they are more resistant to energy supply issues [79].

2.3.3. Integrated Disaster Resilience Planning for a Changing Transport Sector

As covered in the previous sections on increasing the resilience of the electrical grid and the fuel infrastructure, there are a variety of actions that can be taken to accomplish those goals. There may only be limited resources that can be invested into increasing resilience, so choices may have to be made as to where funds are best prioritized. Currently, there is more interest in investing in low-carbon solutions, so increasing the resilience of the power system may be a more suitable choice. If transport continues to shift towards EVs, investment in electrical grid resilience may offer benefits over a longer timeline than investing in the fuel infrastructure. In resilience planning, it will be crucial to plan around how the transport landscape is expected to change. As the timing of a CSZ earthquake is unknowable, quantitative risk assessments could help to facilitate resilience planning. These sorts of insights can also be applied in regions outside of BC when considering their rates of EV adoption and relative earthquake risk.

Table 2-5 collects actions that can be taken to increase fuel resilience and at what level of responsibility.

Table 2-5 - Actions to increase fuel and electrical grid resilience and their level of responsibility

Level of Responsibility	Actions to Increase Fuel Resilience	Actions to Increase Electrical Grid Resilience
Federal	Retrofit the TMPL (regulated by the Canada Energy Regulator), if necessary, and ensure backup power is available at pumping stations, look at earthquake vulnerability of port authorities and retrofit, harden soils, or add additional docking locations or capacity	BC Hydro may receive funding via the federal government providing grants to provinces to upgrade critical infrastructure
Provincial	Increase the resilience of transport networks in the jurisdictions that are crucial to the transport of liquid fuel	Most actions covered in Table 2-4 would have to be taken by BC Hydro which is provincial crown corporation, funding to increase grid resilience may be provided at the provincial level
Municipal	Look at earthquake vulnerability of crucial transport routes for fuel delivery and upgrade as necessary, plan how much fuel should be stockpiled when considering fleet size and composition	Establishing microgrids will ensure the fleet EVs can still be charged during an outage, plan to have enough fuel stock available for back-up generators, consider using EV fleets as mobile energy storage
Private Companies	Ensure that the Chevron Burnaby location is seismically robust, increase earthquake resilience of privately owned petroleum terminals and consider adding additional storage on Vancouver Island, marine transport companies could also add crane transfer capability to ships to work around damaged port locations	Private companies can take the same actions that were taken at the municipal level but will have to plan for the extra costs associated with providing their own back-up power

2.4. Conclusions and Future Work

In the coming years, EV adoption is predicted to increase, and must do so if provincial and national climate targets are to be met. This increase in the number of EVs will result in a shifting dependence from the fuel infrastructure to the power infrastructure. BC has seen among the highest uptake of EVs in North America, with the greatest adoption of EVs in the southwestern portion of the province. Southwestern BC also aligns with the part of the province that would be most affected by a CSZ earthquake event. Increasing the resilience of the power system in this region will help to maintain the use of EVs following an earthquake.

This paper studied past earthquakes in Chile, Japan, and New Zealand and compiled their successes and failures. The Chile earthquake taught the importance of excess generation capacity, using N-1 grid design criteria, establishing private communication networks, and having spare parts available for repairs. The Japan earthquake showcased how earthquake resilience can be increased by installing seismically qualified high voltage transformers, elevating transformers above tsunami height, implementing rolling blackouts when supply cannot meet demand, and utilizing microgrids to provide power during outages. The Japan earthquake also taught the danger of locating generation capacity in tsunami zones, if it is not built to withstand predicted tsunami heights. The New Zealand earthquake provided lessons on the dangers of utilizing buried cables in liquefaction zones but also taught the value of building resilience into the network via upgrading substations, improving key bridge approaches, and risk planning for earthquake events.

Considering these lessons in the context of southwestern BC, suggestions were made for how the region can increase its power system earthquake resilience. Both the Lower Mainland and VI can benefit from using N-1 grid design criteria, relocating vulnerable equipment from tsunami or landslide zones, utilizing above ground cables through liquefaction zones, establishing microgrids, using private communication systems, and establishing aid agreements with surrounding areas. VI specifically would benefit from increasing generation capacity and having a supply of mobile generators and transformers to aid recovery in more remote areas.

In the case of the fuel infrastructure, the Lower Mainland would benefit from seismically upgrading the TMPL, studying the vulnerability of important ports, ensuring the earthquake resilience of the Chevron Burnaby facility, and planning for how fuel will be prioritized after an earthquake. On VI, the fuel infrastructure resilience can be increased by seismically upgrading marine ports, adding additional port locations or capacity, adding additional storage to the region, and planning for alternate sources of fuel in the event that the Lower Mainland is unable to provide after an earthquake. Municipalities on VI can examine fleet composition and plan for fuel needs after a disaster and what sort of storage that would necessitate.

Looking at vehicle availability after an earthquake, EV adoption will increase or lessen risk depending on a few factors. In the first couple of weeks after an earthquake, if the power system is unavailable, then ICE vehicles may be more reliable. This would depend on whether there is a supply of back-up fuel available, as gas stations would also be unavailable due to a lack of power. If microgrids were available to provide charging for EVs during the temporary outage of the larger grid, then that risk could be mitigated. Taking a longer term perspective, if the grid is brought back online after a couple weeks, then the use of EVs would be more reliable than ICE vehicles as fuel supply issues such as the repair of damaged transport networks would likely continue to persist. On VI, if the earthquake was especially damaging and grid resilience had not been improved, an outage in the range of months would leave EVs unusable for that period, and ICE vehicles would provide a more reliable option if fuel canisters could still be delivered to the area. It is worth noting that a power outage extending into multiple months would likely result in much of the population leaving the area.

This research leaves several avenues open for future work. As mentioned previously, resilience planning for earthquakes could be done by conducting quantitative earthquake risk assessments and considering the changing transport landscape. Further research could be conducted into modelling the impacts of a CSZ earthquake on the crucial elements of the electrical and fuel infrastructure in the region. This research would help to understand what elements are the most vulnerable and which would have the longest repair times. This information could help to provide a focus for specific elements to prioritize for increasing resilience. There is also room for further research into establishing microgrids to provide power during a temporary outage of the larger grid. This could be combined with the concept of EVs donating their battery energy using vehicle-to-building (V2B) technology. A model could be constructed for a fleet of EVs that are charging at a microgrid and then providing disaster relief which would help to understand how a microgrid would have to be sized to provide this functionality during an outage. During periods of time when a disaster has not recently occurred, microgrids can help to offset the cost of electricity, so there could also be an economic analysis done on the payback period for a microgrid established in southwestern BC.

Chapter 3. Using Electric Vehicles to Enhance Power Outage Resilience – An Agent-based Study

This chapter is based on a manuscript that will be submitted to an undecided academic journal. The eventual submitted publication will use the same title as this chapter. The paper was authored by M. Churchill, Dr. J. Monroe, Dr. D. Bristow, and Dr. C Crawford. The model used in the paper was a collaboration between M. Churchill and J. Monroe. J. Monroe created the templates for the EV and microgrid classes and functions as well as the basic skeleton of the model. M. Churchill added detail and parameters to all classes and functions, described how the EVs acted in the body of the model, and created various code to output all relevant state variables of the model agents. M. Churchill was responsible for the background research, literature review, methodology, and the preparation of the manuscript. D. Bristow and C. Crawford were responsible for supervision of the work as well as reviewing and editing the manuscript. J. Monroe also assisted with reviewing and editing the manuscript.

3.1. Introduction

Climate change is expected to increase the frequency of power outages caused by high-impact low-probability events [80] [81]. Between 2000 and 2017, 37% of outages in Europe, and 44% in the United States (U.S.), could be attributed to natural shocks and climate change [82]. The expected increase in the electrification of the transportation, building, and industrial sectors will mean that the effects of power outages will become an even greater concern. Power outages can cause severe disruption to critical infrastructures due to the interdependency between power systems and other infrastructures, such as gas, water supply, telecommunications, public health, and transportation [39] [83]. Outages can result from device failures, system faults, cyber attacks, and natural disasters, such as earthquakes, landslides, flooding, lightning, etc. [84] [85].

There are multiple examples from recent years of the impact of power outages. Between 2003 and 2012, the U.S. had seven years with more than 10 million customers experiencing weather-related power outages [81]. In 2012, Hurricane Sandy caused a power outage of several weeks that affected 7.5 million customers on the east coast of the U.S. [86]. A 2015 cyber attack in Ukraine led to a 6h blackout in Kyiv and the surrounding area, affecting 225,000 customers [87]. In Texas, the February 2021 winter storm outage of the Electric Reliability Council of Texas system resulted in thousands of customers without service for more than two weeks and had an estimated cost of over $195 billion [88] [89].

While large-scale power outages are considered to be low-probability events, they can result in extensive socioeconomic costs [88] [90]. During and following a disaster, sustained power loss can impact the provision of health and emergency services, leading to preventable injury and death [87]. At the household level, it has been noted that outages in the range of 12 to 24 hours are acceptable, but outages extending beyond this will start to see problems arising from the lack of water, heat, and light [39].

Mitigating power outages will require resilience. The National Infrastructure Advisory Council presented a 2010 definition of infrastructure resilience as the ability to mitigate the magnitude and/or duration of low-frequency high-impact events. Resilient infrastructure is able to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event [81] [91] [92]. In reference to the power system, resilience would focus on avoiding power loss and restoring power supply as quickly as possible [93]. A resilient electrical grid can reduce the magnitude and duration of disrupting events by absorbing shocks, managing disruptions, and quickly returning to normal operation [94].

Electric vehicles (EVs) continue to see widespread adoption and are projected to gain a market share of 30% by 2030 [95]. The ability of an EV to transfer energy via vehicle-to-grid (V2G), grid-to-vehicle (G2V), vehicle-to-home (V2H), and vehicle-to-building (V2B) can make it an excellent resource during outages [96]. EVs are capable of providing services at both the system and local levels. Through V2G and G2V, EVs can offer such services as peak flattening, filling load valleys, voltage control, and frequency regulation. Through V2B, EVs can donate their power to serve crucial loads during outages [86] [97]. A 2018 report by the U.S. Department of Energy found that G2V and V2B have the largest possible future impact for EVs to improve grid resilience [94]. EVs can also be used as mobile storage which can be of significant value during times when the power grid is rendered dysfunctional [84]. Following both the Japan March 2011 earthquake and the September 2019 Typhoon Faxai, Nissan loaned their LEAF model EVs to provide disaster relief [98]. Nissan has even proposed an emergency EV concept, based on their Nissan LEAF passenger car, called the RE-LEAF. The RE-LEAF would be able to navigate debris-covered roads, connect 110-230V devices to its battery, and run medical, communications, lighting, and other life-support equipment through its energy management system [82].

Microgrids can provide another resource to increase outage resilience. A microgrid is a small-scale power system, capable of operating in grid-isolated or grid-connected modes, which can provide supplementary power and/or maintain a standard service in a defined area [93]. Microgrids can be composed of distributed energy resources, such as hydro, solar, wind, EVs, energy storage, and others and offer a host of benefits, including improved power quality, reduction in transmission and distribution costs, and improved grid resilience to extreme weather conditions [88]. U.S. private equity firms have committed more than $1 billion for new microgrids since 2018, including a 2021 investment of $500 million [99]. In relation to outages, microgrids can supply energy to a local area when the main grid or branch feeders are unavailable. The ability to generate, store, and control energy locally makes the power network less vulnerable to extreme events and can help avoid the economic, health, safety, and security losses from outages [81] [99].

While the bulk of the past work has focused on using EVs to increase the resilience of the distribution grid, or individual buildings, to a power outage, this paper is novel in its focus on using EVs to increase the resilience of a community to a power outage. This is accomplished by studying the use of a fleet of EVs during the immediate aftermath of a disaster to provide disaster relief by donating power to a shelter, delivering critical supplies and people in medical need, and transporting personnel or performing inspections. To achieve this end, an agent-based model (ABM) is used to observe the behaviour of a fleet of EVs providing these functions. In past EV works, ABMs have been used to study EV market diffusion [100] [101] [102] [103] [104] [105] [106] [107] [108] [109], charging demand and infrastructure [110] [111] [112] [113] [114] [115] [116] [117] [118], V2G [119] [120], and vehicle sharing [121]. In this model, the EVs have access to a microgrid that is still operational during the outage and has available fast chargers for the EVs to recharge at. Scenarios are studied for various combinations of storage size, available fast chargers, and fleet composition. The model provides final outputs for such features as the length of time before energy at the microgrid was depleted, the rate of energy donated to the shelter per day, and the rate of energy used at the microgrid per day by the various vehicle types.

Section 2 of the paper focuses on a literature review of past work related to EV V2B and V2H, V2G and G2V, and other resilience applications. Section 3 of the paper provides the methodology used in designing the ABM which follows the ODD (Overview, Design Concepts, and Details) protocol for describing ABMs, as covered in the 2006, 2010, and 2020 papers by Grimm et al. [122] [123] [124]. In Section 4, the results from the model are compiled and analyzed. Section 5 offers a discussion drawn from the results of the model. Finally, Section 6 provides conclusions drawn from the work, along with recommendations for further work.

3.2. Literature Review

The use of EV V2H or V2B for increasing outage resilience has been studied in previous papers. Gong and Ionel [89] analyzed building resilience for a California household during different outage conditions. The simulation studied the influence of energy use patterns, storage capacity, and available EV energy. It was shown that the target home could sustain off-grid operation for at least 72 hours with a 7.2 kW solar system, 11 kWh battery, and an EV with a battery capacity of 80 kWh. Mehrjerdi and Hemmati [125] studied a home energy management system in a building connected to the electrical grid. The system used V2H, a wind turbine, and a diesel generator which were adjusted optimally to minimize the daily costs of the building. It was shown that the system could operate in the absence of one component and could still supply the demand during off-grid operation. Rahimi and Davoudi [126] focused on the use of hybrid EVs and battery EVs to improve the resilience of residential customers to power outages. Simulations showed that hybrid EVs were best able to serve residential customers during power outages, due their ability to supply power through their internal combustion engines and could accommodate seven- and nine-day outages in summer and winter, respectively. Tian and Talebizadehsardari [127] considered two commercial and residential buildings that used a shared parking station for EVs. The buildings used a shared energy management system to handle disruptions and were focused on minimizing energy costs and maximizing resilience during disasters. It was found that EVs could supply loads under a seven-hour outage condition. Shin and Baldick [128] studied using V2H to provide backup power during an electrical grid outage. A model was optimized around maximizing backup duration and was then extended to multiple homes, EVs, and photovoltaic generation. Simulations showed that the V2H system was capable of providing sufficient backup power to a home.

Many past papers have considered the use of EVs to increase the resilience of the electrical grid. Erenoğlu et al. [80] analyzed the use of EVs for distribution grid restoration during a seismic event. Hazard scenarios were generated with Monte Carlo Simulation, and the unavailability of overhead distribution branches was determined with the fragility curve concept. The optimal restoration strategy was then found based on the location and number of EVs which increased load restoration by between 71.84% and 95.32%. Momen et al. [86] looked at the use of aggregated EVs in public and residential parking, along with microgrids, to improve grid resilience. It was found that the use of EVs in the microgrid formation was able to increase the energy supply to critical loads by 45%. If proper charge scheduling was used before the outage, that energy supply could be increased by up to 70%. Simental et al. [88] proposed the use of EVs for power restoration and the supply of residential networked microgrids experiencing an extreme weather outage. When efficiently operated in networked microgrids, it was shown that EVs could provide energy to support the distribution grid and outages could be avoided by using EVs as a backup power source, allowing more rapid power restoration. Razeghi et al. [96] considered the use of EVs as a resiliency resource during grid outages. It was found that EVs could serve critical loads during an outage as well as help to facilitate grid restoration by providing power to restart utility assets. It was noted that clustered parking lot EVs were more suitable for grid restoration due to less necessary technical upgrades compared with residential EVs starting up local substations. Mohsen et al. [129] looked at the use of plug-in hybrid EVs to enhance self-healing of the power system. EV behaviour was modelled, and the parking lots needed for self-healing during an islanding situation were optimally placed. The simulation showed that EVs could improve system self-healing in islanding mode and enhanced power system reliability. Jamborsalamati et al. [130] used EVs as a part of an autonomous load restoration architecture to enhance feeder-level resilience in active power distribution grids for high-impact low-probability events. Through the strategic deployment of available resources, a 10.59% stress reduction on external service restoration resources was achieved. Abdubannaev et al. [131] examined how EV V2G and G2V capabilities could be used to enhance the resilience of the distribution network. The probability distribution method was used to find the number of available vehicles in a parking lot at a specific time of day, and it was found that almost 9 kW of peak power was available to contribute to the distribution network. Yang et al. [132] considered how EVs, along with emergency generators and truck-mounted storage systems, could be used as grid-support resources during a high-impact low-probability seismic disaster. After simulating a seismic hazard, mixed-integer nonlinear programming was used to co-optimize the routing of the mobile power sources and the distribution system dynamic reconfiguration. The results verified a significant reduction in load outages and an improved power system resilience.

Various other EV resilience applications have been studied, related to microgrids, communication networks, and powering critical infrastructure. Ali et al. [92] covered the use of EVs to provide energy to an islanded microgrid from other grid-connected microgrids. A central energy management system determined which microgrids could provide energy to the islanded microgrid, and EVs were then used as a mobile source of energy to provide for that microgrid. Gouveia et al. [133] looked at the use of EVs to facilitate microgrid restoration. Through V2G, an EV can act as either a load or a generator within a microgrid. Simulations showed that integrating EVs in microgrid restoration had a positive contribution to increasing microgrid resilience by reducing frequency deviations and providing additional voltage balancing. Mase and Gao [134] described the use of EVs to power an ad-hoc communication network in the aftermath of the 2011 Great East Japan Earthquake. Each EV was equipped with an antenna that could extend up to 9m which extended the transmission range and decreased radio wave reflection from the ground. Maharjan et al. [84] proposed the use of EVs to provide power to critical infrastructure during outages by connecting EVs, through wireless communication, with residential buildings and critical infrastructure. When an outage occurs, EVs in the parking lot of the critical building would discharge their energy and nearby EVs would also be directed to the building to discharge, if needed. Zhao et al. [135] modeled an emergency supply of EVs, designed to minimize consumer loss during power failure. The K-means algorithm was used to aggregate randomly dispersed EVs to create an emergency power supply scheme at important clustering centers. Hussain et al. [95] focused on optimizing the size and cost of energy storage at a fast-charging station, while also maintaining the ability of an EV to charge during an outage. The resilience load was determined by a function based on the distance to nearest healthy fast charging station as well as the residual state of charge (SOC) of the EV. Moore et al. [136] suggested the use of second-life EV batteries to provide backup power during a disaster. EV batteries are generally retired at around 80% of their original capacity but can be repurposed to see new use with their remaining capacity. The paper focused on using the >23,000 second-life batteries that could be available in Berlin, after 2040, to provide power for emergency traffic signals for up to 380 hours after a disaster.

3.3. Methods

3.3.1. Overview

As mentioned previously, the framework used to describe the model is derived from the formal ODD protocol for describing ABMs as outlined in previous papers by Grimm et al. [122] [123] [124].

Purpose

The purpose of the model is to predict the energy requirements of a fleet of EVs providing disaster relief during a widespread power outage. Following a damaging event, there are separate post-disaster phases of reaction, response, and recovery [137]. This model covers a period following a large-scale power outage, where the fleet of vehicles is operating in the disaster response phase and providing services to a community. The useful outputs of the model are the time to energy depletion of the microgrid storage battery (i.e., the length of time the system is self-sustaining), the rate of energy donated to a shelter via V2B, and the rate of energy used at a microgrid by the various types of fleet vehicle. An ensemble of inputs and outputs are used to provide an overall stochastic assessment of various system configurations over the range of expected operational circumstances.

Entities, state variables, and scales

The model consists of two types of entities: EVs and the microgrid charging station.

EVs are defined by the state variables given in Table 3-1.

Table 3-1 - Electric vehicle state variables

State Variable	Description	Units
Index	Index number to identify a specific EV.	N/A
Task Assignment	Identifies which disaster relief task the vehicle is assigned to. Task 1 is donating energy to the shelter. Task 2 is performing an intensive drive cycle - transporting medicine, food, water, or people in need. Task 3 is performing a less-intensive drive cycle transporting personnel while stopping for longer periods to perform inspections.	N/A
Location	Tracks whether the EV is located at the microgrid charging station or at its assigned location. Location 1 and 4 refer to the shelter and the microgrid, respectively. Location 2 and 3 are specific to Task 2 and Task 3 EVs and track when those vehicles are away from the microgrid.	N/A
SOC	The current state-of-charge (SOC) of the EV. Refers to how many kWh of energy remain in the battery.	kWh
Battery Capacity	The maximum capacity of the EV battery. EVs are assumed to have a battery capacity that is in the range of 80-100% of a new EV battery capacity, to capture the range of vehicles ages in the fleet.	kWh
Charge Threshold	The value of SOC at which the vehicle will stop performing its task and will return to the microgrid to charge.	kWh
Energy Used	The total amount of energy the EV has used so far when charging at the microgrid.	kWh
Energy Donated	The total amount of energy the EV has donated so far at the shelter. This state variable is only used by EVs assigned to Task 1.	kWh

For this model, the charging station is located at a microgrid that is assumed still functional during the power outage. The microgrid is designed to have a 200 kW solar array as well as three possible sizes of battery storage (250 kWh, 350 kWh, and 450 kWh) and one or two 100 kW fast chargers. The microgrid was assumed to be designed around meeting energy needs during non-disaster times, and a solar array was used for power generation to try and reduce organizational emissions. The charging station is defined by the state variables collected in Table 3-2.

Table 3-2 - Microgrid charging station state variables

State Variable	Description	Units
Location	Identifies where the charging station is located.	N/A
# of EVs in Queue	Tracks the number of EVs that are waiting to charge at the charging station.	N/A
# of EVs at Ports	Tracks the number of EVs that are currently charging at the charging ports.	N/A

It should be noted that the shelter itself is not considered an individual entity as the EVs assigned to the shelter have related state variables that track when they are actively donating at the shelter and the total amount of energy that an EV has donated to that location.

EVs in the model are grouped into populations based on their assigned task. The task assignment of each of EV is prescribed when the EV population is generated at the start of the model. The functions of the different vehicle types were derived from the emergency reaction and response needs during the early stage of disaster recovery. In the immediate aftermath of a disaster, there is a need for search and rescue, food, water, shelter, and medicine [138]. The shelter donation vehicles aid in addressing the need for shelter by donating their battery energy to a designated shelter location 20 km from the microgrid. The delivery of food, water, and medicine is addressed by EVs that perform an intensive driving cycle. EVs that perform a less-intensive driving cycle are assumed to be transporting personnel and doing inspections. Henceforth, shelter energy donation is referred to as Task 1, the intensive drive cycle is referred to as Task 2, and the less-intensive drive cycle is referred to as Task 3. Figure 3-1 has a visual depiction of the model at a specific point in time. At this time, one EV is donating energy to shelter, two EVs are charging at the microgrid, one EV is waiting to charge at the microgrid, and two EVs are driving in different urban and highway environments. It should be noted that the distance between the microgrid and the shelter that the Type 1 EVs travel is defined as a 20 km distance. The model is not concerned with exactly where the Task 2 and 3 EVs are spatially but just tracking when they are away from or at the microgrid.

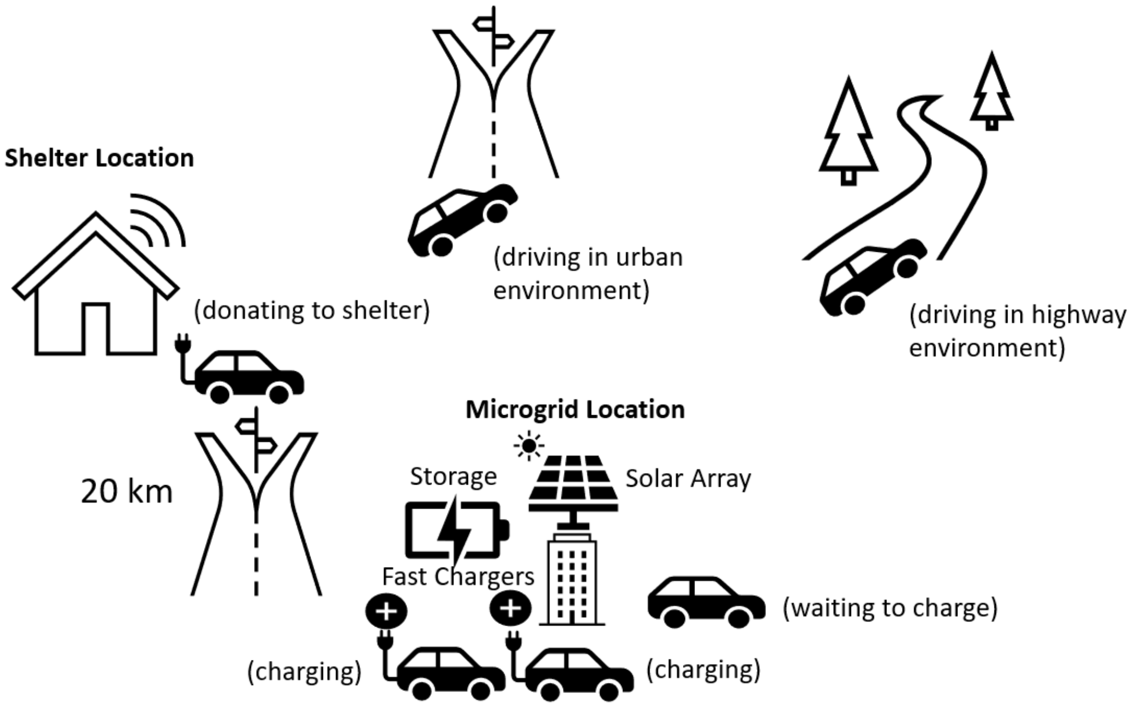


Figure 3-1 - Depiction of the model during a particular instant in time

The model uses a 30-minute time step as appropriate for resolving trip segments and charging events and for computational speed inside the Monte Carlo studies. Individual runs stop when the available energy at the microgrid battery storage has reached 0 kWh or when the model has reached the time horizon of two weeks (336 hours). It is assumed that the EVs provide disaster relief for the full 24 hours of each day. This would be accomplished by municipal employees or volunteers that are working in shifts.

Process overview and scheduling

As mentioned previously, the model uses discrete 30-minute time steps. In the sequence below, bolded names represent submodels that are further defined in section 3.3.3., and state variables are identified with italics. The model process proceeds as follows:

1. EVs **Check Threshold** to determine if their current value of *SOC* is at or below the value of *Charge Threshold* at which they would need to return to the microgrid to charge from their task location.
2. EVs at their task location with an *SOC* above their *Charge Threshold* **Perform Duty**. *SOC* is updated for all EV types and *Energy Donated* is updated for Task 1 EVs.
3. **Check Queue** determines if there are remaining EVs in the microgrid charging station queue waiting to charge from the previous time step.
4. EVs that traveled to the microgrid charging station in the previous time step, and are not yet in the queue, are now added to the queue. *# of EVs in Queue* is updated for the microgrid charging station.
5. EVs that charged at the microgrid charging station during the previous time step, and are waiting to travel to their assigned location, **Move to Assignment** which moves the EV from the microgrid to their task location. *SOC* and *Location* are updated for all EV types.
6. EVs in the microgrid charging station queue **Move from Queue to Charging Ports** (up to the maximum number of ports) and **Charge EVs at Ports** which charges EVs to 80% of their *Battery Capacity*. *SOC* and *Energy Used* are updated for all EV types. *# of EVs in Queue and # of EVs at Ports* are updated for the microgrid charging station.
7. **Remove All EVs from Ports** moves EVs from the microgrid charging station ports to wait to travel back to their task location in the next time step. *# of EVs at Ports* is updated for the microgrid charging station.
8. EVs at their task location with an *SOC* at or below their *Charge Threshold* **Move to Charger** which moves the EVs from their task location to the microgrid charging station. *SOC* and *Location* are updated for all EV types.
9. At the end of the time step, values of *SOC, Energy Donated* (Type 1 EVs only)*,* and *Energy Used* for each EV are written to an output file.

At this point, the time step has ended, and the next time step commences. These steps are executed in order and EV state variables are updated asynchronously.

3.3.2. Design Concepts

This section describes the basic logic and functioning implemented in the model.

Adaption

At each time step, each EV must decide its action based on a set of criteria. EVs that are at their task location will decide whether to continue performing their duty or return to the microgrid to charge based on their current SOC and whether it is at or below the value of charge threshold. If a vehicle has finished charging in the previous time step, and is still at the microgrid location, it will drive to its task assignment location.

At the microgrid charging station, a decision is made for how many EVs are moved to the charging ports based on the number of vehicles waiting in the queue and the amount of available charging ports. If the length of the queue exceeds the amount of available charging ports, the excess vehicles will remain in the queue for the remainder of the time step. When an EV is being charged, the amount of energy provided to the EV is decided based on the difference between 80% of the EV's battery capacity and its current SOC.

Sensing

EVs sense their current SOC and the charge threshold value of SOC at which they will travel back to the microgrid to charge. In real world terms, this would be analogous to the driver viewing a current value of the energy remaining in the battery and returning to the microgrid to charge once the amount of remaining energy has declined to a certain point.

The microgrid charging station senses the current SOC and battery capacity of each EV when charging. The microgrid charging station can also sense the number of EVs in the waiting queue to charge and will not add more EVs from the queue than the available number of charging ports.

Stochasticity

Stochasticity is used in several places in the model.

When the model is initialized, random values are used for the battery capacity of individual EVs, and their starting SOC. At the microgrid, a random value is used for energy in the battery when the simulation starts. The model also draws from a random start time in a week of solar data, and the week of data is assumed to repeat to capture simulations that run in excess of one week.

In the operation of the Type 2 and 3 EVs, there is a certain probability that the EVs are assumed to be driving during an individual time step. The distance traveled when driving is also selected from a specified random range.

Collectives

EVs are grouped into collectives based on their assigned duty. Type 1 EVs are assigned to try and meet the energy needs of the shelter by donating their energy via V2B. Type 2 and Type 3 EVs are also grouped into collectives based on their assigned drive cycles. At the end of model runtime, energy used by each EV type can be aggregated from the energy used by individual EVs.

Observation

For all EVs, data is collected for how the SOC changes with time and how much energy was used at the charging station. For EVs assigned to donate energy to the shelter, the amount of energy donated is also collected. This data is logged at the end of each time step. At the end of model run time, the totals for energy donated at the shelter and energy used at the charging station are then stored for each EV. The data on the energy used at the charging station can be used to illustrate the relative energy needs of the various EV types within the fleet.

Data is also logged on the number of time steps that an EV is waiting to charge at the microgrid, and the number of time steps that there is no EV present at the shelter.

The specific time step when the storage in the microgrid reaches 0 kWh is also stored. This facilitates an understanding of how long the EVs were able to operate for before the microgrid storage would have to be allowed to recharge.

3.3.3. Details

This section is intended to provide more detail of how the model operates. This is accomplished by detailing the exact parameters that are used to initialize a fleet of vehicles, the input files that the model draws upon (in this case, a simulated solar array in Victoria, BC), and the exact layout of the submodels that are used. The section defining the submodels is focused on the EV specific submodels before the microgrid specific submodels. As a reminder, the submodels were referenced in bolded terms in in the previous section on process overview and scheduling and are defined here in the order that they appeared in that section.

Initialization

The available fleet of vehicles is assumed to be composed of six Nissan LEAF Plus EVs which have been tasked by a local municipality to provide disaster relief. Each EV is created with prescribed values for their index, task assignment, and charge threshold. For this model, the EV fleet is assumed to be composed of two of each of the Type 1, 2, and 3 EVs and use a charge threshold of 12 kWh. Battery capacity is assigned based on a range of 80 to 100% of a new Nissan LEAF 62 kWh battery capacity to represent fleet battery degradation. SOC is based on a range from 20 kWh to fully charged. Any range of random values in this model uses uniform random variables (i.e., any value within the range is equally likely to appear).

In the initial population, all EVs are assumed to be initially located away from the microgrid.

A single microgrid charging station is also created with either one or two fast chargers, depending on system design. At the initialization, no EVs are in the charging station waiting queue or actively using the ports.

The disaster event start time is a random variable within the week period of solar data. The week of solar data repeats to capture simulations that run in excess of one week.

Six different simulation scenarios are run for the EV population with three possible microgrid battery sizes (250 kWh, 350 kWh, and 450 kWh) and either one or two 100 kW fast chargers. The initial amount of energy in the microgrid battery is assigned as a random value between 40 to 100% of the available battery storage. In each scenario, 1000 runs of the model are performed. It was observed that 1000 simulations led to statistical convergence of the results.

Input data

This model uses input data for the available solar power at the microgrid previously shown in Figure 3-1. Solar data for July 2020 in Victoria, British Columbia, Canada was sourced from the National Renewable Energy Laboratory System Advisor Model software [139]. The solar array is assumed to have an installed power of 200 kW and the design parameters in Table 3-3.

Table 3-3 - Parameters of 200 kW solar array at microgrid

Solar Array Parameter	**Description or Value**
Tilt type and angle	Fixed tilt, 39.2°
Orientation	South
DC to AC ratio	1.2
Inverter efficiency	96%
Cell type	Monocrystalline

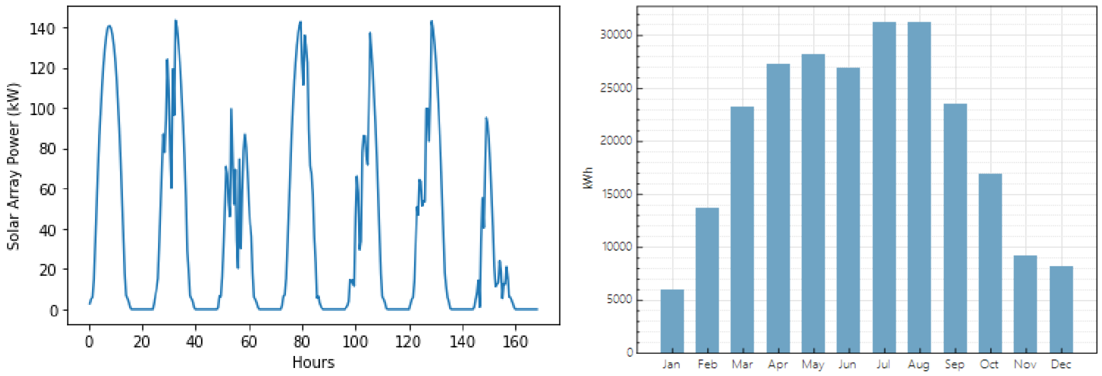


Figure 3-2 - Solar array July 2020 week of power generation (left) and monthly energy generation (right)

It is worth noting that the assumption that the outage occurs in July means that solar conditions are ideal for Victoria, BC during the time of the outage period. As shown in the monthly energy generation in Figure 3-2, an outage occurring in January would require an array that is roughly five times the size to provide the same amount of energy as a 200 kW array in July. The results shown can therefore be roughly scaled down accordingly. Future work could further explore seasonal performance impacts.

Submodels

Electric Vehicle Submodels

Check Threshold: This submodel is used to determine if an EV's value of SOC is at or below the charge threshold value where an EV would return to the microgrid charging station to charge.

Check: SOC <= Charge Threshold

Return: True or False

Perform Duty: Confirms what task an EV is assigned to and adjusts the EV SOC for the amount of energy required for the vehicle to perform its task during the time step.

Check: Task Assignment = 1, 2, or 3

New SOC = Old SOC – Energy Required to Perform Task

For the Task 1 EVs, it has been assumed that the vehicles have access to two bidirectional chargers at the shelter. For this study, the Wallbox Quasar 2 bidirectional charger is used, with a discharge power of 11.5 kW and an efficiency of 97% [140]. It is assumed that the shelter can make use of as much power as the EVs can offer, so both EVs operate at the full discharge power.

Since Task 2 EVs are assumed to be doing a heavier drive cycle, there is a 50% probability that the vehicle will be driving during a given time step. This is intended to capture that the vehicle will not always be traveling and there will be time steps where the vehicle is parked and reloading supplies or performing a task, like providing medical aid. If the vehicle is driving, there is a 50% probability that vehicle will be driving an urban drive cycle and a 50% probability that the vehicle will be driving in an extra urban drive cycle. In the urban drive cycle, the distance is calculated as a random value between 15 and 30 km. In the extra urban drive cycle, the distance is assumed to be a random value between 30 and 50 km. Values for the energy used during these cycles are derived from a paper by Golebiewski and Lisowski [141] that studied the theoretical energy use of the Nissan LEAF EV in various drive cycles. The paper found that the LEAF EV used about 14 kWh/100 km and 12 kWh/100 km in the urban and extra urban drive cycles, respectively.

Task 3 EVs perform a less-intensive amount of driving. Similar assumptions are made for energy use as the Task 2 EVs, with the exception that there is only a 25% probability that the vehicle will travel during a given time step. Like the Task 2 EVs, if the vehicle is driving during a time step, then there is a 50% probability of being in an urban drive cycle and a 50% probability that vehicle travels in an extra urban drive cycle for the same range of random distances as was applied to the Task 2 EVs.

Move to Assignment/Move to Charger: Confirms what task an EV is assigned to and adjusts the EV SOC for the amount of energy required for the EV to travel from the microgrid to the assignment location or from the assignment location to the microgrid.

Check: Task Assignment = 1, 2, or 3

New SOC = Old SOC – Energy Required to Travel to New Location

For Task 1 EVs, the distance between the shelter and the microgrid is assumed to be 20 km, approximated by an urban driving cycle.

For Task 2 and 3 EVs, there is a 50% probability of driving in an urban drive cycle and a 50% probability of driving in an extra urban drive cycle when moving to or from the microgrid charging station location. The same random of range of distances from the previous section are applied here as well.

The EV location state variable is also updated to reflect the new location of the EV at the end of the time step.

Microgrid Charging Station Submodels

Check Queue: Determines if there are EVs waiting to use the microgrid charging station. When several EVs arrive at the microgrid at the same time, priority is given in the order Type 1 > Type 2 > Type 3.

Check: # of EVs in Queue > 0

Return: True or False

Move from Queue to Charging Ports: Determines how many EVs can move from the queue to the charging ports. Excess EVs remains in the queue until the next time step.

Check: # of EVs in Queue <= # of Available Charging Ports

If: # of EVs in Queue <= # of Available Charging Ports, then add all EVs to ports

Else: Add first EVs in queue to ports, up to the maximum number of ports

State variables for tracking the number of EVs in the charging station queue and at the charging ports are updated.

Charge EVs at Ports: Confirms the number of EVs at the charging ports and performs a loop, calculating the difference between each vehicle's battery capacity and SOC and charges the EV for that amount. As the fast charging process slows when charging vehicles in excess of 80% battery capacity, it is assumed that vehicles are charged only to that point. The charging process at the 100 kW fast charger is also assumed to be 94% efficient.

Check: # of EVs at Ports

*Charge Demand = 0.8*Battery Capacity – SOC*

New SOC = Old SOC + Charge Demand

For each EV, the amount of charge demand is added to the energy used state variable, to track the amount of energy that each EV has used at the microgrid charging station. The amount of energy in the microgrid storage is also updated after each charging event.

Remove all EVs from Ports: Performs a loop to create a list of EVs that have finished charging. Performs an additional loop to remove those EVs from the charging ports.

State variable for the number of EVs at the charging ports is updated to zero.

3.4. Results

3.4.1. Simulation Results from 6 EV Population with Shelter Shuttling (2x Type 1, 2x Type 2, 2x Type 3)

The model was run for 1000 simulations of each possible combination of microgrid battery storage (250, 350, and 450 kWh) and fast chargers (one or two 100 kW fast chargers). The aggregate statistical metrics were not found to change with numbers of simulations past 1000 per configuration.

Figure 3-3 shows a histogram of the time to energy depletion in the one or two charger scenarios. The brown region is where 250 and 350 kWh storage overlap, the medium green region is where 350 and 450 kWh storage overlap, and the dark green region is where all storage sizes overlap. One or two fast charger configurations did not significantly affect time to energy depletion for the 250 and 350 kWh storage sizes. Simulations with the 250 kWh storage generally finished within the first 0.5 to 1 day, while simulations with the 350 kWh storage terminated in 1 to 1.5 days. Simulations with the 450 kWh storage lasted about 2 to 4 days on average but had simulations extending to one or two weeks as well. The scenarios with one charging port had a tendency to last longer because they only allowed a single EV to charge in a given time step. The tail-end large frequency of simulations in the 324 to 336 hour bin is due to the condition that the simulation had a maximum runtime horizon of 336 hours. This means that values in that bin represent simulations where the energy depleted in the 324 to 336 hour range, as well as simulations that would have run more than 336 hours.

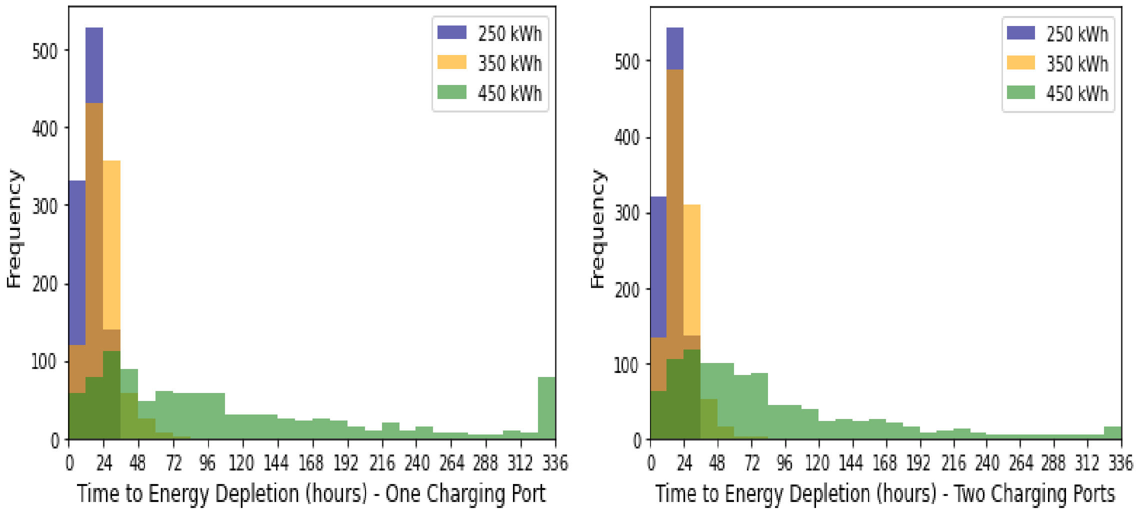


Figure 3-3 - Histogram of time to energy depletion (note that simulations in final bin represent 324-336 hours and 336+ hours)

Figure 3-4 showcases the increased amount of time that EVs waited to charge in the one fast charger scenarios. With one fast charger, most simulations had EVs waiting in the range of 0 to 10 hours, with some waiting up to 60 hours. With two fast chargers, wait times were greatly reduced and the majority fell in the range of 0 to 2 hours. As was shown previously, increasing the storage size also increased the amount of time until the battery was depleted of energy. Simulations that ran longer had more opportunities for multiple EVs to try to charge at the same time, so simulations with a larger storage size would have more time steps with EVs waiting to charge.

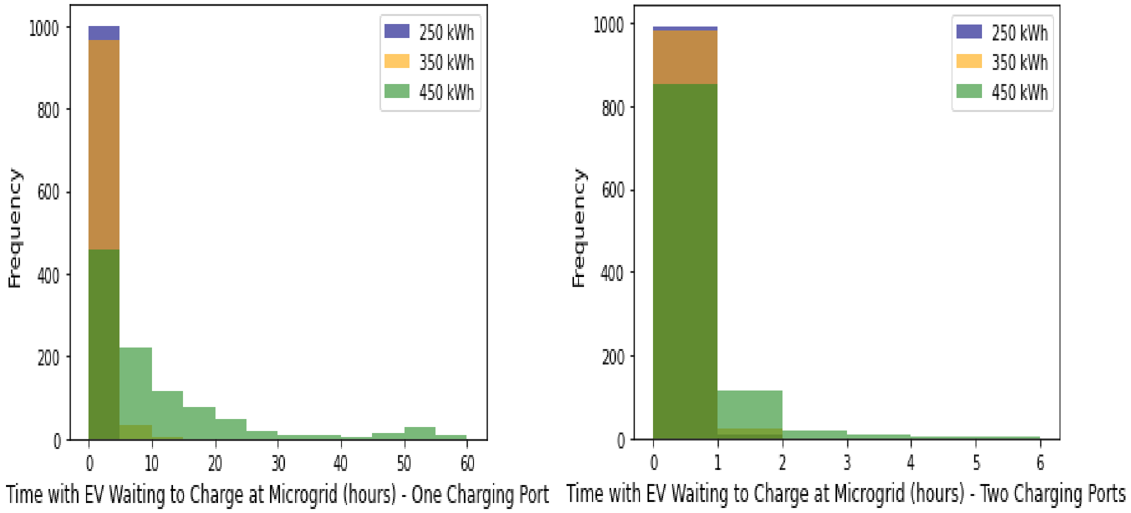


Figure 3-4 - Histogram of total hours with EVs waiting to charge at the microgrid

The difference between the scenarios with one and two fast chargers also creates a trade off at the shelter. With increased waiting times at the microgrid, there will be more time steps where the shelter has one or no EVs providing energy, but, with the one charger scenarios tending to last longer, the shelter will be provided a greater total amount of energy before the microgrid storage is depleted. Figure 3-5 shows the total hours in simulations with no EVs donating energy at the shelter. Most simulations had between 0 and 10 total hours with no EVs discharging energy at the shelter. As battery size increased to 450 kWh, simulations ran longer and the times with no EVs at the shelter would increase.

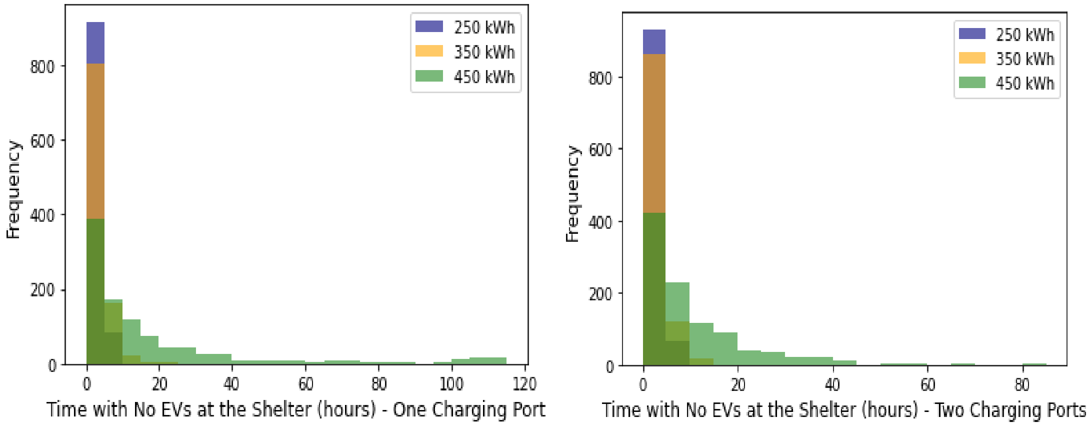


Figure 3-5 - Histogram of total hours with no EVs discharging energy at the shelter

Figure 3-6 is a whisker plot of daily energy provided to the shelter, with the green lines representing median values. The daily energy was found by taking the total amount of energy that had been provided to the shelter and dividing by the number of days that the simulation ran for. The blue box represents the interquartile range (IQR) and contains the median, along with 50% of the data. The horizontal black bars above and below the IQR are 1.5x the size of the IQR. Simulation results above and below these bars are considered outliers. As simulations found that the scenarios with one or two charging ports did not vary much in the daily energy delivered to the shelter, or used at the microgrid, the two port scenarios will be used in figures going forward. In the two port scenarios, the energy per day provided to the shelter was about 350 kWh within a 99% confidence interval.

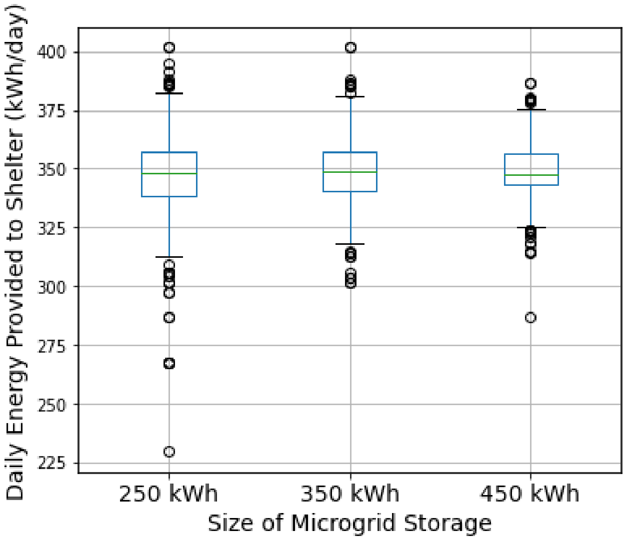


Figure 3-6 - Whisker plot of energy provided to the shelter (kWh/day) in two fast charger scenario

Figure 3-7 shows the daily energy used at the microgrid by the various EV types. Similar to previous, this value was found by taking the total energy an EV used at the microgrid and dividing it by the total time that the simulation ran for. Each Type 1 EV used about 200 kWh/day with most microgrid battery sizes. The Type 2 and Type 3 EVs used about 80 and 40 kWh/day in the 250 and 350 kWh scenarios but trended closer to 100 and 50 kWh/day in the 450 kWh scenarios. This is due to the scenarios with 250 kWh and 350 kWh batteries depleting sooner and depleting mainly due to the repeated return trips by the Type 1 EVs to charge. As the 450 kWh scenarios ran longer, the Type 2 and 3 EVs had more opportunities to charge and could settle into a steadier rate of daily energy use (i.e., the box bounds become tighter with increased battery size). These plots also can offer some insight into charging frequency. As most EVs required in the range of 40 to 50 kWh to recharge, it can be inferred that Type 1 EVs are recharging about four to five times a day, while Type 2 EVs are recharging about twice a day, and Type 3 EVs are recharging about once a day. As a reminder, the differences in the energy use of the various vehicle types stems from their assigned duties. Type 1 EVs are discharging energy fairly rapidly at the shelter, at a rate of about 5.75 kWh/half hour, while the duties of the Type 2 EVs necessitate them driving twice as much as the Type 3 EVs.

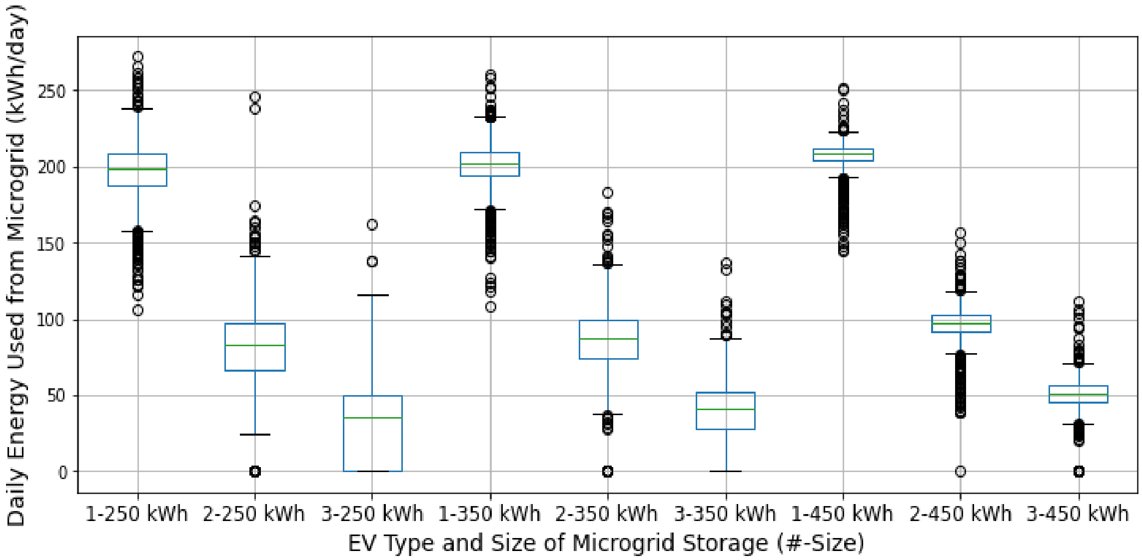


Figure 3-7 - Whisker plot of energy used at the microgrid (kWh/day) in two fast charger scenario

The energy use plot can also be used to infer daily travel distances. With four to five return trips to the microgrid, the Type 1 EVs would travel a total of about 160 to 200 km/day. The Type 2 EVs would travel about 720 km/day, while the Type 3 EVs would travel about 360 km/day. While these distances may seem large, they are a product of the frequent driving profiles of those EVs, and the assumed 24-hour operation of the fleet.

Figure 3-8 relates the start time of the simulation on a 24-hour clock, with the number of hours before the microgrid was depleted of energy. Simulations that started around midnight had the best chance of running longer, if the energy at the microgrid lasted until the following dawn and solar generation could start up again. Simulations that started later in the daytime would deal with a decreasing amount of generated solar energy as the day wore on. Later in the day, several EVs returning to charge could use the remaining energy at the microgrid, bringing it to zero. Larger batteries created a better chance for running multiple days, as they could still provide energy through the evening and nighttime, when the solar resource was unavailable. It is worth noting that the energy being depleted at the microgrid would not completely halt the operation of the EV fleet but would result in a waiting period before the solar array started generating again and energy could be accumulated in the battery. The number of bands of points in the images increase as storage size increases, and the simulations increased in likelihood to run beyond a single day.

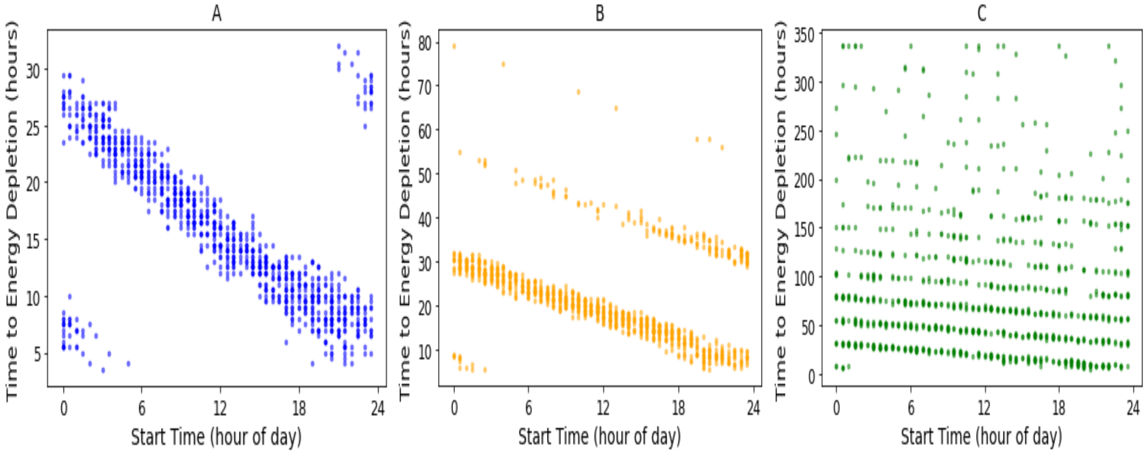


Figure 3-8 - Time to energy depletion vs start time for 250kWh (A), 350 kWh (B), and 450 kWh (C) storage in two port scenario (start time 0 = midnight)

3.4.2. Simulation Results from 6 EV Population, Task 2 and 3 Only (3x Type 2, 3x Type 3)

As it was apparent in the previous section that the Type 1 EVs were using the most energy in the fleet, another set of simulations was run for the same combinations of storage and fast chargers but with a fleet of six EVs composed entirely of Type 2 and Type 3 vehicles. This also represents a baseline case where no shelter exists to use the energy shuttling capability of EVs.

Figure 3-9 shows the histograms of time to energy depletion which now varies substantially from the previous scenarios including Task 1 shelter EVs. For the 250 kWh storage scenarios, outage lengths of 1 to 3 days can now be accommodated. With the larger 350 and 450 kWh sizes, simulations routinely would last until the two week limit of the simulation. In the case of the 450 kWh storage, nearly all 1000 simulations extended into the full two weeks.

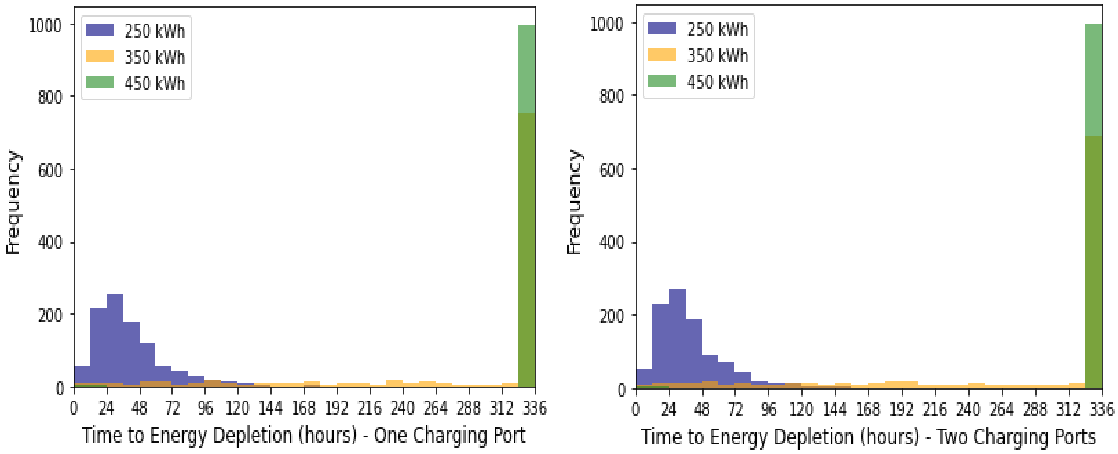


Figure 3-9 - Histogram of time to energy depletion

Figure 3-10 shows that the one fast charger scenario with 250 kWh had most simulations in the 0 to 2.5 hour range for waiting times. Because the 350 and 450 kWh storage scenarios ran for longer lengths (generally two weeks), waiting times varied between 5 and 15 hours. In the case of the two fast charger scenarios, waiting times were mainly in the 0 to 1 hour range with a substantial number in the 1 to 3 hour range as well.

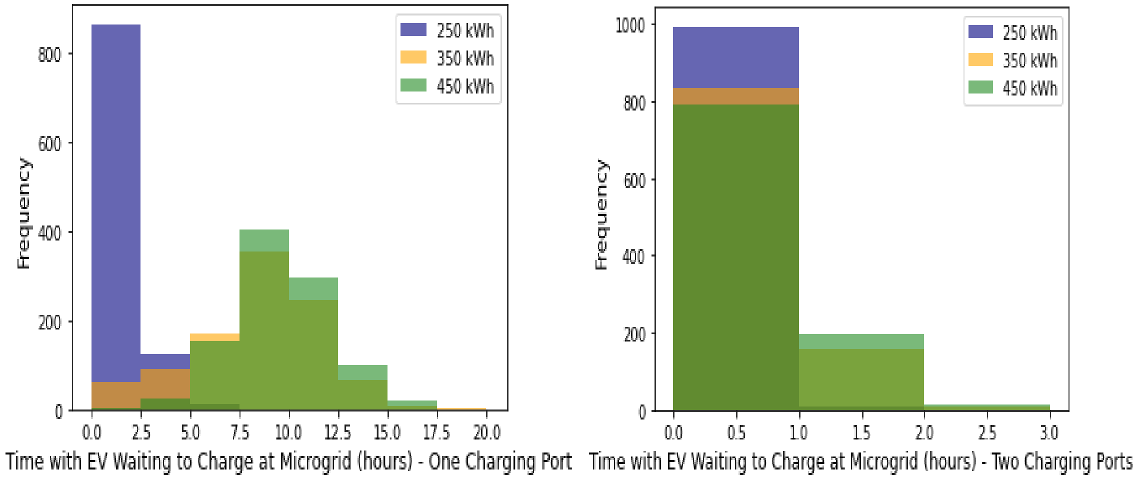


Figure 3-10 - Histogram of total hours with EVs waiting to charge

As the one and two port scenarios were once gain very similar for the rate of energy use, only the two port scenario is shown in Figure 3-11. The daily energy used at the microgrid for the Type 2 and 3 EVs are consistent with the rate used in the previous simulations, with Type 2 EVs consistently using about 100 kWh/day and Type 3 EVs using about 50 kWh per day as simulations ran longer. The standard deviation was observed to get smaller as the storage size increased. In the case of the Type 2 EVs, the standard deviation was 11.27, 4.4, and 2.37 kWh/day for the 250, 350, and 450 kWh storage size scenarios. In the previous simulations, the Type 2 EVs would have had a standard deviation of 28.35, 21.67, and 12.79 kWh/day for the same storage sizes. This suggests design trade offs in the sense that an increase in battery size will increase the expense of the microgrid but will result in less uncertainty for the expected operation profile of the EVs. It also points to the fact that the frequent charging of the Type 1 EVs led to a greater range of performance in the previous simulations.

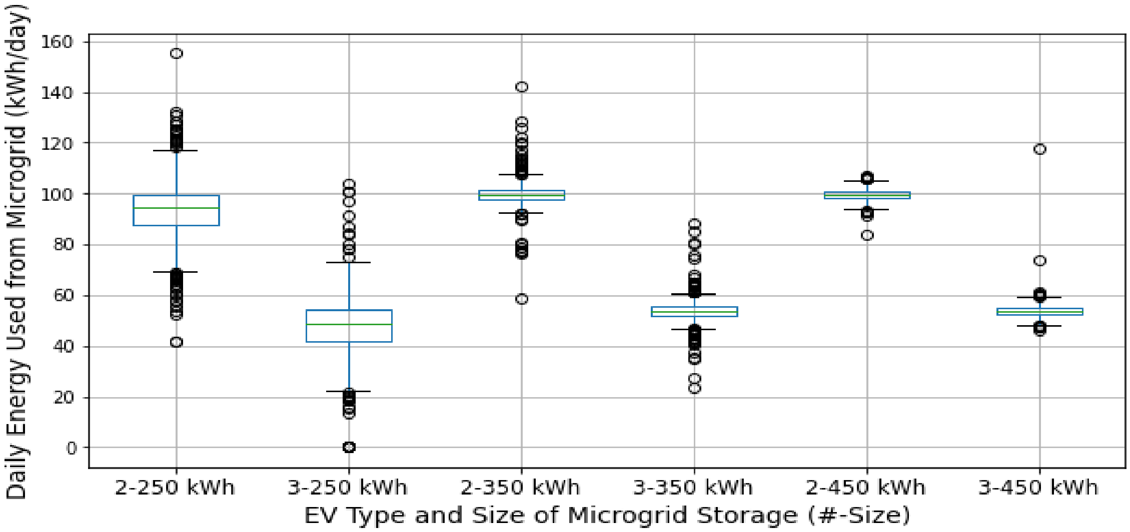


Figure 3-11 - Whisker plot of energy used at the microgrid (kWh/day) in two fast charger scenario

Figure 3-12 also shows substantial changes from the previous simulations in terms of system duration before depletion. The 250 kWh scenario runs longer and forms multiple bands closer to what the 350 kWh scenario did previously. The 350 kWh scenarios now more closely resemble the previous 450 kWh scenarios but with more finishing times at the two-week mark. In the case of the new 450 kWh simulations, effectively every one is able to run for the full two weeks, indicating essentially unlimited operation in this assumed solar profile and solar array size.

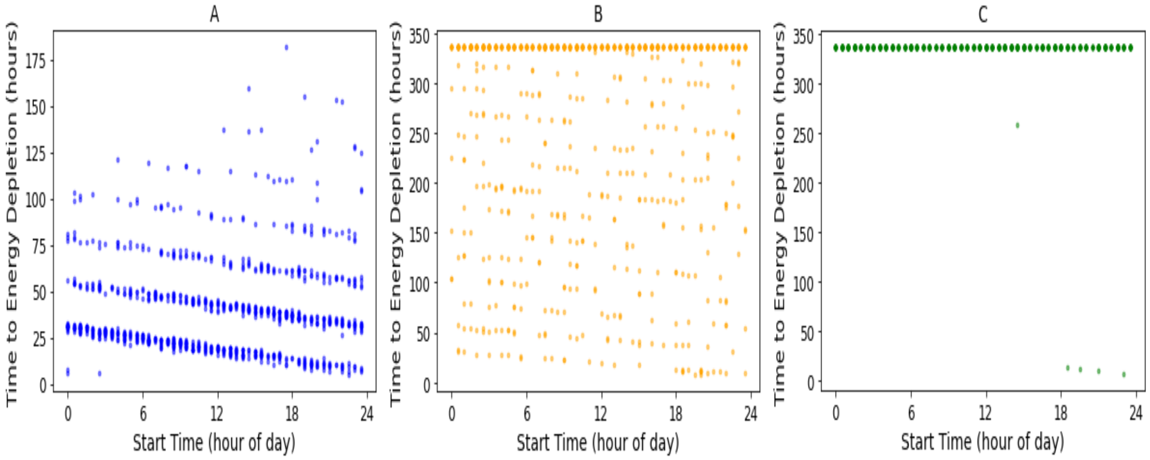


Figure 3-12 - Time to energy depletion vs start time for 250kWh (A), 350 kWh (B), and 450 kWh (C) storage in two port scenario (start time 0 = midnight)

3.5. Discussion

As the first simulations showed with shelter shuttling, the length of outage that the microgrid could provide power for increased as the battery storage increased. For the energy usage of that particular fleet, there would be a storage size, maybe 100 kWh larger than the 450 kWh size, that would allow the fleet to continuously operate without the storage ever depleting, assuming that the solar array was able to keep generating. The daily energy use of the various vehicle types allows for an understanding of the frequency of charging of each vehicle. With this knowledge, an appropriate storage size could be selected.

This is a good opportunity to acknowledge some of the limitations between a simulated model and a real, applied study. It was mentioned previously that there is an assumed human decision to return an EV to the microgrid when the energy in the battery had depleted to a certain point. There would be more of an individual behaviour at play as drivers may differ in their perception of how much energy they need to return their EV and recharge, based on their current proximity to the microgrid. There are also human factors to consider such as the necessity for food and washroom breaks, as well as how mental fatigue would accumulate with long periods of driving. In future, disaster response exercises could be performed with the tasks from this model, while studying the time taken for various tasks and how the needs of a human driver play into things.

In the case of this model, it was assumed that the EVs needed to recharge and return to duty as quickly as possible, so the microgrid storage depleting was set as an exit condition. In reality, the EVs could wait until the microgrid had charged again to recharge and return to their duties. One method of prolonging the energy in the microgrid storage would be to control the amount of charging done and only allow for each EV to recharge a certain number of times in a given 24-hour period. This would obviously have impacts on the amount of possible energy that the Type 1 EVs could donate as well as the amount of driving that the Type 2 and 3 EVs could perform. If the EVs were only assumed to provide disaster aid during the daylight hours, then their daily energy use could be reduced by a factor of one half or one third. A mixed fleet could also be considered, with different vehicle types (i.e., small passenger vehicle and larger pick-up truck); this could provide additional mission profiles and scheduling possibilities and will be considered in future work.

The 350 kWh/day energy use of the Type 1 EVs can be compared to some real-world benchmarks for energy use. During the initial COVID-19 lockdowns in March 2020, for instance, a 40 dwelling social housing building in Quebec City, Quebec saw an average daily energy consumption of 424 kWh/day [142]. This means that the Type 1 EVs would be able to provide about 83% of that amount. As another point of comparison, in 2012, the Canadian Armed Forces Operation NANOOK found an average weekly electricity use of 22,279 kWh for a 350-person camp in Inuvik, Northwest Territories [143]. This value corresponds to a daily electricity use of about 9.1 kWh per person at the camp, meaning the Type 1 EVs could accommodate the energy needs of about 38 people in that setting. As we saw with the simulation that removed the Type 1 EVs, this function came at a cost with respect to the outage lengths that could be supported. The Type 1 EVs donating energy to the shelter substantially shortened the time frame that each of the different storage sizes could provide for the fleet for. One idea to gain the same benefit for a shelter that the EVs were providing would be to locate disaster shelters at locations that have their own microgrids so energy could be generated and used on site. This idea could be extended to designing temporary shelters that can be equipped with their own solar panels and battery storage, although then the logistics of transport and setup of substantial solar arrays would have to be considered. The disaster resiliency of the baseline installed solar array should also be considered in future work (i.e., earthquake resistance of buildings with roof-top solar installations).

The microgrid itself was sized with a commercial scale solar array of 200 kW that would require about 1,500 m^2 of available rooftop area. The National Renewable Energy Laboratory provides costing estimates for solar and battery storage in a 2022 report [144]. The installed pricing for commercial scale solar in USD at the time of writing was about $1,630/kW, while the price of installed commercial scale battery storage was about $610/kWh USD. Looking at this information, the cost of the solar array itself would be $326,000, and the 250, 350, and 450 kWh batteries would cost $152,000, $213,500, and $274,500, respectively. Total system costs could range from roughly $500,000 to $600,000. This brings the question of whether a system like this would be financially viable. It is likely that a microgrid would be sized to offset the energy needs of a particular building in normal operations and would be expected to have a net benefit and expected payback period relative to grid-connected energy costs and amortization periods. The outage resilience feature would be an added benefit, but likely not the main driver behind the purchase of the microgrid. There could also be a resilience benefit gained from just purchasing storage which could still be used to save money by energy arbitrage. In an outage scenario with only available storage, the SOC of the battery at the start of the outage would determine how long a fleet of EVs could operate for. As an example, if the rates of energy use of the Type 1, 2, and 3 EVs of 200 kWh/day, 100 kWh/day, and 50 kWh/day are considered, a fully charged 350 kWh battery could accommodate one of each vehicle type operating for a full 24 hours.

It is interesting to consider a similar post-disaster EV use scenario if there was no microgrid. If there was a large fleet of available EVs, a portion of the fleet could provide disaster relief until their batteries were almost depleted and then returned to the parking garage where the fleet is stored normally. Having the EV returned to its normal location would ensure that it could be recharged when the main grid eventually came back online. After this portion of the fleet had been returned, another portion could be sent out to provide disaster relief and returned once their battery was close to depletion. Using individual portions of the fleet like this would hopefully buy enough time until the grid was brought back online and all fleet vehicles could be recharged. It bears mention that any such fleet deployment strategy comes with trade-offs. If the outage ended up being short in length, then deploying all vehicles would help to smooth out overall operations more than sending out small segments of the fleet. There could also be resilience benefits in maintaining a mixed fleet of vehicle types, with some vehicles still running on conventional fuels that could be stockpiled in preparation of a disaster situation. Likewise, a mixed fleet of EV types would be heterogeneous in vehicle mission capabilities and battery sizes, leading to a rich scheduling problem, in addition to the microgrid design and operations.

3.6. Conclusions and Future Work

Climate change is expected to increase the frequency of power outages caused by high-impact low-probability events. The expected increase in the electrification of the transport sector will make outages an even greater concern. While the continued adoption of EVs will contribute to this electrification process, EVs also offer the potential to be of great use during an outage, with capabilities such as V2G, G2V, V2H, and V2B.

This paper focused on using an ABM to model the behaviour of a fleet of EVs during the immediate aftermath of a disaster. The EV operation profiles were modeled around the needs of a community during a disaster response phase, and EVs were assigned to transport energy to a shelter, deliver critical supplies, and transport important personnel or perform inspections. The EVs were provided with access to a microgrid composed of a 200 kW solar array, various storage sizes (250 kWh, 350 kWh, and 450 kWh batteries), and one or two 100 kW fast chargers. These designs possibilities were used to create different scenarios within the model which were run for 1000 simulations each. The model also drew from a week of Victoria, BC solar data from July 2020 to simulate real world microgrid conditions. Additionally, the EV fleet composition was varied in a separate set of simulation scenarios.

Results from the initial simulations of a six EV fleet with two of each type of vehicle showed that 250 kWh storage could provide for outages of 0.5 to 1 day, while the 350 kWh storage could provide for outages of 1 to 1.5 days. As the storage size increased to 450 kWh, outages of 2-4 days could be accommodated, but in some simulations the storage could provide for outages of one to two weeks. An average daily energy of 350 kWh was delivered to the shelter by the Type 1 EVs. Looking at the operation profile of the various vehicle types, the Type 1, 2, and 3 EVs used to 200, 100, and 50 kWh/day at the microgrid. This corresponded to Type 1 EVs charging four to five times day, Type 2 EVs charging twice a day, and Type 3 EVs charging once a day.

As the Type 1 EVs were observed to use the most energy, a separate set of simulations was done for a six EV fleet composed of three Type 2 EVs and three Type 3 EVs. In this new population, the 250 kWh storage could now provide for outages of 1 to 3 days, while the 350 and 450 kWh storage sizes could routinely accommodate outages up to two weeks. In the case of the 450 kWh storage, nearly all 1000 simulations extended into the full two weeks and potentially could have lasted in perpetuity for the given solar conditions. In the new simulations, it was once again found that the Type 2 and Type 3 EVs consistently used 100 and 50 kWh/day. It was observed that increasing the storage size led to less uncertainty in the operation profiles of the EVs.

The knowledge of the daily energy use of each EV type could be used to select a storage size that would allow for the continual operation of the fleet. The energy use of the fleet could also be controlled by only allowing a limited amount of daily charging. The 350 kWh/day energy that was brought to shelter could provide 83% of the daily energy use of a 40 dwelling Quebec social housing complex in March 2020. As it was observed that the Type 1 EVs used the most energy in the fleet in their duties of transporting energy to the shelter, it could be planned in the future to coordinate microgrids as disaster shelter locations and generate energy to be used on site. The total costs of the microgrid in the model were in the range of about $500,000 to $600,000 USD which was mainly due to the cost of the solar array. Purchasing a battery only, and no solar array, would still offer some resilience benefit but with no capability of recharging during an outage of the larger grid. If there was no available microgrid during an outage, a fleet could still operate by sending out a portion of the fleet at a time until the larger grid was brought back online.

The ABM leaves several avenues open for further work. It was assumed in the model that the shelter was able to utilize the full discharge power of the Task 1 EVs. This could be expanded on by creating a time varying load at the shelter that could consider the power use of things such as lighting, air condition, medical equipment etc. Other than the distance between the shelter and the microgrid, the model was not designed to be spatially explicit. This could be updated to track exactly where each EV is spatially. The model could also consider specific outage causes. In an earthquake, for example, there would be damaged segments of the transport network. The EVs would have to optimize their routes around these damaged locations, and certain roads could be repaired as the simulation proceeds in time. Additional EV functionality could also be added. EVs have the potential to use the energy in their batteries to form an ad-hoc communication network. The model could have EVs that form a communication network and report damaged locations that other EVs are then sent to investigate. Different fleet compositions could also be explored based on fleet age. A fleet could be designed using exclusively brand new EVs with a non-degraded battery capacity, or a fleet could be designed that is fully composed of EVs that are nearing the end of their lifetime. The Nissan LEAF was selected in the model for its bidirectional charging capability, but other types of EVs could be added that may be able to provide different services. An example would be to mix in some of the available varieties of EV trucks.

The microgrid itself has opportunities for further work as well. An economic study could be conducted on the payback period for a similarly sized microgrid to the one in the model, using the energy profile of a business or municipal organization that would have the available rooftop area for a solar array of that size. The study could determine if the microgrid could payback its initial costs over the system lifetime by reducing energy costs for the organization. With respect to the microgrid in the model, different types of energy generation could also be added, such as wind or a dispatchable form of energy, like a biogas with a turbine system.

Chapter 4. Conclusions and Future Work

4.1. Conclusions

Power outages can result from accidental, natural, and intentional threats. As the electrification of the transport sector increases so will society's vulnerability to disaster induced power outages. This thesis aimed to provide two separate contributions to this area. The first was to provide suggestions for increasing the earthquake resilience of the electrical grid and the fuel infrastructure in the Lower Mainland and on Vancouver Island. The second was to study the behaviour of a fleet EVs providing disaster relief, following a disaster induced outage.

Considering the lessons learned from earthquake impacts in Chile, Japan, and New Zealand, suggestions were made in the context of southwestern BC for how the region could increase its power system earthquake resilience. Both the Lower Mainland and VI can benefit from using N-1 grid design criteria, relocating vulnerable equipment from tsunami or landslide zones, utilizing above ground cables through liquefaction zones, establishing microgrids, using private communication systems, and establishing aid agreements with surrounding areas. VI specifically would benefit from increasing generation capacity and having a supply of mobile generators and transformers to aid recovery in more remote areas.

In the case of the fuel infrastructure, the Lower Mainland would benefit from seismically upgrading the TMPL, studying the vulnerability of important ports, ensuring the earthquake resilience of the Chevron Burnaby facility, and planning for how fuel will be prioritized after an earthquake. On VI, the fuel infrastructure resilience can be increased by seismically upgrading marine ports, adding additional port locations or capacity, adding additional storage to the region, and planning for alternate sources of fuel in the event that the Lower Mainland is unable to provide after an earthquake. Municipalities on VI can examine fleet composition and plan for fuel needs after a disaster and what sort of storage that would necessitate.

An ABM was used to study the use of a fleet of EVs during an outage, following a disaster, to provide disaster relief by donating power to a shelter (Task 1), delivering critical supplies and people in need (Task 2), and providing transport for personnel or performing inspections (Task 3). The EVs were provided access to a microgrid with a 200 kW solar array, three possible sizes of storage (250, 350, and 450 kWh) and one or two 100 kW fast chargers. It was observed the storage sizes of 250, 350, and 450 kWh could, on average, provide for outages of 0.5 to 1, 1 to 1.5, and 2-4 days, respectively. Daily energy delivered to the shelter was 350 kWh/day, and Type 1, 2, and 3 EVs used 200, 100, and 50 kWh/day at the microgrid. Eliminating the Type 1 EVs from the fleet substantially increased outages lengths that the microgrid could provide energy for, with many simulations running for a full two weeks.

4.2. Future Work

Both Chapter 2 and 3 of this thesis leave room for impactful future work.

For the topics addressed in Chapter 2, more work could be done to model the impacts of earthquakes on specific elements of the electrical and fuel infrastructure in the Lower Mainland and on VI. The elements could be modeled with the fragility curve concept and Monte Carlo simulations could be done to simulate various magnitudes of earthquakes. Understanding which elements are most vulnerable, and which would have the longest repair times, could help to prioritize items for increasing resilience. While Chapter 2 focused on a Cascadia Subduction Zone event, earthquake impacts could also be modeled for shallow crustal and deep intraslab earthquakes. It was found that VI is very dependent on power derived from the mainland. It would also be of interest to study what amount of power generation would be required to make VI self-sufficient as well as where it could be placed and what sort of grid upgrades would be necessary for it. There could also be simulations done for how much energy VI could provide during a disaster with its current generation capabilities if it was disconnected from the mainland. This could be partnered with studying how that energy would be most effectively utilized and what sort of intermittent service periods could be used. There is also further work that could be done conducting quantitative earthquake risk assessments and considering the changing transport landscape. Economic comparisons could be done, comparing the costs of upgrading the electric grid with the costs of upgrading the fuel infrastructure, while considering the predicted rate of transition from conventionally fueled vehicles to EVs.

For the study from Chapter 3, more work could be done to design a time varying load at the shelter that the Task 1 EVs are assigned to help meet. A disaster shelter could be utilizing power for heating, food preparation, lighting, medical equipment etc. Something like the heating or air conditioning load would change between day and nighttime. Conducting simulations at different times of year would also result in different loads being experienced at the shelter. The model also leaves room to update it to track exact vehicle locations. This could be paired with exploring different outage causes. An earthquake induced outage would have damaged segments of the transport network that the EVs would have to avoid when traveling between locations. A time varying input could be used for a transport network that starts at peak damaged conditions and has different roadways that are repaired over time. As the roads are repaired, the EVs could travel shorter routes between their objectives. There is also room to update EV functionality. A new EV task could be created for EVs to act as nodes in an ad hoc communication network by drawing from their battery power. These EVs would be equipped with an antenna and could communicate with one another. They could report on damaged regions and send other EVs to assess, thus increasing the interaction between the various agents in the model. The time step in the model was set to 30 minutes, but this could also be lowered to increase model detail. If the step was reduced to a minute, energy use while driving could further detailed as well as the exact charging times at the microgrid. EVs charge rapidly to 80%, and charge more slowly following that, so this could also be captured in the model. There is also room to add more varieties of EVs to the model, such as SUVs or trucks. These vehicles could be assigned to tasks that they are better suited to, like delivering larger supplies for repairs. These vehicles could be assigned to specific locations where they make repairs while potentially running equipment from their batteries. The microgrid location offers further work opportunities as well. An economic study could be conducted for the microgrid and what its payback period would look like when trying to meet the energy needs of a business or municipality. In the simulation itself, the performance of the microgrid could also be studied for additional array and battery sizes and different times of year for the solar input at the array. There could also be work done to study the disaster resilience of microgrids themselves and the likelihood that they would be damaged in a disaster. If the microgrid was rendered dysfunctional, then the EVs would not be able to operate as was detailed in the study. The microgrid could also be modeled with different types of energy generation. For example, if the microgrid had a biogas turbine system, then that could be used during days when the solar generation was suboptimal. Wind generation could also be added but would suffer from the same intermittency issues as solar generation.

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