Electric Vehicles Effects on the Power Grid Considering Smart Charging/Discharging: Montréal Case Study

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Abstract

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Mehdi Shamshirband

Electric vehicles (EVs) are increasingly recognized for their potential to save energy, reduce pollution, and protect the environment. This makes the promotion and adoption of EVs crucial for decreasing our reliance on oil, enhancing energy security at national and regional levels, and supporting sustainable economic and social development. Acknowledging these benefits has led to a strategic focus on encouraging the widespread use of EVs. In this regard, countries around the world have begun to implement policies aimed at accelerating the adoption of EVs. These policies range from incentives for EV purchases to investments in charging infrastructure, reflecting a commitment to transition to cleaner forms of transportation. As a part of these efforts, the Government of Canada has introduced new regulations that establish mandatory Zero-emission vehicle (ZEV) sales targets for manufacturers and importers of new passenger cars, SUVs, and pickup trucks. These regulations require that a minimum of 20 percent of new vehicles sold in Canada must be zero-emission by 2026, escalating to at least 60 percent by 2030 and reaching 100 percent by 2035.

In accordance with these new laws and policies, the province of Québec has set its own ambitious target of having two million EVs on the road of Québec by 2030. This goal has led to the need for this study to measure and analyze the impact of Plug-in Hybrid Electric Vehicle (PHEV) charging demand on both the current and future power network of Montréal, the largest city in the province of Québec. In this regard, this study considers the integration of Québec's ZEV policy on the city's grid and will evaluate how the expected growth in the number of PHEVs will affect the network's stability and efficiency. Therefore, a multi-objective problem has been presented in this research study to simultaneously maximize the benefits for PHEV owners while minimizing the power loss

in the system for the current and future network of the city of Montréal. The proposed multi-objective problem is also developed using the Epsilon-Constraint technique, which facilitates solving the complex multi-objective function problem. In this regard, the load profiles of three different parts of the city of Montréal have been considered for specific reasons. The downtown area of Montréal has been chosen as it serves both commercial and residential purposes. To analyze the impact of PHEV charging in residential areas, Cote Saint Luc and Notre-Dame-de-Grâce have been included in the study, where both are considered primarily residential neighborhoods. Additionally, Montréal is well-known for its festivals and events, which led individuals to spend considerable time in the city for leisure. As a result, Quartier des Spectacles and the Old Port have been selected as essential areas where people gather during their leisure time. To address the above-mentioned issue and analyze the effect of PHEVs on the network of Montréal, two different phases and approaches were considered in this study: Immediate Charging, which only uses the Grid-to-Vehicle (G2V) charging strategy, and Smart Charging, which uses both G2V and Vehicle-to-Grid (V2G) strategies with the assistance of an EV aggregator. Additionally, to validate the effectiveness of the Smart Charging results, an alternative approach known as Basic V2G was implemented. This Basic V2G approach serves as a basic V2G concept to evaluate and verify the advantages of using the Smart Charging scenario.

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Nomenclature

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T	Index of optimization periods	$S_{i,j}^{max}$	Line maximum capacity
n	Index of EVs	$S_{i,j}$	Line Capacity
b	Index of buses.	$P_{b,j}^{max}$	Maximum power flow in the lines
		$P_{b,j}$	Power flow limit in the lines
Parameters			
α	Discharging cost coefficient	***Function***	
β	Charging cost coefficient	F_{Cost_Gen}	Total cost of generating the electricity
CL	Power Loss cost coefficient	F_{Cost_Loss}	Total cost of system's power loss
θ	PHEV operation factor	φ	Objective function
ω	Distance traveled by PHEV	$\mathrm{P}_{\mathrm{Total\_Demand}}$	Total electricity Demand
V^{min}	Minimum allowed voltage	$P_{TotalLoss}$	Total power loss
V^{max}	Maximum allowed voltage		
V_b	Voltage of bus b	***Variables***	
R	Resistance	PG_t	Generated power
$\mathcal{Y}$	Admittance	PD_t	Load demand
I	Current	PL_t	Power Loss
ρ^{Ch}	PHEV charging coefficient (G2V)	$P_{t,n}^{Ch}$	Charged power by PHEV n
ρ^{Dch}	PHEV discharging coefficient (V2G)	$P_{t,n}^{Dch}$	Discharged power by PHEV n
E_{PHEV}^{min}	Minimum energy stored in a PHEV	RTP	Real-time price
E_{PHEV}^{max}	Maximum energy stored in a PHEV	CH	PHEV charging
E_{PHEV}	Energy stored in a PHEV	DCH	PHEV Discharging
$X_{t,n}$	Charging process binary variable		
$Y_{t,n}$	Discharging process binary variable		

Chapter 1: Introduction

1.1 Introduction

The rising reliance on fossil fuels, the subsequent increase in GHG emissions, and the growing concerns over climate change have shifted attention toward the integration of EVs and renewable energy sources into the power grid. The Paris Agreement specifically states that the goal is to keep global temperature rise below 2 degrees Celsius by 2050. In this context of decarbonization, the power grid must transform into a smart grid to be able to successfully integrate the various new elements required to reduce carbon emissions, including renewable energy sources and EVs. This transformation affects all significant components of the power grid, including generators, transmission and distribution networks, and end users. It necessitates an entirely new approach to power grid control, which includes regulating frequency, voltage, and current in order to guarantee system stability and efficiency [1].

Traditional electrical supply networks typically consist of four major components: generation, transmission, distribution, and consumer (load) systems. The generation system is often made up of massive, centralized power plants that generate electricity on a large scale. Modern generating units typically have a capacity greater than 1,000 MW. The transmission system has specifically been developed to transport large amounts of power from these generation plants to distribution networks across long distances while using high and extra-high voltage levels. Common transmission voltages include 765 kV, 500 kV, 400 kV, and 275 kV. In contrast, distribution systems were developed to receive electrical power from the transmission network and deliver it to various load locations, such as residential and commercial areas. Notably, distribution networks typically act in a passive role, focusing on transmitting power from generating and transmission systems to end customers only. These distribution networks operate at lower voltages, such as 132 kV, 110 kV, 66 kV, 33 kV, 20 kV, and 11 kV. The conventional structure of electrical supply networks is typically vertical, where electricity generated by power plants passes through the transmission network before being distributed to the loads. Many conventional electrical networks around the world were designed in the 1950s and subsequently constructed during the 1960s and 1970s. These systems were developed before the advent of the microprocessor era and before the substantial advances in networking, automation, and smart appliances. As a result, the architecture of these networks does not consider recent technological advancements that have since emerged. Furthermore, entirely new applications and technologies were developed, which are expected to have a substantial impact on the future operation and management of electrical networks. Examples of emerging applications that will significantly impact the electricity grid include EVs and heat pumps, both of which are expected to have major effects on the existing electrical system with their considerable demands [2]. As a result, it has been widely acknowledged that current electrical networks are aging and out of date, making their modernization an urgent necessity. To address these challenges, prioritizing upgrading the existing electricity grid with smart technologies is a requirement. This modernization effort is crucial for addressing the infrastructural and operational challenges brought about by the energy-climate legislative package. These goals are centered on improving energy efficiency, expanding the use of renewable energy, and lowering GHG emissions.

It has become noticeable that the modifications to electrical networks in recent years have rendered the current grid incapable of supporting future demands [3]. This realization has resulted in an urgent need to modernize existing networks, prompting the development of the Smart Grid concept. The Smart Grid is widely regarded as an essential answer to the challenges of rising energy consumption and the integration of distributed generation, including renewable energy sources, as well as the integration of widespread EV penetration, in addition to energy efficiency, power supply reliability, and power quality. The Smart Grid uses cutting-edge technology to improve the efficiency, adaptability, and resilience of the electrical infrastructure, allowing it to meet both current and future energy demands.

1.2 Smart Grid and Conventional Electrical Networks (Comparison)

The future Smart Grid is expected to be distinct from existing electricity networks in numerous important ways. It will use cutting-edge technologies to provide real-time monitoring, automation, and two-way communication between the utility and its customers. Unlike traditional networks, which generally feature one-way power flow from generating to end consumers, the Smart Grid will enable decentralized power generation and the integration of renewable energy sources like solar and wind power. For example, in the US, a program was established to construct the Smart Grid, which has the following key characteristics [4] and [5]:

1. Enable active participation by consumers
2. Accommodate all generation and storage options

3. Enable new products, services, and markets
4. Provide power quality for the digital economy
5. Optimize asset utilization and operate efficiently

1.2.1. Enable active participation by consumers

The active participation of consumers in electricity markets is expected to benefit both the grid and the environment. Consumers will be provided with access to critical information, control mechanisms, and options that allow them to become involved in power markets once the Smart Grid concept is fully implemented. Furthermore, operators of the grid will consider active customers to be significant resources in the daily operation of the grid. Informed consumers will be able to customize their energy consumption depending on a balance of their own requirements and the grid's ability to fulfill those demands. Dedicated demand response techniques will empower consumers by allowing them to choose when and where they buy energy. This cooperation will help utilities reduce or shift peak electricity demand, allowing them to decrease investment and operating expenses. It will also result in fewer line losses along with decreased reliance on inefficient peaking power plants, which are normally used during times of high demand. As a result, these modifications will have a major environmental impact, including lower GHG emissions and increased overall energy efficiency.

1.2.2. Accommodate all generation and storage options

In a Smart Grid context, integrating diverse types and sizes of electrical generators and energy storage systems will be considerably more efficient due to simplified interconnection processes and the adoption of universal interoperability standards. This technology, referred to as "plug and play," will make it possible for simple integration throughout the grid. While large central generation plants, including renewable energy sources such as wind and solar farms, will continue to play an essential role due to their environmental friendliness, the deployment of a large number of smaller distributed resources, such as PEVs, is expected as well. Furthermore, the Smart Grid will enable the connection of generation units with capacities ranging from small to big at nearly any voltage level. This consists of solar systems, wind turbines, improved battery storage, PHEVs, and fuel cells. Commercial customers, in particular, will find it easier and more cost-effective to establish their own generation systems, such as highly efficient combined heat and power systems and electric storage facilities. This allows for greater energy independence while also potentially providing financial incentives to enterprises that generate electricity on-site.

1.2.3. Enable new products, services, and markets

The Smart Grid will enable smooth interactions between buyers and sellers throughout the energy sector, including consumers, generators, and aggregators. It will promote the development of new electrical markets and tools that will help in reliable energy trading. This integration will extend from home energy management systems installed in consumers' houses to technologies that allow both consumers and third parties to actively participate in energy markets by bidding on energy. Such systems will implement real-time pricing, allowing customers to see variations in prices immediately. As consumers respond to increased prices, their changes in demand and energy consumption will make it possible to reduce the total consumption of energy. This behavior will encourage the implementation of more cost-effective solutions and the advancement of new technology. Furthermore, markets will provide innovative and environmentally friendly energy products as alternatives, supporting a greener energy future. The Smart Grid is anticipated as well to provide consistent market operations across areas, resulting in an enhanced joined and efficient energy marketplace.

1.2.4. Provide power quality for the digital economy

The Smart Grid concept is projected to considerably enhance monitoring, evaluation, and response to power quality issues. This improved capability will result in a substantial decrease in commercial losses incurred by consumers due to poor power quality. By implementing novel power quality requirements, the Smart Grid will balance load sensitivity with power quality. Furthermore, the Smart Grid will allow for the delivery of multiple levels of power quality at varying pricing points, giving consumers more choices. In addition, the Smart Grid's comprehensive monitoring and control features will assist in reducing power quality disruptions caused by the electrical system's transmission and distribution components. Irregularities created by particular customer demands can be separated, minimizing their harmful influence on the electrical system and other users. This will result in a more steady and consistent power supply for all users.

1.2.5. Optimize asset utilization and operate efficiently

The Smart Grid concept is projected to considerably improve power system operations by improving load factors, lowering network losses, and substantially enhancing failure management efficiency. With full adoption of the Smart Grid, the grid will gain additional intelligence, offering useful information to planners and engineers. This improved intelligence will enable greater planning for infrastructure development, allowing for the installation of critical components specifically when they are required. Furthermore, it will help enhance equipment lifespan, enable repairs to equipment before unplanned failures, and optimize staff management for grid maintenance. These developments will result in lower operational, maintenance, and investment costs, eventually easing the growing pressure on the network.

Considering Smart Grids' capabilities and advantages in integrating renewable energy sources and EVs, the following section is going to explore the ways renewable energy and EVs are utilized, as well as the benefits they offer. The investigation will focus on how these technologies, when integrated with Smart Grid infrastructure, can promote sustainable energy policies, improve efficiency, and assist in preserving the environment.

1.3 Benefit of using Renewable Energy Sources

According to the U.S. Energy Information Administration, the preeminent source of human-caused greenhouse gas emissions in the United States is the combustion of fossil fuels, specifically coal, natural gas, and petroleum, for energy consumption [6]. Figure 1 shows the global usage of fossil fuels from 1980 to 2023, while figure 2 is an interactive map illustrating the proportion of electricity generated from fossil fuels (coal, oil, and gas combined) globally. Notably, oil contributes only a minor portion to electricity generation, with the majority being derived from coal and gas sources. As can be seen, worldwide fossil fuel consumption reached 137,236 Terawatt-hours in 2022, marking an increase compared to the previous year and standing as the highest figure within the period under consideration. Approximately 80 percent of the global population resides in countries that serve as net importers of fossil fuels, equating to roughly 6 billion people. This dependency on fossil fuels from other nations renders them vulnerable to geopolitical shocks and crises.

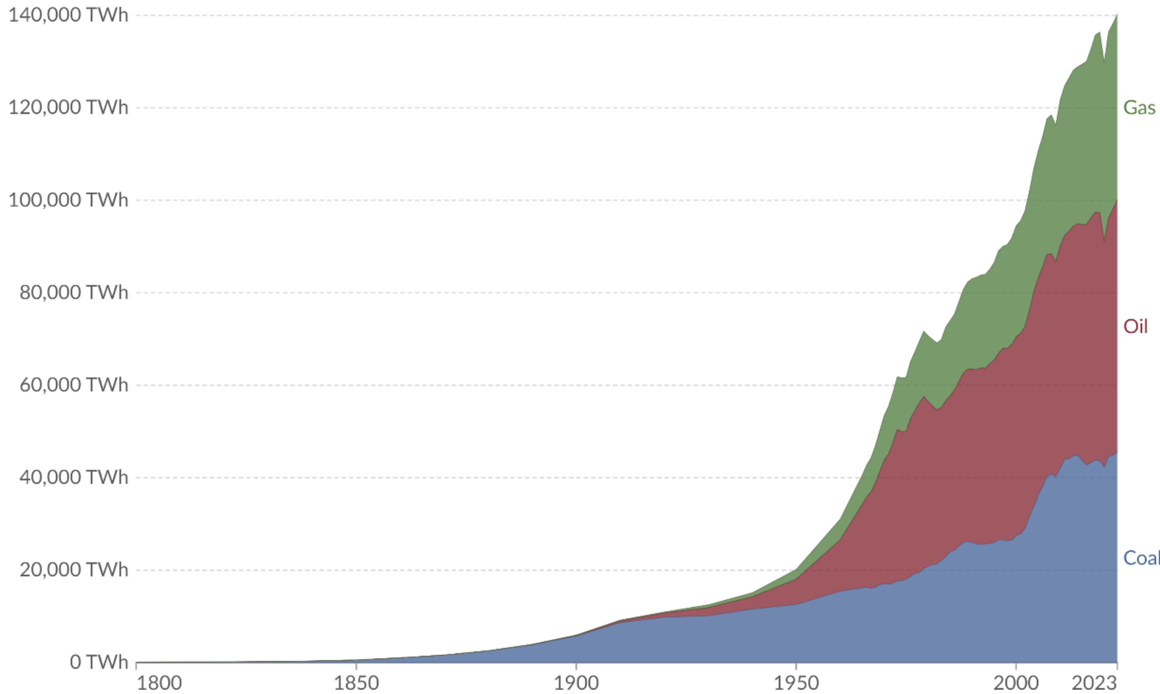


Figure 1. Global usage of fossil fuels from 1980 to 2023 [7]

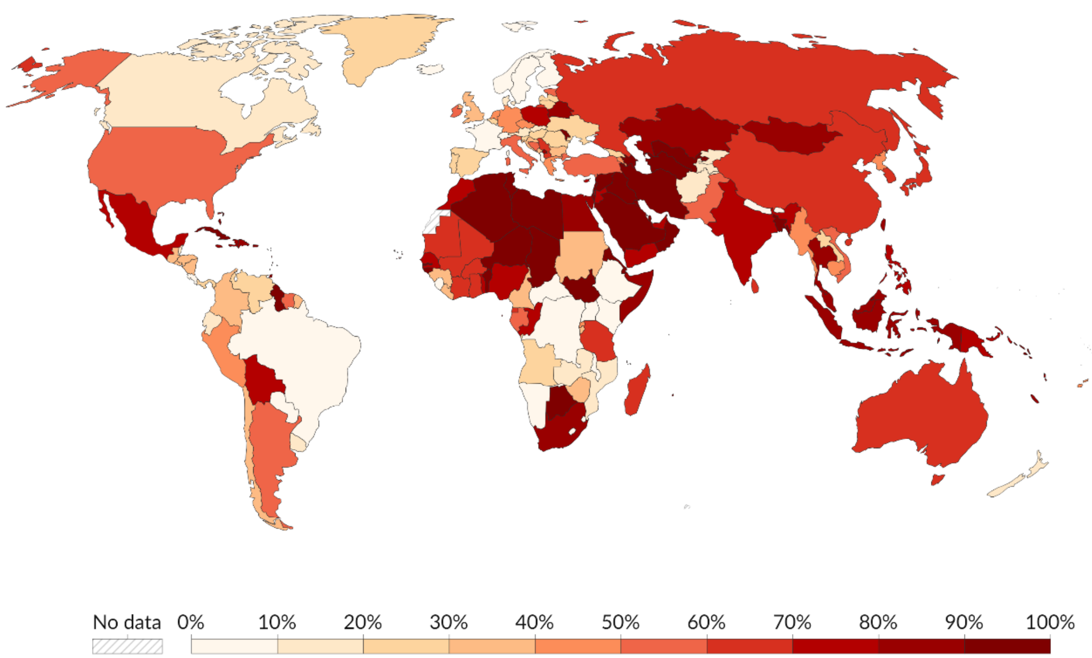


Figure 2. Share of electricity generation from fossil fuels, 2023 [7]

In contrast to fossil fuels, renewable energy sources are accessible all around the world, and their full potential has yet to be realized. The International Renewable Energy Agency (IRENA) suggests that 90 percent of the world's electricity can and should be derived from renewable energy by the year 2050. The generation of renewable energy yields significantly lower emissions compared to the burning of fossil fuels. Embracing renewables provides a path to reduce import dependency, enabling countries to diversify their economies and shield themselves from the unpredictable price fluctuations of fossil fuels. Simultaneously, the transition to renewable energy fosters inclusive economic growth, creates new employment opportunities, and contributes to poverty alleviation.

Renewable energy resources are expected to play an important part in the future of the world's energy landscape. Currently, energy resources are typically categorized into three main groups: fossil fuels, renewable resources, and nuclear resources; where renewable energy sources refer to those resources that can be repeatedly utilized to generate energy, such as solar energy, wind energy, biomass energy, geothermal energy, and more. They are often referred to as alternative sources of energy due to their sustainability. Thus, some of the benefits of using renewable energy sources are as follows [8].

1.3.1. Sustainable Development

A reliable energy resource supply is widely recognized as essential but not solely adequate for societal development. Sustainable development goes beyond this, necessitating an energy supply that is not only secure but also sustainable in the long term, readily accessible, economically reasonable, and capable of meeting all necessary tasks without causing adverse societal impacts. The availability of energy resources such as fossil fuels (coal, oil, and natural gas) and uranium is commonly recognized as finite. In contrast, other sources like sunlight, wind, and hydroelectricity are generally considered renewable, implying their sustainability over the relatively long term [9]. The utilization of renewable energy sources has been acknowledged as an essential element in advancing sustainable development goals. Renewable energy sources are able to create new jobs, enhance economic growth, and contribute to the reduction of GHG. All of these factors collectively play crucial roles in sustainable development, which will be discussed further.

1.3.2. Reducing Greenhouse Gas Emission

Renewable sources of energy have much less environmental impact compared to fossil fuel sources of energy. Using renewable energy sources can reduce GHGs in order to help mitigate the critical issue of climate change, including the life cycle emissions of clean energy. This life cycle includes the emission from each stage of the technology's life, including manufacturing, installing, maintaining, operating, decommissioning, and the global warming emissions associated with renewable energy. The statistical results show a clear difference between renewable energy and fossil fuels. For instance, the combustion of natural gas for electricity results in emissions ranging from 0.27 to 0.9 kilograms of carbon dioxide equivalent per kilowatt-hour (CO2E/kWh), while coal emits between 0.63 and 1.63 kilograms of CO2E/kWh. In comparison, wind energy is responsible for only 0.009 to 0.018 kilograms of CO2E/kWh on a life-cycle basis, solar 0.03 to 0.09, geothermal 0.04 to 0.09, and hydroelectric between 0.045 and 0.22 [10].

1.3.3. Economically Reasonable

According to the UN, renewable energy has emerged as the most economical power choice in many regions worldwide due to the rapid decline in the prices of renewable energy technologies. Specifically, the cost of electricity generated from solar power fell by 85 percent between 2010 and 2020, while onshore and offshore wind energy costs decreased by 56 percent and 48 percent, respectively. The declining costs of renewable energy enhance its appeal globally, particularly for low and middle-income countries where most of the new demand for electricity is expected to come from. Considering this situation and the price drop, there will be more opportunities to supply the majority of the future electricity demand by using these renewable energy sources. This development and the use of cheap energy resources all around the world will be able to provide 65 percent of the total electricity demand of the world by 2030.

In 2022, around $7 trillion was spent to support the fossil fuel industry. This amount includes direct subsidies, tax breaks, and hidden health and environmental costs that are not included in the total price of fossil fuels. On the other hand, around $4 trillion a year needs to be invested in renewable energy, including spending on infrastructure and technology, until 2030 to help reach net-zero emissions by 2050. The initial cost may present a challenge for numerous countries with limited resources, necessitating financial and technical support to facilitate the transition. However, investments in renewable energy will yield significant returns. Simply through the reduction of pollution and climate impacts, potential savings of up to $4.2 trillion annually by 2030 [11]. Therefore, investing in renewable energy resources could benefit the countries in the future, which represents that using these energy sources is economically reasonable.

1.4 Using Renewable Energy Sources Globally (statistic)

As the need to tackle climate change and the limited supply of fossil fuels becomes more urgent, the global energy production sector is experiencing a significant transformation towards renewable energy sources. This shift represents both a critical necessity and a promising opportunity for fostering sustainable development. Although environmental considerations play a central role, the acceptance of renewable energy technologies is also encouraged by the anticipated economic and social benefits they offer.

At the COP28 climate change conference in Dubai, the world is set for a massive increase in renewable energy installations over the coming five years, surpassing the total installations made since the first commercial renewable power plant was built over a century ago. Nearly 3,700 gigawatts (GW) of new renewable capacity are projected to be brought online from 2023 to 2028, driven by supportive policies implemented in more than 130 countries. This period is anticipated to mark several significant milestones in renewable energy development, including:

1. By 2024, the combined generation of electricity from wind and solar photovoltaic (PV) sources is expected to exceed that from hydropower.

2. In 2025, renewable energy sources are forecasted to surpass coal as the primary source of electricity generation.

3. Wind and solar PV are anticipated to individually overtake nuclear electricity generation in 2025 and 2026, respectively.

4. By 2028, renewable energy sources are projected to account for over 42% of global electricity generation, with wind and solar PV's combined share doubling to 25%.

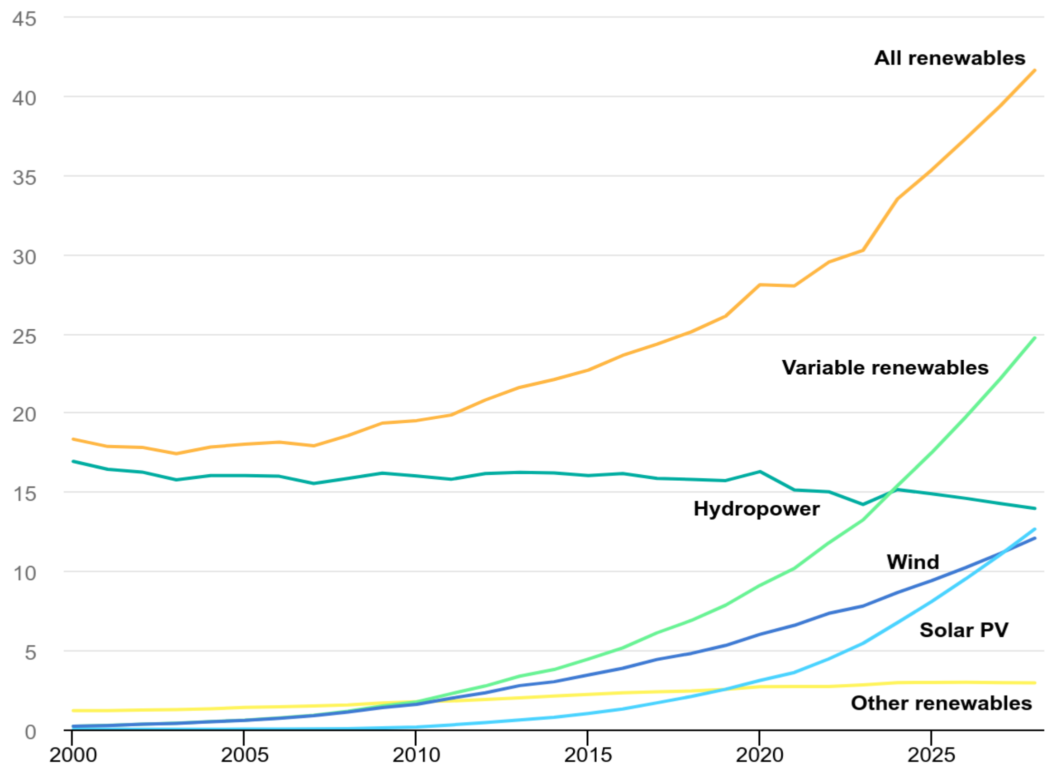


Figure 3. Share of renewable electricity generation by technology, 2000 to 2028

Figure 3 presents the share of renewable generation from 2000 - 2028. However, it's important to note that these predictions do not forecast future curtailment of wind and solar PV, which could potentially be significant in certain countries by the year 2028 [12].

In countries with extensive hydroelectric resources, such as Brazil, Colombia, Canada, New Zealand, Sweden, and Norway, renewable energy sources constitute a historically significant portion of their electricity generation, exceeding two-thirds. On the other hand, in other countries, the implementation of progressive renewable energy policies coupled with a decrease in the cost of producing electricity from solar and wind technologies has accelerated the development of renewable power. This has notably enhanced the proportion of renewable energy sources within their energy mix. Specifically, in Europe, this proportion has witnessed a 43% growth since 2010, marked by notable surges in the United Kingdom (43%), the Netherlands (40%), Germany (44%), and Turkey (42%). Similarly, the prevalence of renewables in the energy composition has escalated by 31% in Australia, 55% in Chile, 22% in the United States, 31% in China, 22% in

Japan, 18% in Thailand, and 10% in South Africa. Figure 4 indicates the share of renewable energy sources in 2022, breakdown by country in percentage.

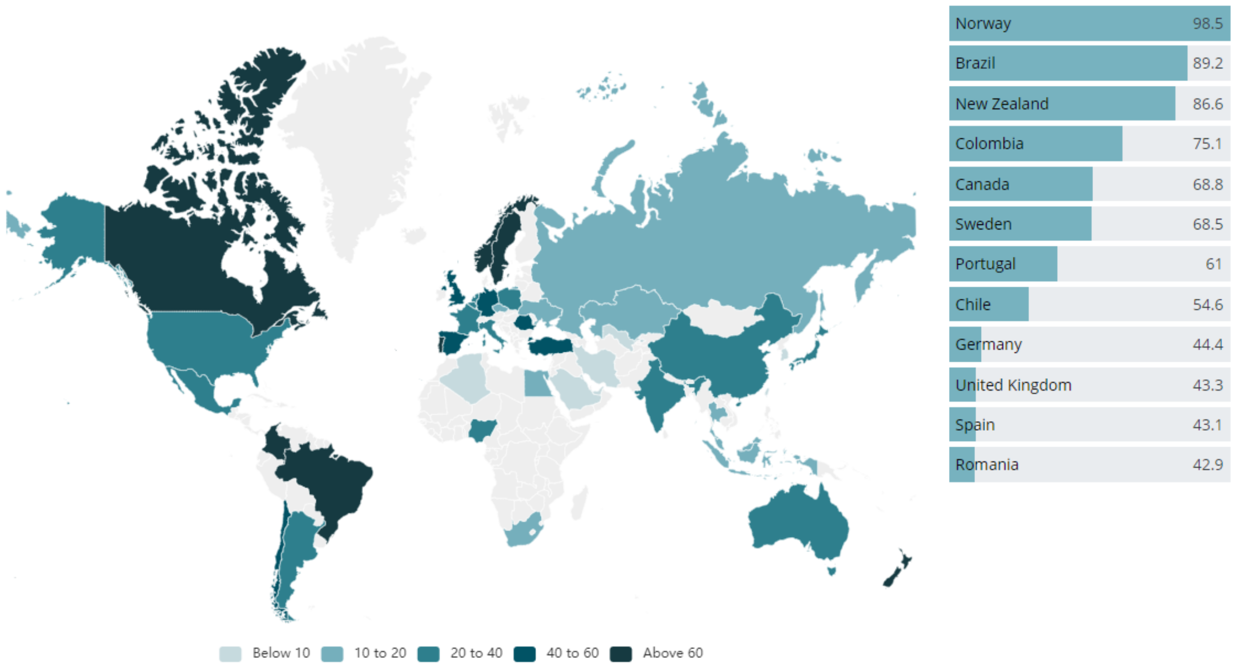


Figure 4. Share of renewable energy sources globally in 2022 – Unit: % [13].

1.4.1. Use of Renewable Energy Sources in Canada

Canada holds a prominent position globally in the production of electricity from renewable and non-emitting sources. Beyond its longstanding and substantial hydroelectric resources, the country has experienced a notable expansion in non-hydro renewable energy, mainly wind and solar, during the previous ten years. The anticipation is that electricity generation from renewable sources will persist in its upward path, propelled by rising electricity demand and the ongoing decarbonization of Canada's electricity generation sector.

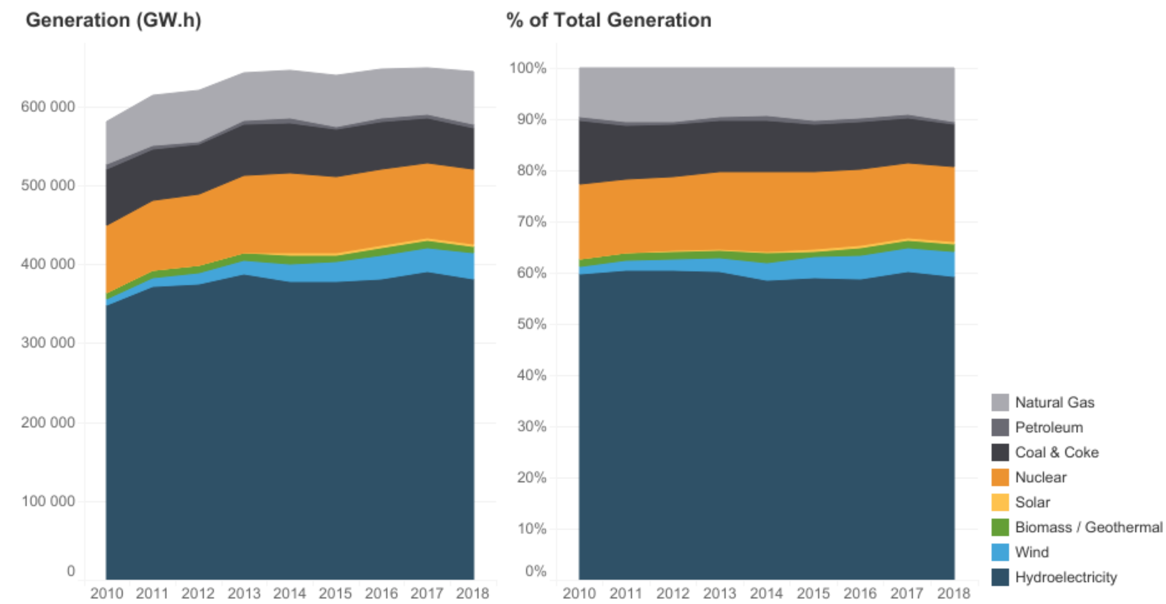


Figure 5. Renewable energy sources electricity generation by type, 2010-2018 [14].

Figure 5 illustrates the upward trend in electricity generation from renewable sources in Canada between 2010 and 2018. In 2010, renewable energy accounted for 62.8% of the country's total electricity generation, amounting to 364,681 gigawatt-hours (GW.h). By 2018, this share had increased to 66.2%, representing 425,722 GW.h. while the electricity generated from thermal sources, including nuclear, coal, coke, natural gas, and petroleum, decreased during the same period of time. In addition, Fig. 5 highlights that in 2018, hydroelectric power was the leading source of electricity in Canada, representing 59.4% of its total electricity output. Yet, the availability of hydro resources varies significantly across the country. Regions such as Alberta, Saskatchewan, and Nova Scotia primarily depend on fossil fuels like coal and natural gas for their electricity generation due to a lack of adequate hydro resources. Conversely, in Ontario, the major source of electricity generation is nuclear power, which distinguishes it from the other provinces. In Québec, nearly 95% of electricity generation comes from hydroelectric power, positioning the province as a leader in the use of renewable energy for electricity production. This reliance on hydroelectricity has allowed Québec to emerge as a forerunner in advancing the use of renewable energy sources in Canada's electricity sector. Additionally, Fig. 5 reveals a positive trajectory in the generation of electricity from renewable sources throughout Canada between 2010 and 2018. The contribution of renewable energy to Canada's total electricity output increased from 62.8% (equivalent to 364,681 gigawatt-hours, or GW.h) in 2010 to 66.2% (or 425,722 GW.h) by 2018, which illustrates a considerable increase in the integration of renewable energy sources into the country's electricity generation mix. Figure 6 presents the proportion of electricity produced from renewable energy sources across various provinces in Canada for the year 2018. According to this figure, adopting renewable energy sources in place of fossil fuels for electricity generation in Canada will also contribute to the reduction of GHG concentrations in the atmosphere.

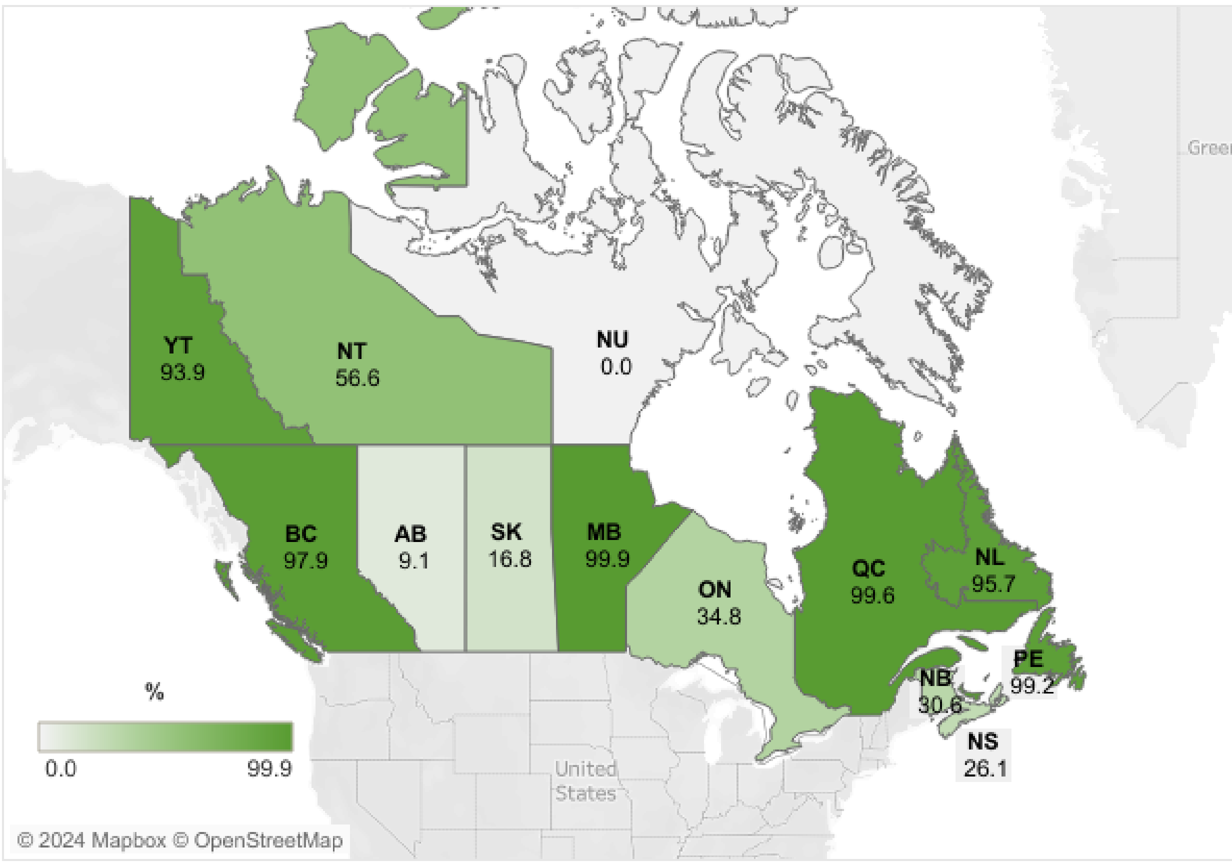


Figure 6. % of energy produced in Canada by using RES in 2018 [14].

1.5 Considering Electric Vehicles to Reduce the GHG

EVs are increasingly recognized for their potential to save energy, reduce pollution, and protect the environment. This makes the promotion and adoption of EVs crucial for decreasing our reliance on oil, enhancing energy security at national and regional levels, and supporting sustainable economic and social development. Acknowledging these benefits has led to a strategic focus on encouraging the widespread use of EVs.

The oil crisis of the 1970s, along with escalating environmental concerns, prompted developed countries like the United States, Japan, and Germany to begin research and development aimed at improving EV technology. These initiatives have resulted in the establishment of a robust technical foundation and a comprehensive market system for EVs. As fluctuating oil prices continue to affect economies and the urgent need to reduce GHG emissions grows, the shift towards EVs has become a significant trend in the global automotive industry, indicating a direction that is expected to progress further in the future.

With increasing awareness of the depletion of fossil fuels and the environmental damage they cause, there's a global shift towards electrifying transportation. Road transport significantly contributes to air pollution and greenhouse gas emissions. Transportation is responsible for 30% of nitrogen oxides, 10% of particulate matter, 54% of carbon monoxide, 14% of carbon dioxide, and 47% of non-methane hydrocarbon emissions worldwide [15]. In response to these environmental and economic challenges, countries around the world have begun to implement policies aimed at accelerating the adoption of EVs. These policies range from incentives for EV purchases to investments in charging infrastructure, reflecting a commitment to transition to cleaner forms of transportation. EVs offer a more energy-efficient alternative to internal combustion engine vehicles, thanks primarily to electric drive systems and regenerative braking technologies that capture energy during braking.

1.5.1. Electric Vehicles in Canada

Transportation plays a crucial role in driving socioeconomic progress throughout history, facilitating the movement of goods and services essential for human survival and development. However, the modern transportation sector is responsible for approximately 25% of global CO2 emissions from human activities, significantly impacting climate change. Transitioning to alternative fuels and enhancing transportation efficiency stands as a fundamental starting point in the journey toward decarbonization.

As one of the largest countries globally, Canada encounters distinct challenges in its transportation sector, particularly as the automotive industry undergoes rapid changes. Additionally, the rising global demand for energy, alongside the pressing issues of climate change and greenhouse gas emissions, presents a challenging obstacle to the advancement of Canada's transportation industry. The need for innovative solutions and policies to address these challenges is more crucial than ever, as they play a significant role in shaping the future of transportation in Canada and its contribution to global efforts in combating climate change.

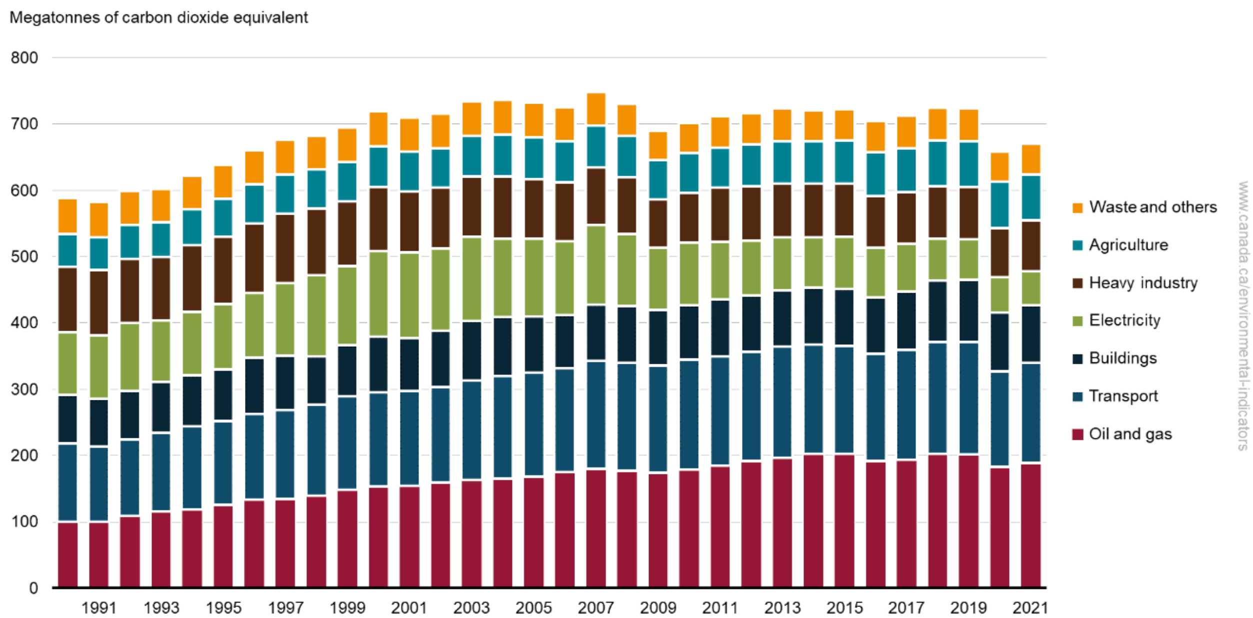


Figure 7. GHG across different economic sectors in Canada, 1990-2021 [16].

Following the Paris Agreement in 2015, Canada selected the year 2005 as the reference point for its GHG emission reduction goals. In addition, Canada committed to cut its GHG emissions to 40-45 percent below the levels of 2005 by the year 2030. Historically, after Canada approved the Kyoto Protocol, the year 1990 was established as the baseline year for measuring greenhouse gas emissions. Figure 7 illustrates the distribution of greenhouse gas emissions across different economic sectors in Canada from 1991 to 2021. It is evident that the transportation sector is the second-largest source of GHG emissions in the country, accounting for one-fourth of Canada's overall GHG emissions. Given these alarming trends, there's a worldwide push for a significant change towards vehicles that are more environmentally friendly, rechargeable, and efficient, aiming to promote a more sustainable environment.

1.5.2. Planning of Zero Emission Policy in Canada

To effectively combat GHG emissions and mitigate climate change, the Canadian government has placed a strong emphasis on the adoption of EVs as a sustainable alternative to cars powered by traditional combustion engines. This policy is part of a broader strategy aimed at reducing CO2 emissions while simultaneously providing financial relief to families by lowering their monthly bills. The encouragement toward EV use reflects a comprehensive approach to address environmental concerns and alleviate the economic pressures faced by Canadian households. This initiative gains further relevance in the context of global oil price unpredictability and an increasing determination among Canadians to lessen their environmental footprint. The unpredictable nature of oil prices, along with a national shift towards environmental sustainability, has prompted a growing number of households and businesses to explore alternatives to conventional gasoline and diesel vehicles. As a result, there is a notable shift towards zero-emission vehicles (ZEVs), supported by the government's measures to ensure a smoother transition for Canadians eager to adopt cleaner transportation options. In response to this trend, the Canadian government is taking steps to ensure an increase in ZEV availability for consumers. As a part of these efforts, the Government of Canada has introduced new regulations that establish mandatory ZEV sales targets for manufacturers and importers of new passenger cars, SUVs, and pickup trucks. These regulations require that a minimum of 20 percent of new vehicles sold in Canada must be zero-emission by 2026, escalating to at least 60 percent by 2030 and reaching 100 percent by 2035. The intention behind these targets is to boost the availability of ZEVs, thereby enabling more Canadians who wish to purchase a ZEV to find one available [16]. With the ZEV initiative, Canada aims for all new vehicles sold by 2040 to be zero-emission. In line with this objective, the Québec government has introduced two draft regulations designed to enhance the requirements of the ZEV standard. These regulations will provide Québec consumers with access to a greater variety and quantity of such vehicles and align with the government's goals for transportation electrification, specifically the target of having two million EVs on Québec roads by 2030. It also sets out the structure for the proposed restriction on the sale of gasoline-powered light-duty vehicles by 2035 [17]. This initiative is a significant step towards achieving the province's environmental and sustainability objectives, ensuring a cleaner and more sustainable future for transportation in Québec.

Despite a clear plan to reach this goal, several obstacles delay the widespread adoption of EVs. One major challenge is the relatively high initial purchase price of EVs compared to traditional gasoline vehicles. Even though it's anticipated that the cost of EVs will equal that of gasoline vehicles by 2025, the upfront cost remains a significant barrier. A survey by British Columbia Hydro indicated that 56% of people in British Columbia think EVs are too costly [18]. Research by the National Renewable Energy Laboratory in 2018 highlighted that individuals earning more than $100,000 annually are more motivated to buy EVs in Canada, which is less common among those with lower incomes. Supporting this, the Tesla S and Tesla X, priced over $96,000 and $110,000 respectively, were the highest-selling battery electric vehicle (BEV) models in British Columbia in 2017, according to British Columbia Hydro. Like many products, the demand for various electric and hybrid vehicles is closely tied to their cost, including the purchase price, operating expenses, and the total cost of ownership [19]. Residents of suburban and rural regions, predominantly from low and middle-income groups, often hesitate to purchase electric and hybrid vehicles. This hesitancy is primarily because, although EVs are less costly to maintain than vehicles with internal combustion engines in the long run, the upfront costs of purchasing or leasing EVs can be excessively expensive. While the reduction in battery costs and the availability of financial incentives to buy EVs represent positive developments, the option to purchase gasoline vehicles continues to appeal to many due to their more affordable initial prices. A significant barrier to the broader adoption of EVs in Canada is the lack of sufficient charging infrastructure. The growing presence of EVs on Canadian streets is not matched by a corresponding investment in charging facilities, which haven't been as profitable as traditional oil infrastructure. This issue delays the shift towards more environmentally friendly electric and hybrid vehicles, highlighting the challenges in moving away from fossil fuel dependency.

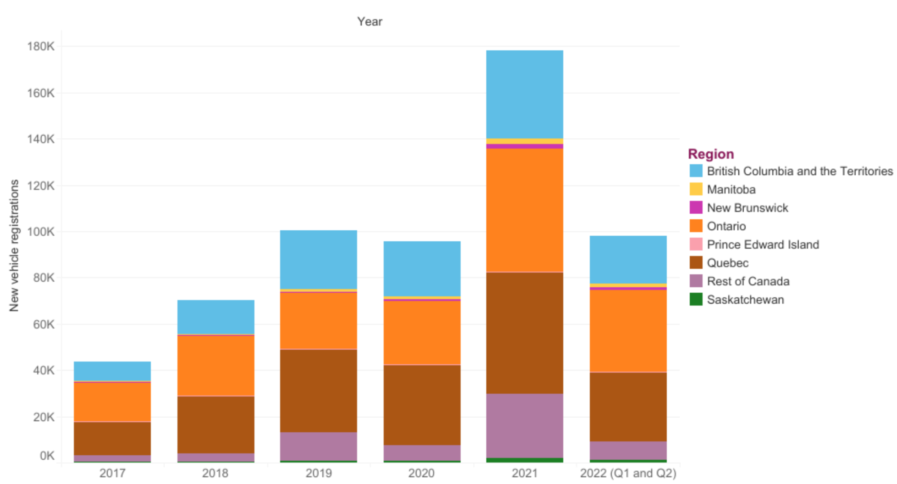


Figure 8. New HEV/PHEV/BEV registrations by region in Canada, 2017-2022 [14].

Figure 8 illustrates the registration trends for new hybrid, plug-in hybrid, and battery-electric vehicles in Canada. Despite the obstacles mentioned earlier, this figure demonstrates an increasing interest in EVs. It emphasizes the need for Canada to establish firm and strong measures, along with improving facilities to accommodate the growing demand for these new types of vehicles.

1.5.3. EVs Effects on the Environment

To prevent the push for EVs as a means to reduce transportation-related GHG emissions from leading to unwanted side effects, conducting thorough environmental evaluations of these technologies under different scenarios before their mass adoption is crucial. The method best suited for assessing the environmental consequences of transportation alternatives is the life cycle assessment. Life cycle assessment distinguishes itself by accurately measuring the use of resources and the emissions from the start to the end of a product's life. If EVs are used to lower GHG emissions, the environmental impact of EV batteries must be carefully considered. The production and processing of materials for batteries can lead to GHG emissions and, potentially, to the release of toxic substances. How the materials in batteries are managed when they reach the end of their useful life, whether through recycling, downcycling, or disposal, plays a significant role in the overall environmental impact.

Figure 9 illustrates a study by Argonne National Laboratory researchers, who calculated GHG emissions for both a gasoline-powered car and an EV with a 300-mile electric range. The blue bar in the figure demonstrates emissions from the manufacture of the EV's battery. The orange bars represent emissions from the remaining stages of car manufacture, such as material extraction, manufacturing and assembly of other vehicle components, and the vehicle's end-of-life activities, including recycling or disposal. The grey bars represent emissions that come from the generation of gasoline or electricity (based on the United States energy mix), while the yellow bar represents exhaust emissions generated during vehicle use.

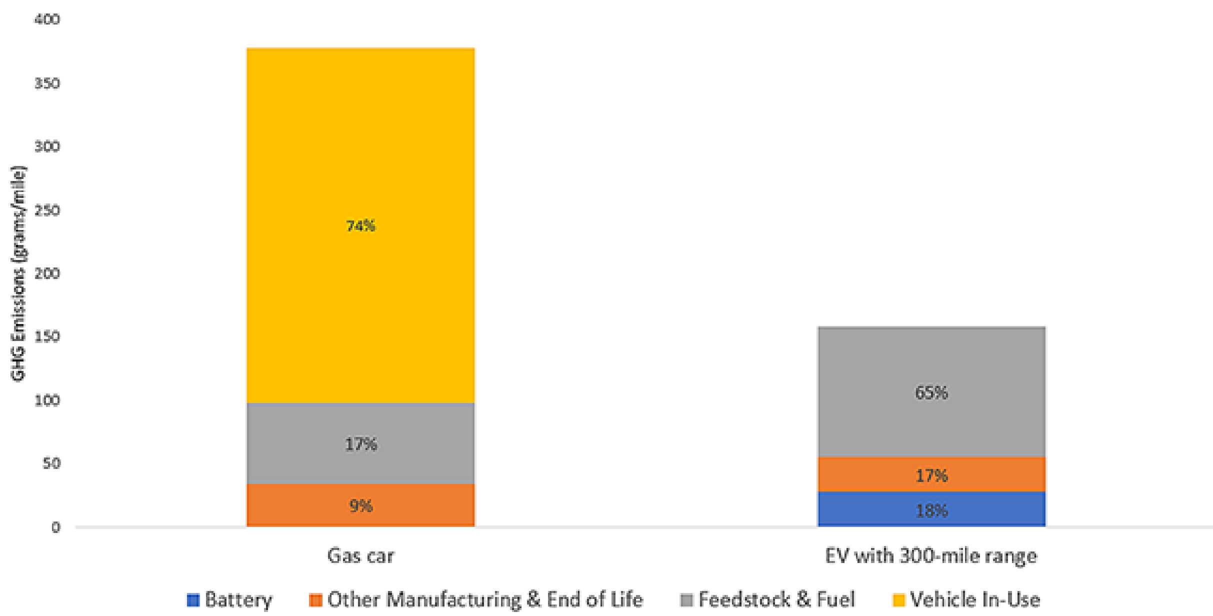


Figure 9. Lifecycle GHG for an EV and a Gasoline car

Recycling EV batteries plays a crucial role in reducing emissions by decreasing the need for new materials. Although there are current limitations, ongoing research is focused on improving both the effectiveness and efficiency of the battery recycling process. While GHG emissions from EV manufacturing and end-of-life processes are higher (as indicated by the orange bars), the overall GHG emissions of EVs remain lower than those of gasoline-powered vehicles [20], [21], and [22].

1.6 EVs effects on the grid

Generally, the power grids in many countries have enough capacity to handle the charging of EVs, particularly at night when the demand for electricity from other economic sectors is lower. However, significant issues could occur if EVs are charged during peak demand hours or if many EVs are charged within short time frames. According to the data presented in Fig. 8 and analyses of reports on the rising demand for EVs, a significant challenge facing power grids is the potential for uncoordinated charging demand from these vehicles. This challenge is made worse by concerns about how these new electricity demands will affect existing energy generation capacities. Particularly, the energy required to charge these vehicles is significantly higher than that of typical household electricity use. For instance, an average Nissan Leaf requires about 3.6 kW of power for charging, which is double the electricity demand of residential homes. Furthermore, the Tesla Model X requires an average of about 11 kW for charging [23]. This substantial energy demand from EVs underlines the possible pressure on power grids and has the potential to create an additional peak load on the power grid, particularly if the charging of EVs isn't effectively controlled and takes place during peak hours, which could lead to several issues including a decrease in the system's reliability, an increase in overall load demand, violating voltage limits, and increasing power losses within the grid. These issues highlight the importance of detailed planning and implementation of new technologies for grid management. Taking these steps is essential to make sure that adding EVs to our transportation systems doesn't negatively impact the stability and effectiveness of the current power infrastructure. Therefore, smart strategic planning and the introduction of intelligent charging systems are necessary. These measures aim to guarantee that the shift towards EVs doesn't negatively impact the stability and effectiveness of the current power infrastructure [24]-[25]. Given the points mentioned above, there's a growing focus on the importance of structured scheduling for the charging and discharging of EVs in power systems. Although the widespread adoption of EVs may initially pose challenges to the distribution system and may potentially increase energy costs for consumers. However, the integration of these vehicles with renewable energy sources promises to bring substantial benefits.

1.6.1. EV Charging Technologies

Considering the impact of EV charging on the power grid, the power transformer stands out as one of the most expensive components of the power distribution system. As the number of EVs grows, this increase can negatively affect power transformers by overloading them. Therefore, to address this issue, the implementation of smart charging techniques is necessary.

Multiple technologies are available for charging EVs, each with distinct working principles and associated advantages and disadvantages. These technologies are ranked based on their overall scores, considering several performance criteria, effectiveness, and suitability for different applications. EV charging technologies are primarily categorized into three main types: (1) conductive charging, (2) wireless charging, and (3) battery exchange or swapping. Conductive charging involves an electrical connection between the charging station and the EV, allowing it to provide power at various levels, namely Level 1, Level 2, and Level 3 charging. This method of charging is noted for its high efficiency in energy transfer due to its direct connection to the vehicle [26]. While Level 1 charging is commonly utilized at home, Levels 2 and 3 are predominantly used at public charging stations. Chargers that deliver power below 3.3 kW (1-phase) are classified as slow chargers or Level 1 chargers using 120V AC outlets. These can either be incorporated into the vehicle's powertrain or installed as a convenience outlet in residential settings. The charging time for Level 1 chargers is relatively lengthy, requiring approximately 4 - 11 hours for a 1.4 kW charge suitable for a PHEV battery with a capacity of 5–15 kWh and about 11–36 hours for a 1.9 kW charge appropriate for an EV battery with a capacity of 16–50 kWh. Level 2 chargers are capable of charging EV batteries with power outputs of up to 22 kW. They accommodate both single-phase and three-phase connections and use 240V AC outlets according to the US standard and 400V AC outlets following the EU standard. Like Level 1 chargers, Level 2 chargers can be integrated into the vehicle or be part of the dedicated Electric Vehicle Supply Equipment that is placed outside the vehicle. Depending on the power output and battery capacity, Level 2 chargers offer various charging time scenarios. For instance, a 4 kW charge for a PHEV with a battery capacity of 5 - 15 kWh takes approximately 1 - 4 hours. For an EV with a battery capacity of 16 - 30 kWh, an 8 kW charge requires 2 - 6 hours. Additionally, a more rapid 19.2 kW charge for an EV with a battery capacity of 3 - 50 kWh takes nearly 2 - 3 hours. In contrast, level 3 chargers are exclusively external installations as part of the Electric Vehicle Supply Equipment and offer power levels up to 200 kW. Level 3 chargers come with voltage outputs ranging from 208–240 V AC to 200–600 V DC, offering both AC and DC power options. These chargers are typically found in commercial settings similar to traditional filling stations, and because of their ability to charge quickly, they are known as fast charging stations. For example, a 50 kW fast charging station can charge a battery within 0.4 to 1 hour, while stations with a capacity greater than 90 kW can charge batteries in just 0.2 to 0.5 hours. The batteries compatible with these chargers typically have capacities ranging from 20 to 50 kWh [27]. The first two charging levels, Levels 1 and 2, exert a relatively minor impact on the electrical distribution system. In contrast, Level 3 charging can significantly impact the system, causing issues such as voltage deviations, reduced system reliability, and increased transmission or power losses. Moreover, the use of Level 3 chargers not only increases the peak demand but also potentially shortens the lifespan of transformers [28]. Additionally, conductive charging offers a V2G capability that can deliver several advantages to the electrical network. These benefits include reducing grid losses, maintaining voltage levels, preventing power overloads in the grid, supporting active power, and compensating for reactive power using the vehicle's battery [29].

1.6.2. Vehicle to Grid

V2G technology has recently achieved significant attention due to its potential to decrease reliance on small, costly electricity generation units and reduce the expenses associated with establishing these units. Additionally, V2G helps manage load and peak load fluctuations, provides primary frequency control, and improves network reliability. Furthermore, EVs can interact with electricity markets by exchanging the energy stored in their batteries, contributing to the economic dynamics of power systems. To facilitate this energy exchange from EV batteries into the markets, aggregators and microgrids can act together to serve as an interface [30]. In order to build a V2G system, the EV needs three factors, including a specific charger, power bi-directionality, and communication capability [27]. Thus, by having the advantages of bidirectional power exchanges, EVs are able to take part in the V2G system, which allows EVs to act as a battery backup source. Figure 10 shows the V2G system using bidirectional and unidirectional power flow.

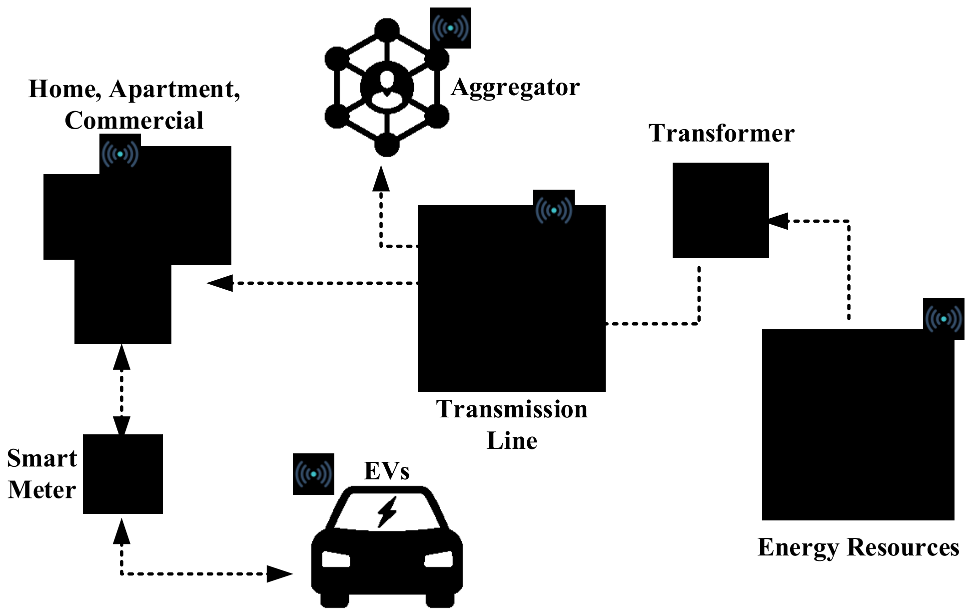


Figure 10. V2G system using bidirectional and unidirectional power flow

Additionally, under the assumption of uncertainty in the grid, V2G technology enables a bidirectional flow of energy, enhancing the interaction between the grid and EVs. In this scenario, EV owners are not only consumers of energy, but they can also become producers of energy thanks to the energy stored in their EV batteries. This capability transforms ordinary vehicle owners into active participants in the energy market, potentially stabilizing the grid and contributing to its efficiency.

1.6.3. Ancillary services

A power system's grid dependability, supply and demand balance, power quality, and other factors can all be managed using ancillary services. The V2G application mode can deliver the best ancillary services, such as voltage and frequency regulation, peak shaving, and load management, by using demand-side management.

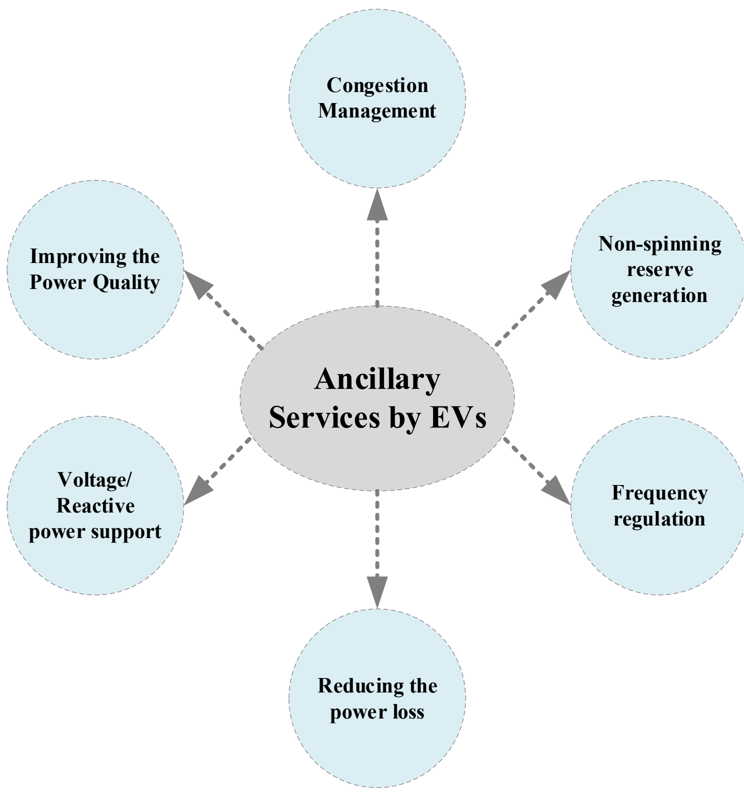


Figure 11. Ancillary services are provided by EVs

Additionally, in the event that the power system collapses due to the system operator's inability to keep the generation/load balance, ancillary services also offer the resources needed to restart the power system. Figure 11 shows the ancillary services that can be provided by EV smart charging. V2G technology can lead to peak shaving and load management by discharging the battery of EVs during peak hours and charging the battery during off-peak hours. This smart and coordinated charging and discharging scheduling of EVs can help the grids flatten the load demand as well as valley filling. In addition, the frequency of the power system is a vital indicator of the health of the electrical system. It provides a quick indication of the generation and load balance throughout the whole power system. When the load exceeds generation, the frequency decreases, and when generation exceeds load, it increases. Power system failure and equipment damage can be the result of significant frequency variations, which, using frequency and voltage regulations, make it possible to control these matters. Furthermore, due to the larger market demand for regulation and low stress in the power system from EVs, frequency, and voltage regulation are typically given a higher priority in V2G applications. Nowadays, large generators powered by fossil fuels are typically used to regulate frequency. Utilizing EVs and their battery capacities in this regard may be preferable because they can provide fast regulation by altering their charging and discharging modes.

According to all of the mentioned-above information regarding the smart use of G2V and V2G by considering smart charging and discharging management, EVs can assist the grid in increasing the reliability of the network, reducing the power loss, peak shaving, load management, as well as frequency and voltage regulation. In this context, and in accordance with the policies that countries have put in place to promote the use of EVs, investigating the implementation of EVs on the electricity network has become more important. Therefore, the following chapter will focus on the literature review and previous research that has been carried out in various search studies. This chapter will also highlight the gaps in past research and discuss the contribution of this research study. The third chapter of this study will be dedicated to modeling and equations. The case study and the results of this research are provided in chapter 4, while the final chapter is dedicated to the conclusion.

Chapter 2: Literature Review

2.1. Literature Review

To address the increasing demand for energy consumption and the growing market for EVs, which in turn increases charging demands, electric companies and system designers are turning to the use of smart grids. Smart grids are equipped to provide accurate monitoring and enable two-way communication between consumers and utilities, facilitated by the network operator. This technology allows for more precise management of energy flows and enhances the overall efficiency and reliability of the power system. Therefore, issues like the unpredictability of renewable energy sources, the charging and discharging of EVs, and high load demands can be resolved with careful planning, precise monitoring, two-way information sharing, and bi-directional power flow between customers and utilities. By implementing these strategies, power systems losses can be reduced, and system reliability can be greatly increased. An overview of the literature, including the advancements and developments made in this area, will be covered in this chapter.

The authors in [31] concentrated on enhancing interconnected EV charging points energy management. They introduced an innovative direct load control model designed to optimize the charging and discharging operations of EV batteries by aggregation units. This model incorporates plugged-in patterns, charging-discharging state, and individual battery characteristics. Furthermore, the model integrates decisions related to G2V charging, V2G discharging, and Vehicle-to-Vehicle (V2V) energy transfers, considering the hourly electricity prices to buy and sell energy in the day-ahead market of the Iberian System. In addition, to demonstrate the potential energy cost savings achieved with this model, a scenario was analyzed involving a parking garage with 50 plug-in vehicles exhibiting various mobility patterns, including household, commercial, and mixed. The study detailed in [32] analyzes the integration of EVs and demonstrates their capability to supply power back to the grid, enabling operators to utilize the energy stored in the EV batteries. This analysis was carried out using a typical scenario within the Western Danish power system, which is notable for its significant share of fluctuating wind power generation. The findings indicate that by employing this technology, the need for reserve power from traditional energy sources can be substantially reduced, showcasing the supportive role of EVs in enhancing grid stability and reducing dependency on conventional power sources. In reference [33], researchers applied an intelligent load management algorithm for the optimal charging of EVs.

The primary objective of this method is to enhance the reliability and security of distribution networks by minimizing voltage deviations, overloads, and power losses, especially in comparison to uncoordinated EV charging strategies. This approach presumes the presence of bidirectional communication between the system operator and the charging points, allowing for controlled management of the EV recharging process. In addition, the algorithm in this study divides time periods into distinct intervals, enabling customers to choose priorities for their charging intervals. At each step of the process, a sensitivity index is employed to select and utilize the most suitable EVs, aiming to decrease overall power loss effectively. The study in reference [34] presents an on-line adaptive scheduling system that aligns with the EV charging framework. This system is designed to optimize the charging schedules of EVs with the goal of minimizing network problems such as voltage limits, three-phase voltage variations, and transformer capacity violations. This is accomplished while considering the satisfaction of network constraints as key constraints. The framework is tested within the IEEE 33-bus distribution system and considers varying levels of EV penetration. This approach ensures that the charging infrastructure efficiently supports the increasing presence of EVs without compromising the stability and reliability of the electrical distribution network. In order to enable load shifting, the authors of reference [35] present a novel method for determining the best times to charge and discharge Plug-in Electric Vehicles (PEVs) that are connected to the grid in a decentralized manner. The scheduling challenge presented in this study is modeled as a mixed discrete programming problem, which is characterized as NP-hard and known to be extremely challenging to solve directly. The study employs the water-filling algorithm under the assumption that the energy exchange between the PEVs and the grid is bidirectional, leveraging both G2V and V2G technologies. This method allows PEVs to return energy to the grid, specifically targeting the shift of peak demand periods to enhance the overall load profile curve. In reference [36], the study explores the operation of a microgrid in a grid-connected mode, which includes a thermal power plant, renewable energy sources, and a parking lot for EVs. The management of this setup is achieved by implementing an optimal model that accounts for the energy supplied by EVs. The primary goal of the model is to minimize the overall anticipated expenses over the next 24 hours. These costs encompass generation costs, day-ahead market, battery wear, and real-time balancing costs. The model also considers challenges such as demand uncertainty of the EVs as well as the intermittent integration of renewable energy resources into the grid. To solve this complex problem, the Benders decomposition algorithm is used. The effectiveness of the proposed approach is demonstrated through simulations conducted using the IEEE 14 bus test system, highlighting its potential to enhance operational efficiency and cost-effectiveness in microgrid management. In reference [37], the study introduces an intelligent method for scheduling the utilization of available energy storage capacity from PEVs as well as EVs. This research provides a comprehensive review of the battery capacity of both PEVs and EVs, considering G2V and V2G capabilities. The primary objective function of this study is to maximize profits for vehicle owners while following the system constraints and satisfying the requirements of vehicle owners. To achieve this, the authors implemented an optimized charging and discharging schedule using binary particle swarm optimization. This method incorporates price curves obtained from the California Independent System Operator database. This approach not only enhances the financial benefits for EV owners but also ensures the efficient integration of vehicle energy storage into the larger power system infrastructure. In reference [38], the authors developed a practical conceptual framework designed to address the limited storage capacity of battery vehicles (BVs) by employing extensive aggregation. This framework capitalizes on BVs' deployment and physical attributes, maximizing their utility while parked by utilizing their batteries to contribute positively to the grid as both a load and a generation/storage device. In this regard, the aggregated BVs help stabilize the grid load during off-peak hours at night when the vehicles are charging. This action effectively reduces the necessity for down-regulation services during these periods by leveling the load. Conversely, during the daytime, when the BVs are parked, the aggregation of these vehicles can provide both up and down-regulation services and help with peak shaving. Consequently, the BVs serve dual roles: they act as controllable loads to stabilize demand and as generation/storage units during peak times to deliver capacity and energy services to the grid.

In order to optimize costs and emissions in power systems, the study in reference [39] presents an intelligent unit commitment (UC) strategy utilizing V2G technology. This study demonstrates that UC with V2G integration is significantly more challenging than conventional UC, which typically focuses only on thermal power units. The authors of this research employed a Particle Swarm Optimization method to effectively manage the trade-offs between cost reduction and emission mitigation in UC by considering the V2G approach. This approach was applied to the IEEE standard 10-bus system, where it demonstrated improved capabilities in balancing local and global search efficiencies, as well as optimizing the trade-off between operational costs and emissions.

The application of this strategy not only enhances the reserve and reliability of power systems but also contributes to reducing the negative impacts of climate change by optimizing the integration and operation of EVs within the grid. Plug-in Hybrid Electric Vehicles (PHEVs) are promoted as a promising technology to reduce fuel consumption in vehicles, thereby reducing transportation-related emissions and dependence on imported oil. Therefore, in order to lower greenhouse gas emissions, researchers in [40] looked at the effects of PHEV integration into the Ohio power grid. The study evaluated two distinct charging scenarios: controlled and uncontrolled, which provide the grid operator with varying degrees of control over the timing of PHEV charging. It has been proposed that the grid operator could delay PHEV charging to align with power system operations, potentially optimizing energy use. On the contrary, allowing PHEV owners to charge their vehicles whenever they are parked offers convenience but possibly leads to coordination losses and a potential increase in peak loads. However, this approach could decrease gasoline consumption for midday trips, offering a trade-off between grid management efficiency and fuel savings. In reference [41], researchers utilized the UC model of the Texas power system to simulate operations with various sizes of PHEV fleets without V2G service to evaluate the economic value of this service. The study introduced a model to manage the operation of power plants alongside a set of PHEVs capable of connecting to the grid. The primary objective was to demonstrate how a PHEV fleet could benefit the power system, particularly by providing ancillary services and reducing the need to reserve conventional generator capacity. The analysis indicated that PHEV owners benefit financially from offering V2G services, which also help shorten the payback period of the higher initial investment in PHEVs compared to other types of vehicles. The study modeled a controlled charging scenario in which PHEV charging is strategically managed by the system operator in accordance with power system operations while taking specific service requirements into consideration. This controlled approach showed that a PHEV fleet could yield significant savings to the power system, with potential annual savings of over $200 per vehicle in some scenarios. This highlights the significant operational and financial advantages of integrating PHEV fleets into the grid, especially when their charging is coordinated with system requirements. Reference [42] explores the possibility of lowering energy losses through different strategic charging and discharging procedures as part of the continuous investigation of efficient energy use in transportation, particularly with PHEV. The study highlights the effectiveness of a time-coordinated optimal power flow, which demonstrates how the network operators can minimize energy losses by effectively managing PHEV storage units and tap-changers. Additionally, the approach to storage modeling in this research involves piece-wise time optimization, which improves the accuracy and effectiveness of energy management. Furthermore, the batteries of the PHEV fleet are modeled collectively as if they were a large concentrated battery for the entire fleet. The aggregated modeling technique could allow for more simplified and efficient management of power resources, emphasizing the benefits of coordinated operational strategies in reducing overall energy consumption and losses. In reference [43], researchers developed a planning model that incorporates a fleet of PHEVs capable of connecting to the grid alongside wind turbines and demand response. This model was tested within the Illinois power system using four distinct charging scenarios: unconstrained charging, constrained charging with a three-hour delay, smart charging, and smart charging integrated with demand response. The findings from these simulations indicate that the implementation of a demand response program significantly reduces costs. The primary goal of the unit commitment model used in this study is to minimize the production costs of the power generation units while meeting the necessary load demand. Additionally, the PHEVs in this model offer valuable ancillary services to the power system, such as regulation and spinning reserves. They achieve this by strategically shifting their charging times from peak hours to off-peak hours, optimizing both energy utilization and cost-efficiency within the system. Innovative demand management strategies such as Time of Use (TOU) and Interruptible/Curtailable service are presented in reference [44] as effective tools to help in balancing the load profile. These programs serve as effective incentives for consumers to adjust or reduce their energy consumption in response to high energy price conditions on the power grid or in certain areas. This reduction typically occurs during peak demand periods, such as during the summer for electricity and the winter for gas. In addition, the TOU approach employs energy pricing strategies to encourage customers to use energy during off-peak hours when prices are lower. Under this approach, energy prices are set higher during peak hours and lower during off-peak hours. This pricing structure motivates consumers to shift their energy usage to off-peak hours, thereby reducing their overall energy costs. Consequently, this approach helps flatten the load profile curve and causes a shift in the hours when the customers will consume the energy. This contributes to more efficient energy utilization and enhances the stability of the energy system. In reference [45], researchers developed a functional model that utilizes V2G technology for the aggregation of PHEVs. This model is designed to manage the charging and discharging of

PHEVs with the goal of minimizing power losses in the IEEE 33-bus system. The study explored two different scenarios: controlled and uncontrolled charging. The study indicated that power losses were significantly reduced in the scenario where charging was controlled. This demonstrates the effectiveness of managing PHEV charging schedules over the uncontrolled approach in enhancing the efficiency of the power system.

The widespread adoption of EVs introduces a variable load demand to the power grid, necessitating a detailed investigation of the impact of EV charging on the operation of the distribution network. In this context, the authors in [46] developed a novel model to study the effects of G2V and V2G technologies within power systems. The primary goal of this study was to quantify the power exchanged between the grid and EVs to assess its impact on the demand profile, reliability indices, and stability index of the grid. To achieve this, the researchers initially analyzed real transportation sector data to identify daily patterns in G2V and V2G energy exchanges. Following this, the research examined how EVs influence the load demand curve and the stability and reliability parameters of the system. To enhance the accuracy of system reliability calculations, the improved minimal path method was employed which offered a more robust framework for assessing the resilience and efficiency of the power grid in the context of increasing EV integration. In reference [47], researchers introduced a novel model for intelligent charging and discharging of EVs within smart grids, designed to assess the impact of EV battery charging on the power system's load profile. To explore different management strategies, three distinct scenarios were simulated: uncontrolled charging, controlled off-peak charging, and smart charging. Each scenario aimed to shift energy consumption from peak times to off-peak times, with the ultimate goal of flattening the variation in the load profile. This strategy contributes to the stability of the power system and enables the more effective use of energy resources. In reference [48], researchers focused on a group of PHEVs connected to the grid, acting as a controlled load. By implementing a new charging schedule during off-peak hours, where they successfully flattened the grid load profile curve. To further explore this approach, the authors examined several scenarios projecting future penetration levels of PHEVs in the coming years, using Grid-for-Vehicle energy transfer as the main strategy. This research was applied to a case study in Portugal, exploring how strategic charging schedules can effectively integrate PHEVs into the grid to optimize energy distribution and enhance grid performance. In references [49] and [50], significant investments have been explored within the electricity and transportation sectors, particularly focusing on EVs. In [49], the study proposes a multi-objective, multi-stage collaborative planning model for EV charging stations and the power distribution network. This model considers the slow and fast charging needs of EVs based on the specific driving and travel patterns of vehicle owners. The primary goals of this planning model are to minimize investment and operational costs while maximizing the annually captured traffic flow to ensure effective use of the charging infrastructure. On the other hand, reference [50] presents a multi-objective model from the perspective of EV operators, which considers both the investments of service providers and their service capacity. A case study based on the real charge-swap service network of a specific city is used to implement both single-objective and multi-objective optimizations. These optimizations aim primarily to minimize the investment required by service providers, thereby enhancing the cost-effectiveness of deploying and operating EV charging facilities.

In electricity markets, demand response is a strategic tool used to manage customer consumption under specific supply conditions. The primary advantage and goal of demand response is to enable both consumers and power companies to benefit from an intelligently planned energy consumption schedule. Traditionally, power systems operated by quickly feeding load demands with available generation resources. However, the modern approach tries to minimize demand fluctuations to enhance system efficiency. The important aim of demand response is to smooth the system load profile curve by shifting consumption from peak hours to off-peak hours. This shift has traditionally been managed by using the TOU method, which encourages consumers, including EV owners, to adjust their charging schedules to off-peak hours. However, the effectiveness of this method is limited to conditions where electricity demand remains smaller than the electricity generation capacity. In this regard, with the initiation of Advanced Metering Infrastructures and Energy-Management Controllers, along with sophisticated and intelligent algorithms for demand response, the challenges of shifting peak-hour demand to off-peak hours can be more effectively addressed. In addition to dealing with excessive electricity consumption management, these technologies optimize EV charging schedules, improving process efficiency and responsiveness to the grid and consumer demands. This technological advancement ensures that the demand response mechanisms are more adaptive and beneficial in maintaining grid stability and reducing energy costs. In reference [51], the primary objective was to reduce the cost of electricity bills for customers. By focusing on minimizing the total cost of the customers' bills, the load curve is effectively flattened, resulting in fewer fluctuations for the electricity company. Consequently, this approach leads to a dual benefit: it not only minimizes the operational costs for the electricity company but also reduces the financial burden on customers. This strategy of load management not only improves system efficiency but also enhances customer satisfaction by making energy costs more manageable. The discussed article examines a smart grid system integrated with PEVs and renewable energy sources, such as solar cells and wind turbines. Within this system, there exists a market enabling customers to sell energy generated by distributed generators or the energy stored in their PEVs' batteries. To facilitate this, the article introduces an algorithm based on the Alternating Direction Method of the Multipliers, which enables efficient energy management. This method requires each consumer to report only their stored energy to the electricity company, which helps to maintain customer privacy. The pricing model used in the study is also divided into two categories: the base price and a fluctuation cost, which is considered for fluctuation in energy cost. The simulations conducted by the authors in this study also consider scenarios where users have the option to sell back the generated or stored energy to the grid, enhancing the flexibility and potential financial benefits of this integrated smart grid system. This model demonstrates a dynamic approach to managing energy distribution and pricing, promoting efficient energy usage and participation by consumers in the energy market. In addition, an electricity consumption model incorporates four types of load, including base load, scheduled load, the load from EVs connected to the grid, and distributed generators have been presented. By utilizing the Alternating Direction Method of the Multipliers algorithm, the centralized optimization problem is decomposed into distributed and parallel optimization problems. This decomposition proved effective, as it was demonstrated that the load curve became flatter, and there was a reduction in the cost of electricity bills for each customer. This method illustrates the potential of distributed optimization in improving energy management systems by simultaneously enhancing efficiency and lowering costs. A novel Mixed-Integer Linear Programming model is presented in reference [52] in order to address the problem of EV charging coordination in unbalanced electrical distribution systems. The expressions used to represent the steady-state operation of the distribution system by incorporating a three-phase representation of circuits and addressing load imbalances enhance the accuracy of system operations modeling. This model specifically addresses the problem of scheduling EV battery charging in a way that minimizes costs and maximizes efficiency in the distribution system. Therefore, a comprehensive, detailed 394-node distribution system was used to implement this program. The main objectives of this study are to minimize the cost associated with EV charging, to maximize the amount of energy charged into the EV batteries, and to reduce power losses throughout the system. The planning model in this study was implemented under three different energy management scenarios, including G2V and V2G, as well as energy exchange between two vehicles called vehicle-to-vehicle energy exchange. The simulations demonstrated that implementing a priority program for EV charging gives their owners the option to decide between more expensive fast charging and more affordable regular charging at a lower price, which is more cost-effective. The findings of this study highlight the effectiveness of this approach in addressing the challenges associated with EV charging coordination in distribution systems. Moreover, the results indicated that vehicles charged beyond the scheduled timeframe could weaken the voltage profile and increase energy costs. On the other hand, integrating these vehicles into the EV charging coordination program was able to mitigate these issues significantly and optimize both system performance and cost efficiency. In reference [53], a UC model was developed to manage the scheduling of various energy generators and consumers within a power system. This included components such as a wind turbine, PEVs, electrical batteries, thermal storage, and boiler systems, all operating under specific device and system constraints. Given the unpredictability associated with non-dispatchable renewable energy sources and the complex dynamics of power generation and demand, this UC model employed a probabilistic approach. This approach optimally schedules wind power, forecasts load demands, and manages the controllability of vehicles by outlining a microgrid structure. Subsequently, the model addressed the uncertainty associated with wind energy, load demands, and the integration of PEVs. In the third phase, an optimization program was created to include PEVs connected to the grid and enhance the model's applicability and effectiveness. In the final stage, a PSO algorithm was utilized as an advanced method to adjust the model within the circuit. The objective function of this study was to maximize the expected total profit from the UC schedule across various scenarios from the perspective of microgrid management.

Renewable energy sources offer the significant benefits of increasing electricity capacity and enhancing the resilience of energy systems. However, the fluctuation in the nature of renewable energy sources poses challenges, as it can lead to inefficiencies and instabilities in the power system. These variations often result in imbalances between the supply and demand of electricity. EVs, however, can play a crucial role in addressing these challenges by acting as mobile energy storage units. Integrating EVs into the power system will help the grid to store the surplus of the generated energy from renewable energy sources when production exceeds demand. This capability is critical in lowering the need to limit renewable energy resources, which happens when extra energy cannot be efficiently used. Using EVs to store and later utilize this surplus energy contributes significantly to increasing the integration and penetration of renewable energy sources into the electric grid. In this context, the authors in [54] investigated how to make a balance between demand and supply by incorporating electricity demand response and taking consumer comfort into account. In order to achieve this, they have developed a novel bi-level optimal dispatching model for the Combined Integrated Energy System with an EV Charging Station that works in various scenarios where there are multiple stakeholders involved. This model integrates a demand response program that accommodates the flexible thermal comfort requirements of users. In order to accomplish this, a predictive mean voting index within this model was introduced, aiming to achieve a balance between energy supply and demand while making sure that overall user satisfaction remains within acceptable limits. Furthermore, to guide EV owners in utilizing renewable energy sources, the authors propose a dynamic pricing mechanism. This mechanism integrates both TOU and Real-Time pricing strategies, designed to optimize the use of renewable energy sources by providing financial incentives based on the timing of energy consumption. This approach not only promotes the efficient use of renewable energy sources but also aligns with the principal goals of enhancing system sustainability and customer engagement. The concept of transactive coordination of PEVs was introduced in [55] as a strategy to mitigate the negative effects of their uncoordinated integration into the grid. The authors attempted to facilitate the involvement of these PEVs in a real-time retail electricity market, utilizing the principles of transactive energy and incorporating V2G technology. Under this strategy, PEV owners are encouraged to determine their willingness to pay or accept charges through a user-friendly approach and to communicate their estimated values to the retail market operator. Moreover, the study develops a network-constrained transactive coordination model that manages the charging of PEVs within real-time retail electricity markets. This model employs an agent-based modeling approach, which does not require access to the private information of PEV owners and enhances their privacy. With the help of this creative strategy, PEVs can be successfully integrated into the electrical market while maintaining the confidentiality of consumer data and balancing the interests of these owners with grid operational needs. In [56], the authors introduced a novel charging scheduling strategy designed to mitigate the negative aspects of EV charging while improving the overall convenience and efficiency of transportation systems, power networks, and charging stations. The research extended its scope beyond a single type of EV, incorporating diverse EV fleet types such as taxis, buses, and privately owned EV vehicles. Additionally, it considered the decision-making processes of drivers, which significantly influence the effectiveness of the charging infrastructure. The study identified three key decisions that drivers typically consider: 1) choosing routes that either have the least traffic or the shortest travel time to the charging station, 2) selecting charging or battery swap options that require the least waiting time, and 3) opting for the nearest station to minimize power consumption. Accordingly, the proposed scheduling strategy integrates considerations of drive time, wait time at charging stations, and the distance to each station. The objective of this study was to ensure the safe and efficient functioning of transportation and power infrastructures and charging stations in the context of large-scale EV utilization. This involves addressing a complex multi-objective optimization problem, aiming to balance various operational and user-preference factors to optimize the charging process across different types of EV fleets. A novel methodology aimed at mitigating economic limitations through the utilization of EVs is introduced in [57], focusing on the reduction of both energy waste and economic losses. This approach includes the development of a location-based incentive algorithm that considers the constraints of the distribution network, which avoids congestion. By incorporating the limitations of the distribution infrastructure, this algorithm ensures efficient and effective distribution of incentives to optimize the use of EVs within the system. In addition, a comprehensive response model has been developed to address the stochastic nature of EV arrivals that considers factors such as demand and price elasticity, time pressure, and charging stress. By employing PSO, the algorithm is able to account for the dynamic responses and behaviors of EVs, ultimately enhancing the efficiency and reliability of the charging infrastructure. In [58], three innovative pricing schemes are introduced for the day-ahead optimal scheduling of EVs, utilizing both centralized and decentralized architectures. These pricing schemes are designed to optimize the objectives of various stakeholders, including EV owners, aggregators, and distribution system operators, who influence one another's decisions. Specifically, the objective for EV owners is to minimize their charging costs while meeting their energy needs, whereas the distribution system operator aims to maximize its profit while following system constraints. Furthermore, the study effectively addresses the issues of valley-filling and rebound peak by adjusting the profit coefficients for each scheduling period and implementing penalty factors to mitigate transformer overloading, which ensures that the system remains balanced and efficient even under varying load conditions. In addressing the uncertainty associated with future EV demands, researchers in [59] have employed a scenario tree and Benders decomposition method to tackle the stochastic optimization problem. Consequently, they have developed a multi-stage stochastic programming model aimed at minimizing the total energy costs over a defined time horizon. This model is designed to provide a robust solution for managing the unpredictability of EV demand and optimizing energy usage. To implement this model, the study assumes a public parking lot where the charging schedules of EVs are systematically managed. Upon arrival, each EV owner specifies their energy requirements and departure time to the system. The system then promptly processes these inputs and provides immediate feedback, either fulfilling the energy demand or suggesting necessary adjustments. This real-time interaction ensures that the energy distribution is optimized, meeting the demands of EV owners while maintaining system efficiency and cost-effectiveness within the given timeframe. In [60], a detailed stochastic model for managing multi-mode EV charging is introduced, specifically designed to address the complexities associated with new photovoltaic-assisted charging stations and their uncertain characteristics. This model incorporates a comprehensive stochastic approach to account for EV charging demands, considering both semi-fast and fast charging modes. This enables the development of multiple EV charging scenarios, effectively addressing demand through stochastic programming techniques. To validate the effectiveness of the developed model, the study employs a benchmark mid-size charging station. This validation method demonstrates the model's capability to handle the uncertainties and fluctuating charging demands seen in photovoltaic-assisted charging stations. In [61], a two-stage stochastic approach is proposed for managing EV charging in a commercial parking lot, taking into account the uncertainties related to electricity prices, EV arrivals and departures, and charging demands. This approach employs a two-stage optimization framework that integrates Approximate Dynamic Programming with the Hybrid Big Bang Big Crunch algorithm. Additionally, a Multi-Layer Perceptron Artificial Neural Network is utilized to predict electricity prices. The primary objective of this optimization scheme is to minimize the costs incurred by the parking lot owner under the TOU and demand response program without affecting the welfare of EV owners. This innovative scheme controls the predictive capabilities of the Multi-Layer Perceptron Artificial Neural Network to forecast electricity price fluctuations, which are crucial for the effective implementation of the TOU and demand response program. As a result, the model optimizes the charging schedule to achieve cost savings for the parking lot owner without negatively impacting the experience or convenience of EV owners. A joint interval-based method was developed by the authors in [62] to manage V2G and G2V operations in a parking lot from the operator's point of view. They implemented an incentive/punishment system to encourage EV owners to discharge their vehicles during peak hours. The energy management strategy is divided into two steps. In the first step, a scheduling method is proposed to accurately determine charge and discharge times based on identifying joint time intervals and optimizing the number of these intervals. This method ensures accurate timing and maximizes the profits for EV owners by aligning their cost and profit preferences with the parking lot operator's schedule. In the second step, the authors present an innovative management approach for parking lots based on a set of rules and equations and the introduced incentive/punishment policies. This includes penalties for mismatched power flow directions and rewards for aligning EV power flow with the parking lot's needs.

2.2. Contribution of this study

Following the Paris Agreement, over a dozen countries have introduced regulations requiring that all new vehicle sales be fully electric by 2035 or sooner. This includes countries such as Canada, the United Kingdom, the European Union, China, Brazil, and India, as well as several U.S. states. Despite these significant policy shifts towards electrification and the transition to net-zero emission vehicles, the existing literature on EV development and their integration into the power grid has not yet fully addressed the implications of these recent commitments and policies [63]-[64]. Besides, none of these studies have employed real-data case studies to examine the impact of these new EVs on the actual power systems of a city by considering various travel patterns and times of the day. Additionally, the previously mentioned research studies have not compared their proposed smart charging methods to the basic V2G approach. In the basic V2G method, PHEV owners independently decide when to discharge and sell the energy stored in their batteries back to the grid without coordinated charging and discharging management. Consequently, this thesis aims to fill this gap by developing a model to investigate the future demands of PHEVs in accordance with the Canadian government's law to prohibit the sale of new combustion engine vehicles by 2035. Focusing on the city of Montréal, this thesis will concentrate on the increased adoption of PHEVs in this city by analyzing the effects of the unpredictable charging demands of these vehicles on both the current and future power systems using real data considering the Québec ambition to have 2 million EVs on the road of this province by 2030.

The objective of this study is to provide a comprehensive understanding of how these new policies and the consequent demand of these new PHEV charging demands will impact urban infrastructure and the grid in a real-world context. By addressing this crucial gap, the research seeks to provide insights into the challenges and opportunities that the transition to EVs under new governmental laws presents. In this regard, a multi-objective function problem will be presented in order to maximize the profit of the PHEV owners as well as decrease the power loss of the system. This problem will be solved by presenting a smart charging/discharging management that considers both G2V and V2G strategies. In addition, this work will introduce a separate V2G method in order to validate and compare the efficiency of the presented smart charging/discharging management. Eventually, the main contributions of this research study are summarized as follows:

- Presenting a new PHEV smart charging/discharging management and analyzing the effects of the growing number of these vehicles on the current and future electric grid of Montréal, in line with Québec's 2030 goals.
- Presenting a scenarios-based program that incorporates a multi-objective function, addressing the economic considerations for both utility companies and PHEV owners.
- Presenting a smart G2V/V2G management system that takes into account the TOU pricing scheme and validates its effectiveness by comparing it with an alternative V2G method.
- Modeling heterogeneous EV aggregation agents, incorporating different types of PHEVs with varying travel patterns based on diverse routes and times of the day.
- Considering different charging/discharging patterns in three different zones of the city of Montréal with various functions, including Commercial, Residential, as well as recreational zones.

The next chapter will be dedicated to the modeling, objective function, and constraints, as well as the methods presented in order to reach the best optimal solution to this problem.

Chapter 3: Modeling and Equations

3.1. Proposed Method

This thesis will focus on the impact of the increasing demand for new PHEVs on the distribution network, as their numbers are projected to rise in accordance with Québec regulations. Consequently, this chapter is dedicated to modeling the integration of PHEV into the grid, incorporating both G2V and V2G technologies. The primary objective is to analyze the effects of these vehicles and their associated demands on the distribution network. Additionally, this chapter will outline the technical and economic constraints relevant to the study, aiming to benefit both the utility companies and PHEV owners. Through this investigation, the study aims to contribute to a more efficient and sustainable implementation of PHEV and V2G technologies in order to assist the power infrastructure.

Technically, the penetration of PHEV primarily introduces additional distributed demand across the distribution network, overlapping with electricity demand during specific time windows. This is particularly due to immediate charging, where PHEV owners charge their vehicles immediately upon reaching home or workplace, regardless of peak or off-peak hours. Typically, PHEV owners plug in their vehicles as soon as they arrive, which might be early afternoon when they get home or approximately nine in the morning when they arrive at work. Additionally, it is assumed that PHEV owners expect their vehicles to be charged and ready for use by the next morning, either fully or above a certain threshold. In this case study, this threshold is considered to be an 80% charge level. This simultaneous charging behavior can lead to significant line overloading, causing severe power losses during peak periods. Therefore, this thesis aims to develop a multi-objective function that will optimize the charging and discharging processes of PHEVs. The primary objective function of this study is to maximize the benefits for PHEV owners. The secondary objective function is treated as a constraint focusing on minimizing network power losses. This dual approach strategy aims to enhance the overall efficiency and sustainability of the distribution network while ensuring optimal outcomes for PHEV owners. In the next section, the main objective function of this study will be discussed.

3.1.1. Objective Function

To optimize the charging and discharging processes of a large number of PHEVs within the distribution network, this study proposes a multi-objective program. The primary objective of this program is to maximize the profit for PHEV owners, which will be explained in the equations below.

$$OF = Maximize\,\{Benefit^{PHEV\_Owners}\} \qquad 3.1$$

$$Benefit^{PHEV_{Owners}} = \sum_{t=1}^{T}\sum_{n=1}^{N_{PHEV}}\{\left(P_{t,n}^{Dch} \times \omega_{t,n}^{Km} \times \alpha\right) - \left(P_{t,n}^{Ch} \times \beta\right) \qquad 3.2$$

$$-\theta \times \left(P_{t,n}^{Ch} + P_{t,n}^{Dch}\right)\}$$

Where the equation (3.1) and (3.2) explained the main objective function of this study. In these equations, θ presents the operation factor, which is the proportion of time in which the PHEV n participates in the charging/discharging process. This takes a value between 0 and 1. A value of 1 indicates full participation in charging or discharging, while a value of 0 means no involvement. Besides, $P_{t,n}^{Ch}$, $P_{t,n}^{Dch}$ demonstrate the amount of charge and discharge by PHEV n during period t. In addition, $\omega_{t,n}^{Km}$ represents the distance traveled by each PHEV based on GPS data. This distance is used to determine the amount of energy that will be discharged from the battery of each vehicle. In equation (3.2), α and β also demonstrate the cost coefficient related to the discharge and charge of PHEV n during a period t expressed in dollars per kilowatt-hour, respectively.

3.1.2. Constraints of the study

The optimization problem presented in the previous section is subject to numerous technical constraints. These include power balance, distribution line capacity, line power flow limit, and voltage limit. Additionally, there are specific constraints related to PHEVs, such as charging and discharging limits and battery state of charge (SOC). These constraints are essential to ensure the system operates efficiently and to prevent issues arising from the charging of PHEVs, which are as follows.

$$\sum_{t=1}^{24} PG_t = \sum_{t=1}^{24}\sum_{n=1}^{24}\left[PD_t \pm P_{t,n}^{Dch/Ch} + PL_t\right] \qquad 3.3$$

Which PG_t presents the power generated and PD_t indicate the load demand of the neighborhoods for the time tth hour. Furthermore, $P_{t,n}^{Dch/Ch}$ demonstrates the amount of discharge and charge by PHEV n during period t. In addition, PL_t also shows the power loss of the distribution network in period t. In addition, considering the capacity of the distribution lines, which must transfer power within specific limits due to restrictions such as thermal limits, it is essential to address these constraints to ensure safe and efficient operation. This refers to the maximum current that can flow through the lines without causing overheating and potential damage, which is a critical factor in maintaining the integrity and reliability of the power distribution network. Consequently, Eq. (3.4) presents the constraint related to the distribution line capacity as follows.

$$S_{b,j} \leq S_{b,j}^{max} \qquad 3.4$$

Where $S_{b,j}$ in this equation represents the power flow of the lines between bus b and j called as distribution line capacity. In addition, $S_{b,j}^{max}$ shows its maximum capacity between bus b and j. In addition to the distribution line capacity constraint, which focuses on the physical capabilities and safety of the conductors and the maximum amount of electrical current that a distribution line can safely carry without exceeding its thermal limit, the line power flow limit primarily addresses operational considerations in an electrical distribution network. This limit is set to ensure system stability, maintain voltage levels within prescribed boundaries, manage the overall load distribution, prevent network overloads, and ensure the performance and reliability of the network. The line power flow limit constraint has been expressed in equation (3.5).

$$\left|P_{b,j}\right| < P_{b,j}^{max} \qquad 3.5$$

Where $P_{b,j}$ in this equation represents the power flow in the lines connected between bus b and j and $P_{b,j}^{max}$ shows its maximum capacity of the line connected between bus b and j. In this research, the voltage limit constraint for the distribution system is defined by establishing upper and lower voltage limits. In the context of an ideal voltage profile set to 1 per unit in an electrical distribution system, according to the American National Standards Institute (ANSI C84.1-2020), standards are typically defined within a specific tolerance range to accommodate usual operational fluctuations. For a nominal system voltage, this range is set at +5% to -5% of the nominal voltage, translating to a range of 0.95 to 1.05 per unit [65]. However, for the purposes of this study, a broader limit is set within a range of ±10%, with $V^{min} = 0.9$ per unit and $V^{max} = 1.1$ per unit. This adjustment allows the study to accommodate more extreme but still permissible fluctuations in voltage levels. Such fluctuations can occur under various operational conditions, especially with the integration of renewable energy sources and EVs that introduce additional variability into the system. By considering this wider range, the study aims to account for potential voltage variations that might arise due to these factors, ensuring a more robust and comprehensive analysis of the distribution system's performance under diverse conditions.

This allowable range will establish a standard whereby the voltage at any node b (from node $b = 1$ to n) should remain within these specified bounds. The equation regarding this constraint is shown below.

$$V^{min} \leq V_b \leq V^{max} \qquad for \qquad b = 1, 2, 3, \ldots, n \tag{3.6}$$

In addition to the aforementioned constraints, this problem will also incorporate several constraints specific to PHEVs which will be discussed further. These constraints are critical to ensure the proper integration and operation of PHEVs within the distribution network. One of the most important constraints to consider in the modeling of PHEVs is that each PHEV cannot be simultaneously charged and discharged within the same time period. This fundamental constraint ensures the accurate representation of PHEV operations and prevents any unrealistic scenarios in the optimization process.

$$X_{t,n} + Y_{t,n} \leq 1 \qquad for \qquad n \in N_{PHEV}, t \in \{1, 2, 3, \ldots, T\} \tag{3.7}$$

Where in this equation $X_{t,n}$ and $Y_{t,n}$ are for the binary variables for charge and discharge process of nth PHEV at tth hour. Additionally, in the operation of PHEVs, their battery charge balance must be considered. Thus, in Eq. (3.8), $SOC_{t,n}$ represents the SOC, indicating the amount of energy stored in the battery of PHEV n at period t. The energy consumed for traveling during hour t is denoted as $SOC_{t,n}^{Trip}$ and it is balanced with the energy remaining from the previous hour and the energy gained or lost through charging or discharging over the time interval. This equation will act as an accurate representation of the battery's energy dynamics throughout the operation, as follows.

$$SOC_{t,n} = SOC_{t-1,n} + \rho_n^{Ch} \times P_{t,n}^{Ch} - SOC_{t,n}^{Trip} - \frac{1}{\rho_n^{Dch}} \times P_{t,n}^{Dch} \tag{3.8}$$

$$for \qquad n \in N_{PHEV}, t \in \{1, 2, 3, \ldots, T\}$$

According to equation (3.8), ρ_n^{Ch} and ρ_n^{Dch} respectively represent the charge coefficient for the G2V and V2G processes. On the other hand, a minimum and maximum of energy range should be taken into account when PHEVs are either in charging or discharging mode, which is presented as follows.

$$E_{PHEV}^{min} \leq E_{PHEV} \leq E_{PHEV}^{max} \tag{3.9}$$

Where this equation presents the minimum and maximum amount of energy that is able to be stored in PHEV batteries.

3.1.3. Ɛ-constraint method

As mentioned earlier, the multi-objective optimization problem in this thesis includes two objective functions. The first objective was maximizing the profit of PHEV owners, which has been previously discussed. In this section, the focus will shift to the second optimization objective function and the method that will be employed to address this aspect of the problem. Therefore, this section will provide a detailed explanation of the second objective function and the approach that will be adopted in order to solve this multi-objective optimization problem effectively.

The aim of the second objective function in this study is to reduce the power loss as well as power generation cost within the network while simultaneously increasing the benefits for PHEV owners. Several methods can be employed to address this multi-objective function problem. One of the simplest and most commonly used techniques for multi-objective optimization is the weighted sum method. This method combines multiple objective functions by adding them together, each multiplied by a specific weight. By assigning appropriate weights to each objective function, the weighted sum method allows for the balancing of different goals, facilitating an optimized solution that considers both the reduction of power loss and power generation cost and the maximization of PHEV owners' benefits. However, this method has some disadvantages, including the need to convert all objectives to a single type to solve the problem. Additionally, a uniformly distributed set of weights does not ensure a uniformly distributed set of Pareto-optimal solutions [66]. Furthermore, two different sets of weight vectors do not necessarily result in two distinct Pareto-optimal solutions, while the Ɛ-constraint method has a better performance in this matter. The Ɛ-constraint method is another approach for performing multi-objective function optimization. In this method, one objective function is selected to be optimized while the other objective functions are constrained to specific values [67]. Given the specified constraints on the other objectives, this approach ensures that the solution is optimal for the primary objective. By constraining the additional objectives, the Ɛ-constraint method allows for a more focused optimization process, effectively balancing the trade-offs between multiple objective functions. In addition, this method is the preferred approach for generating Pareto fronts because it produces a more robust curve and effectively avoids situations where the Pareto front is non-convex, which can pose challenges when using the weighted-sum method.

Therefore, in this thesis, to solve the optimization problem with the primary objective function of increasing the profits of PHEV owners and the secondary objective of reducing network power losses and power generation cost, the Ɛ-constraint method was applied and is formulated in the following equations:

$$OF = Max\{\varphi_1\} \tag{3.10}$$

Where

$$\varphi_1 = \sum_{t=1}^{T} \sum_{n=1}^{N_{PHEV}} \{ (P_{t,n}^{Dch} \times \omega_{t,n}^{Km} \times \alpha) - (P_{t,n}^{Ch} \times \beta) - \theta \times (P_{t,n}^{Ch} + P_{t,n}^{Dch}) \} \tag{3.11}$$

Subject to

$$\varphi_2 \leq \varepsilon \qquad for \qquad \varphi_2^{min} \leq \varphi_2 \leq \varphi_2^{max} \tag{3.12}$$

Where

$$\varphi_2 = F_{Cost\_Gen} + F_{Cost\_Loss} \tag{3.13}$$

In which F_{Cost_Gen} represents the total cost of generating the electricity which will be considered as electricity demand which will be formulated as below:

$$F_{Cost\_Gen} = \sum_{t=1}^{T} P_{Total\_Demand}(t) \times RTP \tag{3.14}$$

Where

$$P_{Total\_Demand} = \sum_{t=1}^{T} P_{Load\_Demand}(t) + P_{PHEV\_Demand}(t) \tag{3.15}$$

Where the real-time price will be considered as RTP. In addition, F_{Cost_Loss} demonstrates the total power loss of the system while CL presents the power loss cost coefficient which is shown below:

$$F_{Cost\_Loss} = \sum_{t=1}^{T} P_{TotalLoss}(t) \times CL \tag{3.16}$$

In this equation, $P_{TotalLoss}$ will also define as below.

$$P_{TotalLoss} = R \times I^2 = \sum_{t=1}^{T} \sum_{b=1}^{B} R_{b,b+1} \left(|V_{b+1} - V_b| |\mathcal{Y}_{b,b+1}| \right)^2 \tag{3.17}$$

Where the $R_{b,b+1}$, V_{b+1}, and $\mathcal{Y}_{b,b+1}$ represent the resistance, voltage, and admittance of the line section between node b and $b+1$ in period t. As can be deduced from Eq. (3.12), the second objective function, which is minimizing the power losses and power generation cost of the network, is constrained by φ_2 and can vary between φ_2^{min} and φ_2^{max}. Therefore, the optimization problem is solved for each value of φ_2, and the optimal results are obtained. Finally, a set of all optimal results obtained from various φ_2 raging between φ_2^{min} and φ_2^{max} can be presented as a Pareto optimal front. This Pareto front illustrates the trade-offs between the main objective function and the secondary objective, showing how variations in the primary objective function correspond to changes in the secondary objective function.

3.1.4. Optimization

Meta-heuristic algorithms are a category of stochastic algorithms widely employed to discover optimal solutions for complex optimization problems. In this thesis, the Particle Swarm Optimization (PSO) algorithm is implemented to effectively plan the charging and discharging management of PHEVs within the power network in order to enhance the profitability for PHEV owners while simultaneously reducing the power losses and power generation cost across the power grid. The PSO algorithm is a population-based optimization technique that draws inspiration from the social behavior observed in flocks of birds and schools of fish as they search for food. This behavioral analogy implies that individuals within a group move towards optimal regions by adapting to their environment. In the context of PSO, the dimensionality of the particles is determined by the number of variables in the optimization problem, and the efficacy of each particle's solution is evaluated using a fitness function. PSO is widely recognized as a form of swarm intelligence that can be seamlessly integrated into a multi-objective optimization framework and a powerful tool for determining the optimal values of complex functions operating on the principles of particle movement [68], [69], and [70]. Therefore, by utilizing this approach, both aims of this thesis, along with its multi-objective functions in the power network, will be solved.

3.1.5. Power Flow

There are several common methods that assist researchers in investigating the voltage profile and power losses in distribution power grids. Among these, the Gauss-Seidel and Newton-Raphson methods are popular techniques used to analyze the aforementioned network characteristics.

However, these conventional methods cannot determine the optimal operating points of radial and meshed distribution systems due to the high R/X ratio of feeders. This high R/X ratio poses significant challenges for achieving convergence and accuracy in power flow analyses using conventional techniques [71]. To address these challenges, the Backward/Forward Sweep Method is employed for power flow computations. This method is based on Kirchhoff's current law and Kirchhoff's voltage law, which are used in backward and forward sweeps. In this context, the Backward/Forward Sweep Method can be used to solve a system of differential equations, whether they are linear or nonlinear [72], [73]. In addition, this method is specifically developed to handle the unique characteristics of distribution networks, ensuring accurate and reliable results. By using the Backward/Forward Sweep Method, researchers can effectively analyze voltage profiles and power losses, overcoming the limitations of traditional approaches, which makes it a preferred choice for studying the complexities of distribution power networks.

The backward/forward sweep method begins by initializing the complex voltages at each bus using an initial guess. During the forward sweep, the power flow equations are integrated from each bus, calculating the resulting voltage magnitudes and angles at all other buses within the network. Subsequently, in the backward sweep, the voltage magnitudes and angles of one or more buses are adjusted based on the differences between the computed values and their desired values. This iterative process of forward and backward sweeps continues until convergence is achieved. Once convergence is reached, the optimal solution for the load flow problem is determined. It is important to note that while this technique is effective for solving simple linear and nonlinear problems, it can also be applied to more complex issues, such as optimal power flow or unit commitment. By combining the backward/forward sweep method with other algorithms or mathematical models, it is possible to efficiently solve even more complex optimization problems in power systems. In this thesis, the integration of the backward/forward sweep method with the PSO algorithm helps to handle a wider range of variables and constraints. This combined approach proves to be a powerful tool in the analysis and optimization of power distribution networks, including the charging and discharging management of PHEVs within the distribution power network. A flowchart of the proposed optimization process for the mentioned problem in this study has been presented in Fig. 12.

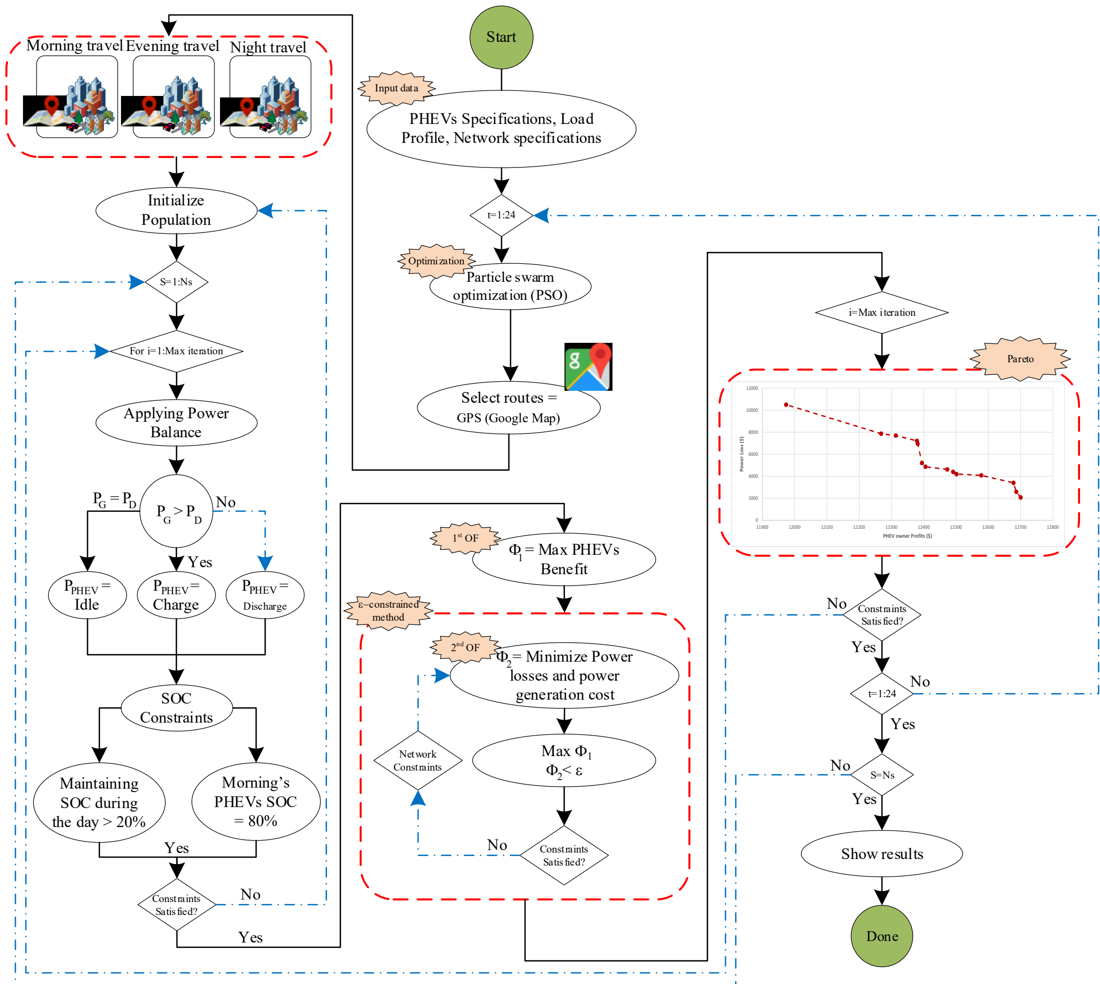


Figure 12. Flowchart of the proposed program

Chapter 4: Case Study and Results

4.1. Case Study

This chapter will focus on investigating the results obtained from integrating these PHEVs into the city of Montréal's power grid, with a step-by-step gradual increase in the penetration levels of PHEVs in alignment with the Québec government's goals. To investigate the effects of the gradual increase in the penetration of PHEVs and to provide charging and discharging management for these vehicles at different penetration levels on the power grid of the city of Montréal, this study was implemented and analyzed on the IEEE 69 bus radial distribution network. The distribution network was modeled using a real load profile dataset provided by Hydro Québec for three distinct parts of Montréal, including Côte Saint-Luc, along with Notre-Dame-de-Grâce, Downtown, and Quartier des Spectacles, along with the Old Port. Furthermore, these areas were categorized into three different types of loads, each characterized by its own traffic patterns, usage, and behavior, reflecting the unique travel habits of people in these areas during the day. This classification helps in understanding the varying impacts on the power grid and facilitates the development of developed charging and discharging strategies for each load type, ensuring a more effective and reliable integration of PHEVs into the city's distribution network.

As shown in Table 1, the Côte Saint-Luc and the Notre-Dame-de-Grâce neighborhood's load profiles are considered residential load profiles and include three different postal codes. Downtown, the second area, is categorized as a mixed commercial and residential load, including four different postal codes. The third area, Quartier des Spectacles, along with the Old Port, are considered commercial load profiles that include two different postal codes.

Table 1. Different neighborhoods, as well as the type and related postal codes

Zone #	Name	Type of Load	Postal Codes
Zone A	Cote Saint Luc + Notre-Dame-de-Grâce	Residential	H4W, H3X, H4V
Zone B	Downtown	Residential + Commercial	H3H, H3G, H3A, H3B
Zone C	Quartier des Spectacles + Old Port	Commercial	H2X, H2Y

Figure 13 presents the total load profile of these three areas, which were captured on February 1st, using per-unit values to maintain the confidentiality and sensitivity of the data. Figure 14 demonstrates the load profile dedicated to each postal code of Côte Saint-Luc, along with Notre-Dame-de-Grâce, Downtown Montréal, Quartier des Spectacles, along with the Old Port.

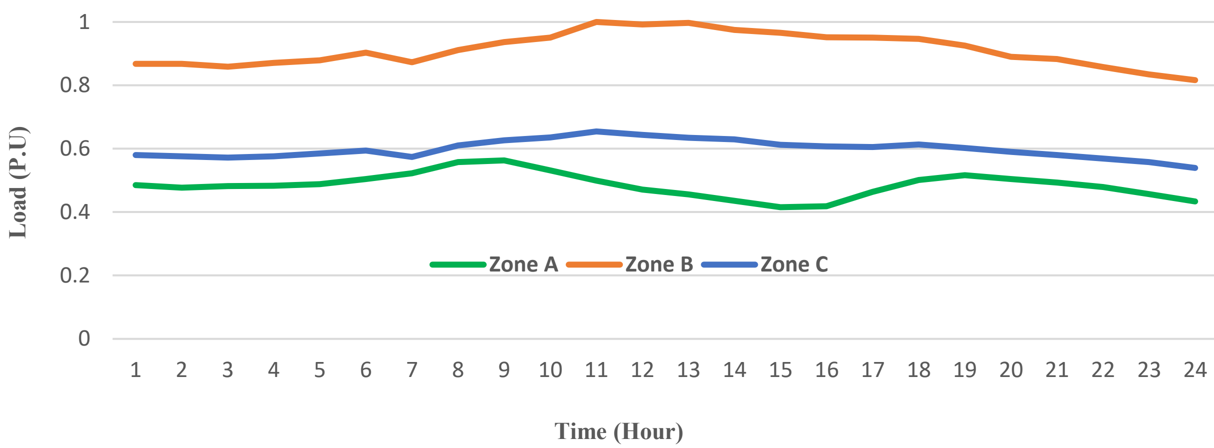
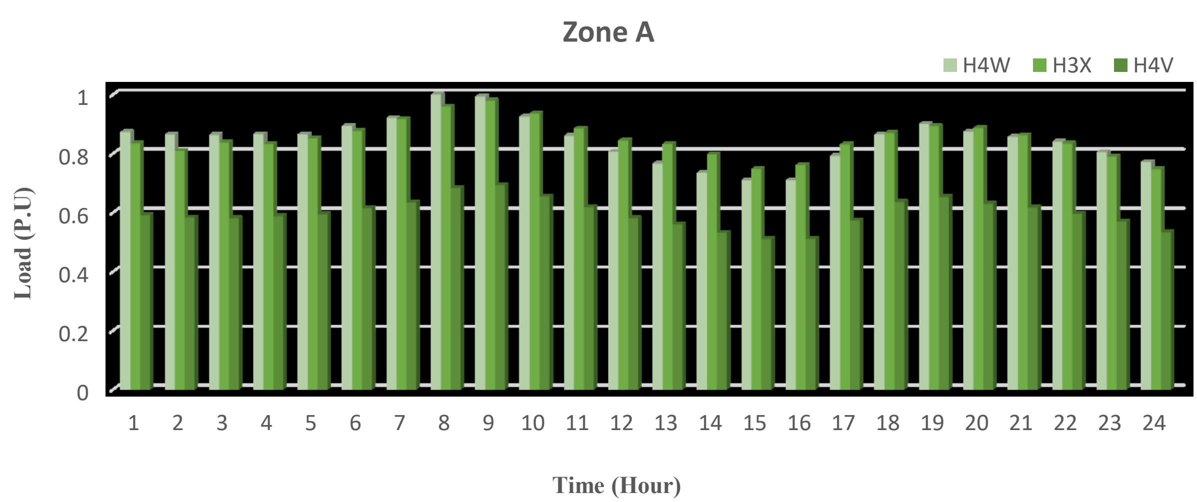
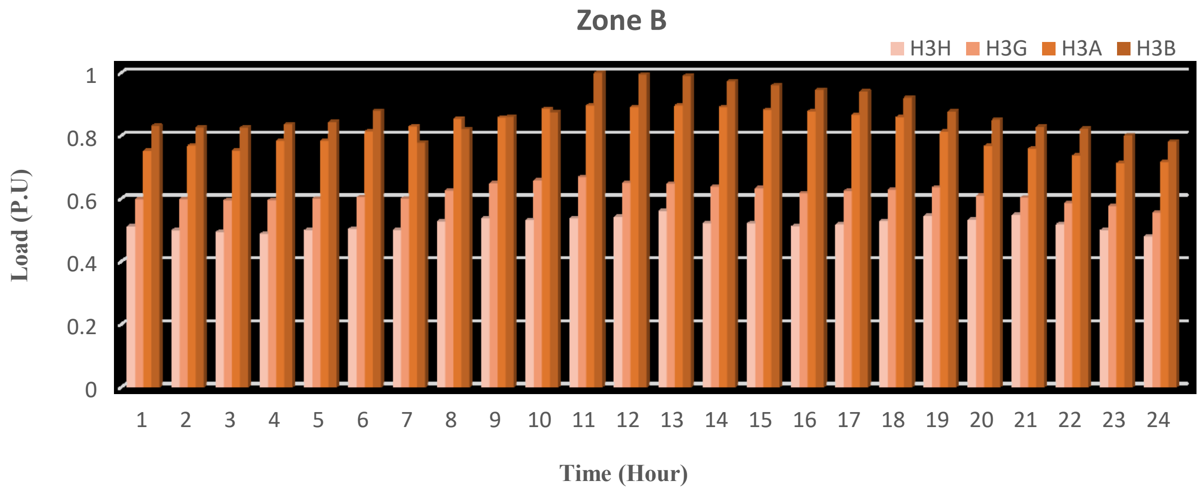


Figure 13. The total load profile of three zones in P.U

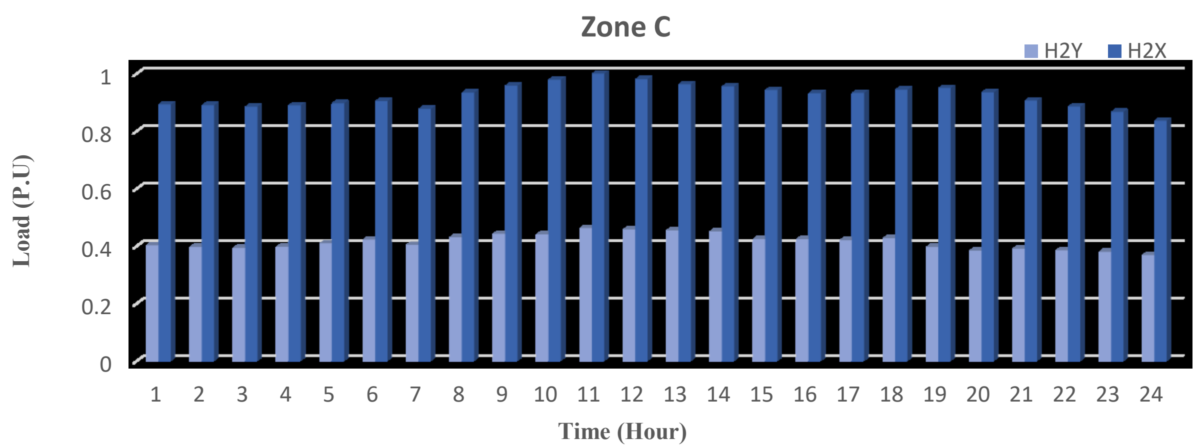
This detailed analysis enables this study to apply a comprehensive view of how different load types and geographical areas within Montréal and the behavior of the residents of that area could have a significant impact on the distribution network under various PHEV penetration scenarios. Consequently, to apply these load profiles to the IEEE 69-bus test system, this study assigned each area to a specific range of buses. Buses between nodes 51 to 69 have been designated as residential loads, representing neighborhoods such as Côte Saint-Luc and Notre-Dame-de-Grâce. Buses between nodes 1 to 35 have been considered as the downtown area, reflecting the commercial and mixed-use nature of this zone. Meanwhile, buses between nodes 36 to 50 have been allocated to recreational areas, including Quartier des Spectacles and the Old Port of Montréal.



(A)



(B)



(C)

Figure 14. Detailed load profile of the three chosen areas in the city of Montréal. (A). Load profile of Cote Saint Luc and Notre-Dame-de-Grâce (B). Load profile of Downtown (C). Load profile of Quartier des Spectacles and Old Port in P.U.

The reason for choosing these three different areas to implement this network is to better predict the behavior of PHEV owners and develop more accurate scenarios of their activities in the city. Therefore, Zone A includes two residential neighborhoods, Côte Saint-Luc and Notre-Dame-de-Grâce. These areas have been considered as residential load profiles in this study, as the majority of vehicles will travel and reside in these neighborhoods. Zone B represents the downtown area of Montréal, where PHEV owners frequently travel for work or shopping. This zone captures the commercial and mixed-use characteristics of a central urban area. The third zone, referred to as Zone C, includes areas where people go shopping and engage in recreational activities, such as attending festivals at Place des Arts located in Quartier des Spectacles. These areas are the primary locations for most of the festivals in Montréal. Consequently, this thesis considers these two areas as significant destinations where PHEV owners will travel for recreational activities. By considering this diverse zoning approach, this study has more potential to provide a comprehensive understanding of PHEV usage patterns and their impact on the power grid in diverse urban settings while considering the different behaviors of the PHEV owners. Figure 15 demonstrates the map of chosen areas in the city using the Geojson map [74]. In addition, Fig. 16 illustrates the detailed map of the three zones considered in this study separately, which helps to visualize the distribution and specific characteristics of each zone under consideration.

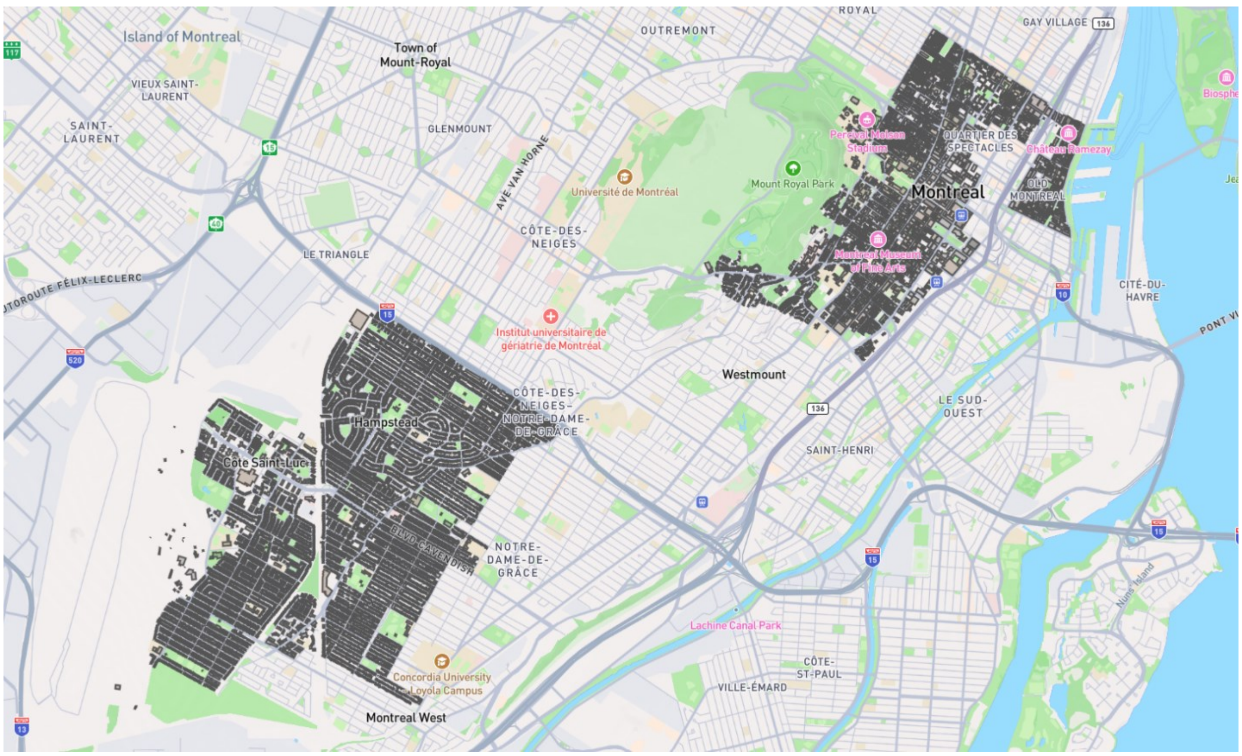
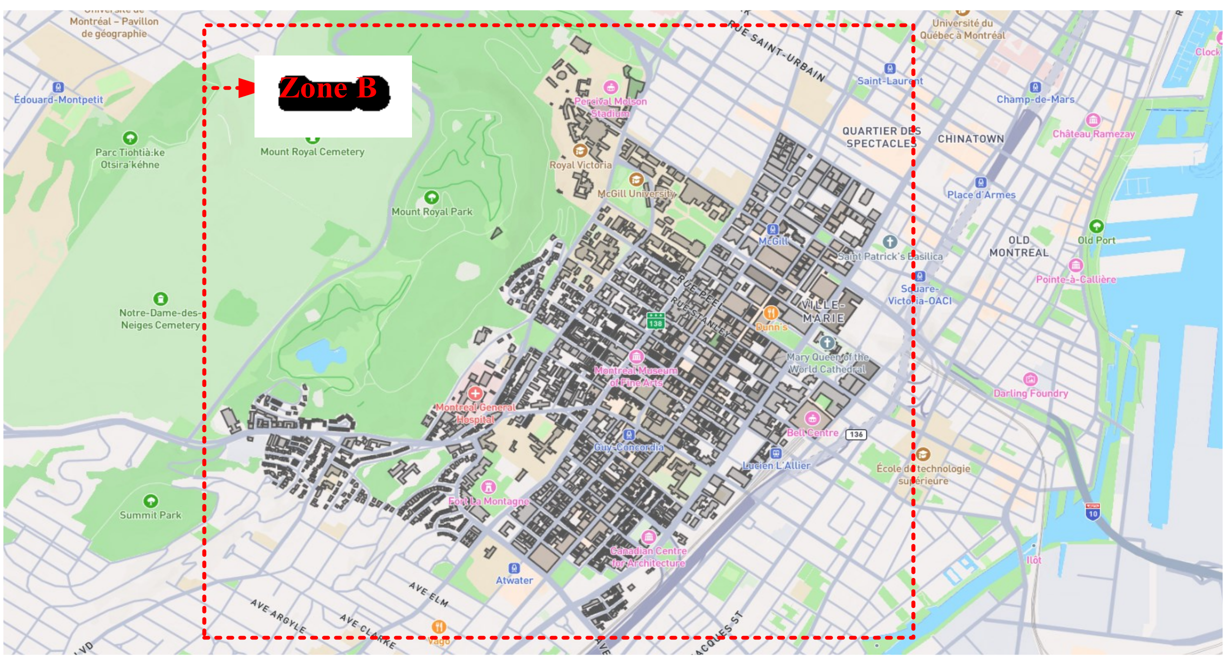


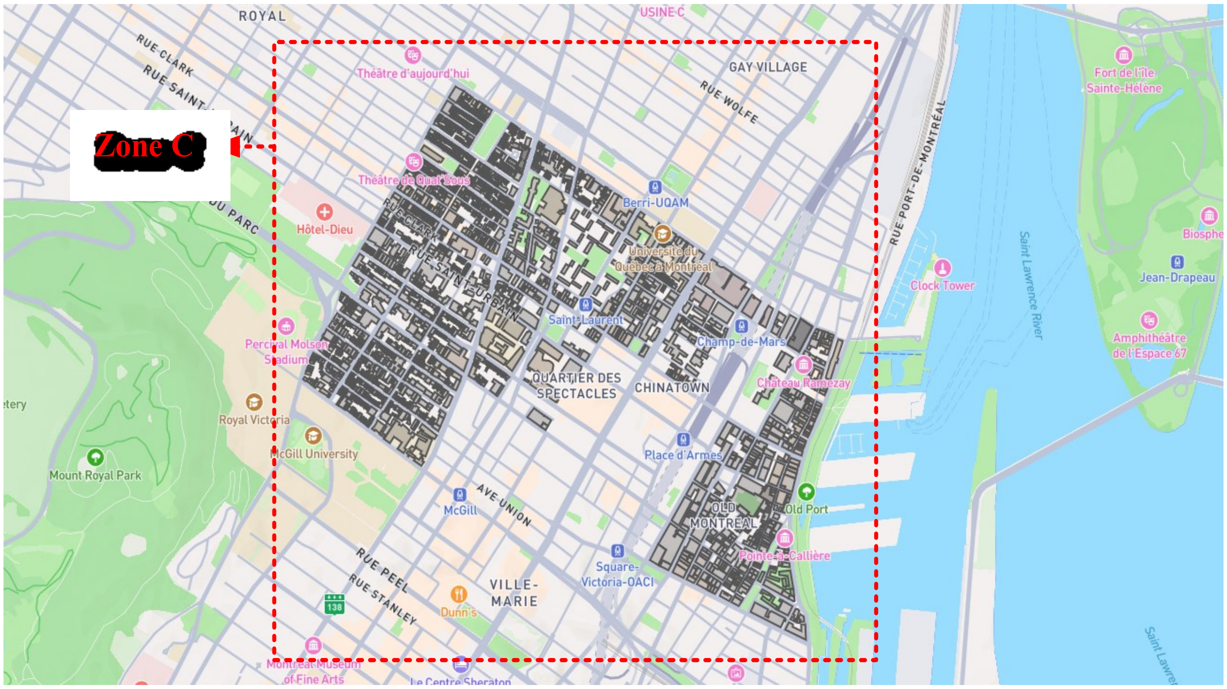
Figure 15. Map of the three chosen areas in the city of Montréal.


Zone A
Holiday Inn Montreal Airport
Travelodge Hotel by Wyndham Montreal Airport
CN Taschereau Rail Yard
Côte Saint-Luc
Hampstead
Hospital Mount Sinai
Hopital Richardson
Côte-Sainte-Catherine
Centre Segal des arts de la scène
CÔTE-DES-NEIGES–NOTRE-DAME-DE-GRÂCE
NOTRE-DAME-DE-GRÂCE
Marianopolis College
Summit Park
Westmount
Vendôme
Hospital Catherine Booth
Falaise Saint-Jacques
Concordia University – Loyola Campus
Montreal West
Lachine Canal
Lachine Canal Park
Famous Delly Boys
Bangkok Express
Aux Vivres
Meadowbrook

(A)


Zone B
Mount Royal Cemetery
Mount Royal Park
Parc Tiohtià:ke Otsira'kéhne
Notre-Dame-des-Neiges Cemetery
Summit Park
Édouard-Montpetit
McGill University
QUARTIER DES SPECTACLES
CHINATOWN
OLD MONTREAL
Old Port
VILLE-MARIE
Montreal General Hospital
Montreal Museum of Fine Arts
Guy-Concordia
Lucien-L'Allier
Atwater
Bell Centre
Canadian Centre for Architecture
Saint-Laurent
Champ-de-Mars
Place-d'Armes
Square-Victoria-OACI
Darling Foundry
Pointe-à-Callière

(B)



(C)

Figure 16. Detailed map of the three chosen areas in the city of Montréal. (A). Zone A, Cote Saint Luc and Notre-Dame-de-Grâce (B). Zone B, Downtown Montréal (C). Zone C, Quartier des Spectacles and Old port of Montréal.

Energy prices used in this study have been based on TOU pricing provided by Alectra Utilities Corporation in Ontario, Canada [75]. Alectra Utilities Corporation serves approximately one million homes and businesses across a 1,924 square kilometer service territory. This territory includes 17 communities such as Alliston, Aurora, Barrie, Beeton, Brampton, Bradford West Gwillimbury, Guelph, Hamilton, Markham, Mississauga, Penetanguishene, Richmond Hill, Rockwood, St. Catharines, Thornton, Tottenham, and Vaughan. Table 2-(a) and Table 2-(b) present the TOU rates applicable from May 01, 2024, to October 31, 2024, as well as from November 01, 2023, to April 30, 2024. It is important to note that the load demand data in this study was captured on February 1st, and therefore, the pricing used corresponds to the rates between November 01, 2023, and April 30, 2024. As can be seen in these tables, there are various pricing categories, which include Mid-Peak, On-Peak, and Off-Peak rates, applied during different hours of the day, including morning, afternoon, evening, and night, which are considered for weekdays. However, weekends and holidays are classified as Off-Peak throughout the entire day.

In addition, Table 3 illustrates the charging and discharging coefficients of PHEVs at various times of the day, considering different tariffs and periods.

Table 2. Time of Use Price Rates

(a). TOU rates from May 01, 2024, to October 31, 2024

Day of the Week	Time of Day	TOU Period	TOU Price
Weekends and Holidays	All day	Off-Peak	\$0.087 per kWh
Weekdays	7 A.M. – 11 A.M.	Mid-Peak	\$0.122 per kWh
	11 A.M. – 5 P.M.	On-Peak	\$0.182 per kWh
	5 P.M. – 7 P.M.	Mid-Peak	\$0.122 per kWh
	7 P.M. – 7 A.M.	Off-Peak	\$0.087 per kWh

(b). TOU rates from November 01, 2023, to April 30, 2024

Day of the Week	Time of Day	TOU Period	TOU Price
Weekends and Holidays	All day	Off-Peak	\$0.087 per kWh
Weekdays	7 A.M. – 11 A.M.	On-Peak	\$0.182 per kWh
	11 A.M. – 5 P.M.	Mid-Peak	\$0.122 per kWh
	5 P.M. – 7 P.M.	On-Peak	\$0.182 per kWh
	7 P.M. – 7 A.M.	Off-Peak	\$0.087 per kWh

Table 3. PHEV charging and discharging coefficient

Coefficient	Time of Day	Price
Charging β	7 A.M. – 11 A.M.	\$0.182 per kWh
	11 A.M. – 5 P.M.	\$0.122 per kWh
	5 P.M. – 7 P.M.	\$0.182 per kWh
	7 P.M. – 7 A.M.	\$0.087 per kWh
Discharging α	7 A.M. – 11 A.M.	\$0.182 per kWh
	11 A.M. – 5 P.M.	\$0.122 per kWh
	5 P.M. – 7 P.M.	\$0.182 per kWh
	7 P.M. – 7 A.M.	\$0.087 per kWh

While this study considers three different areas to capture the diverse load behaviors in different parts of the city of Montréal, it also aims to provide more accurate scenarios regarding the behavior of PHEV owners. As shown in Table 4, four different types of PHEVs were considered in the study to achieve more realistic and accurate results. These four PHEVs are among the best-selling models in Canada, which could help this study to simulate better real-world conditions [76]. The operating coefficient cost of PHEV is also considered to be 0.014$/Km [77]. Table 4 details the characteristics of these PHEVs, including type, acceptance rate, battery size, and electric range. It is worth noting that this study assumed that all PHEVs were equipped with V2G technology. This assumption was critical in determining the function of PHEVs in energy management and their ability to store and return energy to the grid via smart charging and discharging in this study.

Table 4. Detail characteristics of different PHEVs.

Type	Model	Acceptance Rate (kW)	Battery Size (kWh)	Electric Range (Km)
PHEV	Ford Escape	3.3	14	59
PHEV	Toyota Prius Prime	3.3	6.2	40
PHEV	Jeep Wrangler 4Xe	7.4	17.3	35
PHEV	Hyundai Tucson	7.2	13.8	53

As discussed previously, this study aims to analyze the impact of EVs on the Montréal power grid, which will consider the federal and provincial goals for increasing the number of EVs on the road in Canada. Consequently, this thesis will examine the impact of the step-by-step increase in PHEVs on the roads of Montréal in accordance with Québec's targets. The Québec government has established an ambitious goal to have two million light EVs on its roads by 2030. This target is set in response to the rapid increase in EV adoption, aiming to align with the growing trend and ensure sustainable transportation development within the province of Québec [17]. According to Statistics Canada, there were a total of 215,553 EVs registered in Québec by 2023, with 34.62% of these being PHEVs, accounting for approximately 74,661 vehicles [78], [79]. Additionally, data from the Institut de la statistique de Québec and Statistics Canada indicate that the current populations of Québec and Montréal are 8,572,020 and 1,762,949, respectively [80], [81]. Considering these numbers, it can be estimated that the current number of EVs and PHEVs in Montréal are approximately 44,317 and 15,342, respectively. Following the Québec target for 2030, the number of EVs and PHEVs in Montréal is projected to increase to 411,200 EVs and 142,357 PHEVs by 2030.

To analyze and better understand the increase in the number of PHEVs in the city of Montréal and their impact on the power grid, it is essential to have a comprehensive understanding of the behavior of these vehicle owners. Therefore, this study considers different potential behaviors of PHEV owners based on the aforementioned load profiles and neighborhoods. Consequently, the travel patterns of these owners have been examined, and various travel patterns have been developed to capture these behaviors. These patterns help in modeling the impact of PHEV adoption on the power grid more accurately by considering the specific characteristics of residential, commercial, and recreational areas. In this regard, four travel patterns during weekdays have been considered to capture the diverse behaviors of PHEV owners.

Travel Pattern 1: In this pattern, owners primarily spend their daytime at work. They travel from home to work in the morning and return home in the evening. This pattern has been considered to represent a simple daily commute.

Travel Pattern 2: Owners follow the same behavior as in Travel Pattern 1 but add an extra trip for shopping after work. This results in additional travel and increased energy consumption compared to Travel Pattern 1.

Travel Pattern 3: Owners engage in activities from Travel Pattern 2 and also attend festivals and events at the end of the day. This pattern involves two additional trips, leading to increased travel and higher energy consumption compared to travel pattern 1, as owners travel from work to shopping, then to festivals/events, and finally back home.

Travel Pattern 4: This travel pattern is for owners who do not work. They travel only for shopping and attending festivals and events at Quartier des Spectacles and Old Port. The travel pattern includes three trips during the day, which are from the residential area to the downtown area, from the downtown area to the recreational area, and finally from the recreational area back to the residential area.

The consumption of each vehicle is highly dependent on the route that each driver uses throughout the day. To enhance the accuracy of this study and its results, the routes suggested by Google Maps at different hours of the day have been utilized. This approach helps to avoid traffic and reduce travel time for vehicle owners. Consequently, various commute routes have been considered for each travel pattern. Table 5 illustrates the daily travel patterns of the owners in each pattern, who are commuting between the three mentioned neighborhoods: Côte Saint-Luc and Notre-Dame-de-Grâce (Zone A), Downtown (Zone B), and Quartier des Spectacles along with Old Port (Zone C).

Table 5. Total daily travel of PHEV owners in different travel scenarios.

Scenarios	Networks	Distance
Travel Pattern 1	Zone A and B	18 km
Travel Pattern 2	Zone A and B	19.5 km
Travel Pattern 3	Zone A, B, and C	24.7 km
Travel Pattern 4	Zone A, B, and C	29.2 km

Table 6. Travel patterns across various postal codes.

Scenarios	Postal Codes
Travel Pattern 1	H4W → H3H → H4W
Travel Pattern 2	H3X → H3G → H3B → H3X
Travel Pattern 3	H4V → H3A → H2Y → H4V
Travel Pattern 4	H4W → H3B → H2X → H4W

As shown above, Table 6 presents the travel patterns of PHEV owners throughout the day across different postal codes and neighborhoods.

4.2. Numerical results

This research aimed to analyze the impact of the increasing number of PHEVs in specific parts of the city of Montréal. The objective was to investigate the effects on Montréal's power grid and to propose solutions to mitigate these impacts in line with Québec's shift towards ZEVs. Therefore, the initial step will involve presenting the current state of the network after incorporating the load demand from the three above-mentioned neighborhoods where PHEVs do not participate in charging and discharging. Following this, the analysis will proceed in two phases.

In the first phase, the impact of the current number of PHEVs on the existing network will be examined. In the second phase, the number of PHEVs will be increased to assess the effects of this growth on Montréal's power network, aiming to meet Québec's ZEV targets. Within each phase, two scenarios will be considered. The first scenario will investigate the impact of immediate charging demand. In this scenario, PHEV owners will immediately charge their vehicles whenever they need to, without considering whether it is an off-peak or on-peak period for the network. The second scenario will focus on a smart charging and discharging program. In this scenario, PHEV owners will consider both the network's situation and the electricity prices. Unlike the first scenario, which only involves G2V charging, the second scenario is designed to be more intelligent. Owners will charge their vehicles during off-peak periods and discharge them using V2G technology during peak hours. This smart strategy helps to reduce the stress on the grid during peak hours and allows vehicle owners to profit by selling the energy stored in their vehicle batteries back to the grid.

Figure 17 presents the voltage profile of the current system without the contribution of PHEVs, considering only the load profile of the city of Montréal. Meanwhile, Fig. 18 illustrates the power loss in the network under the same conditions for the 24-hour period.

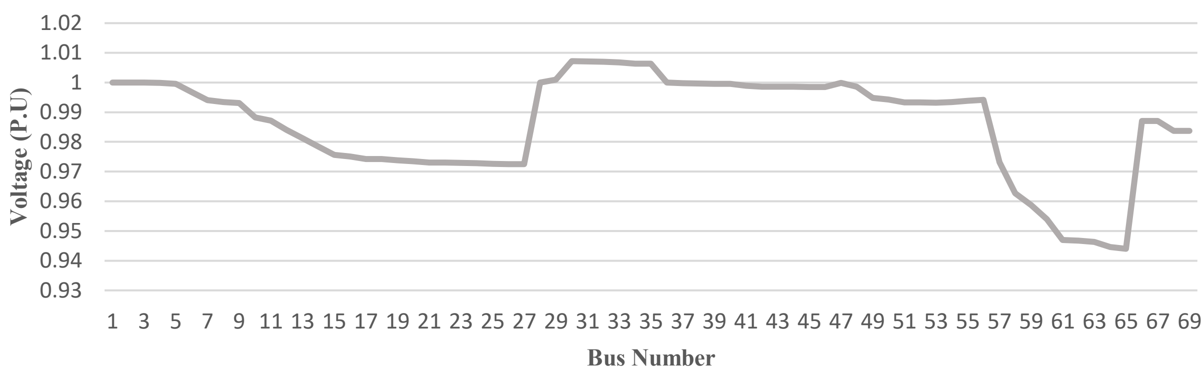


Figure 17. Voltage Profile of the system without the contribution of PHEV.

Figure 18. Power losses of the system without the contribution of PHEV.

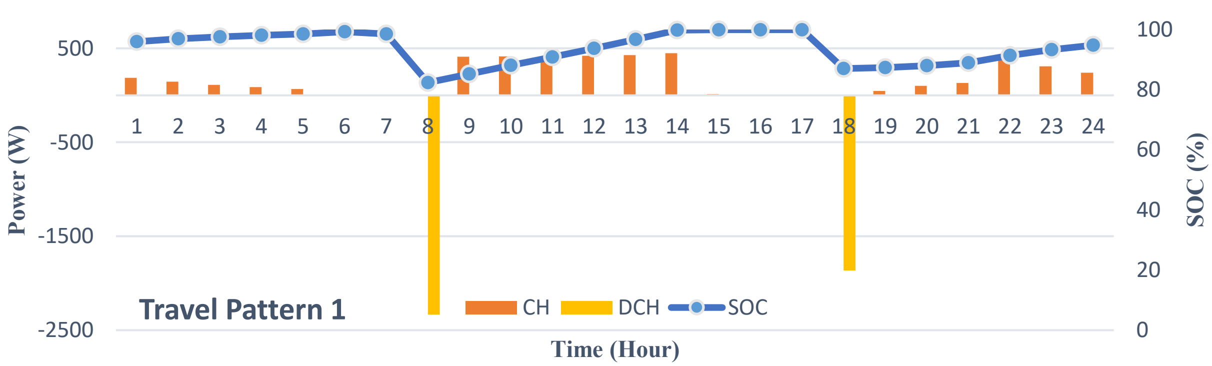
To analyze the effect of PHEVs in the network, we will first consider the current number of PHEVs in the city. However, since this study focuses on only three areas of the entire city, we will consider one-tenth of the current number of PHEVs on the roads of the city. Therefore, the results of the abovementioned study are as follows.

In the first phase, one-tenth of the current number of PHEVs on the roads of the city will be added to the existing network. Within this phase, two different scenarios will be considered.

Scenario 1 (Immediate Charging): In this scenario, only G2V technology will be applied, and it will mainly focus on the impact of uncoordinated charging on the network. Therefore, drivers will charge their vehicles immediately upon arrival, regardless of the network's peak or off-peak status.

Scenario 2 (Smart Charging): In this scenario, smart charging will be implemented. PHEV owners will not only charge their vehicles but also use V2G technology to transfer the stored energy in their vehicle's battery back to the network. This helps to alleviate grid stress during peak hours. In addition, this scenario will encourage drivers to charge their vehicles during off-peak hours in order to optimize both the cost and efficiency of the network and increase the benefit of the PHEV owners.

Figure 19 demonstrates the charging and discharging pattern of the current number of PHEVs, considering only the immediate charging scenario.



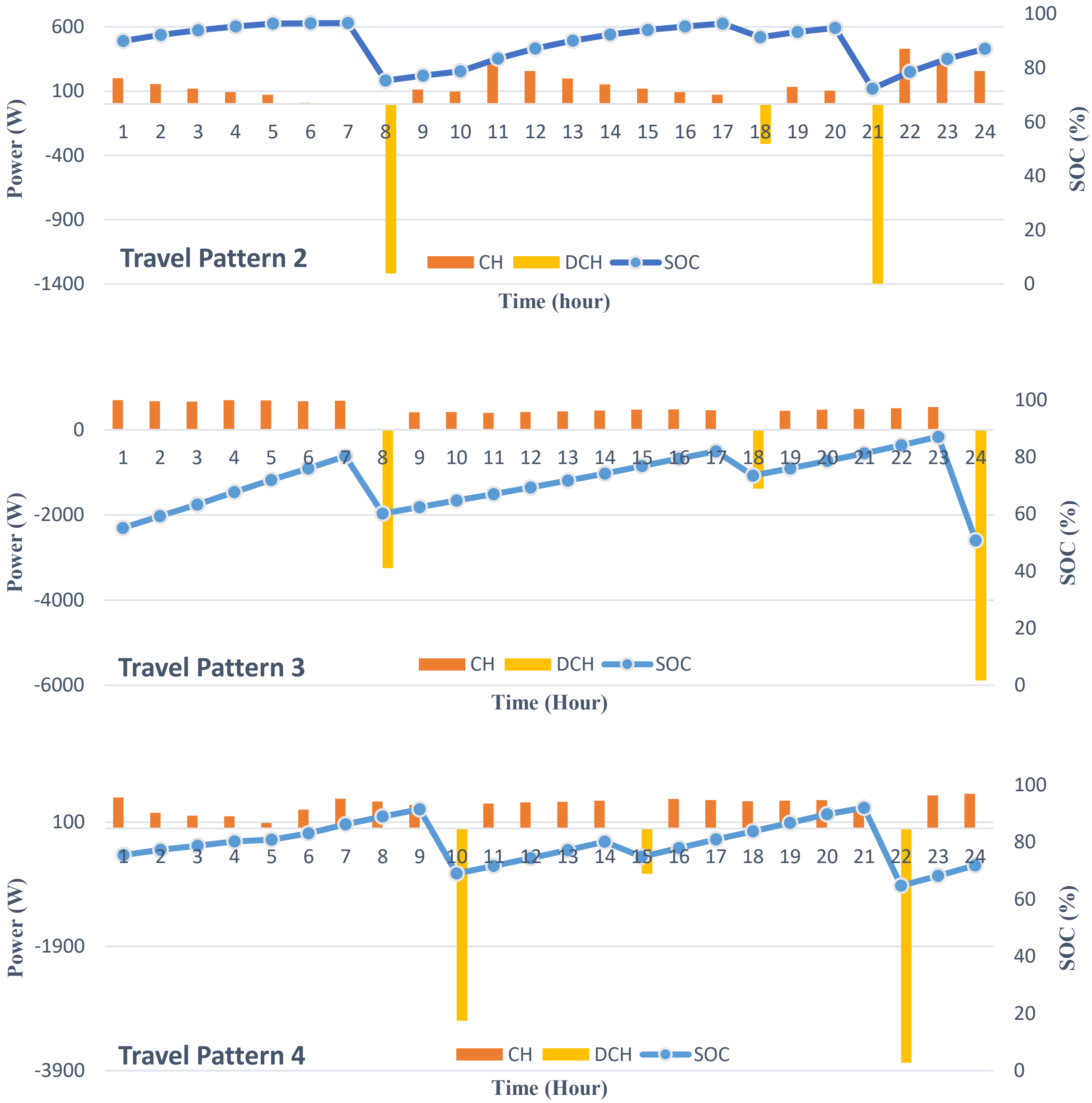


Figure 19. Immediate charging scenario for the current number of PHEVs in the city of Montréal under four different travel scenarios.

In the immediate charging scenario that has been shown in Fig. 19, all PHEV owners from the four travel scenarios will begin charging their vehicles as soon as they conclude their travel. This approach is taken to recharge their PHEVs without considering the grid's status, whether it is during on-peak or off-peak hours by only using the G2V strategy. This behavior of PHEV owners could significantly affect the reliability of the grid, as discussed earlier. In this regard, Fig. 20 presents a comparison between the power losses in the network with and without the contribution of the PHEV considering the immediate charging scenario where only the G2V strategy has been considered. Additionally, a comparison of the voltage profile for these two conditions at different hours of the day is presented in Fig. 21.

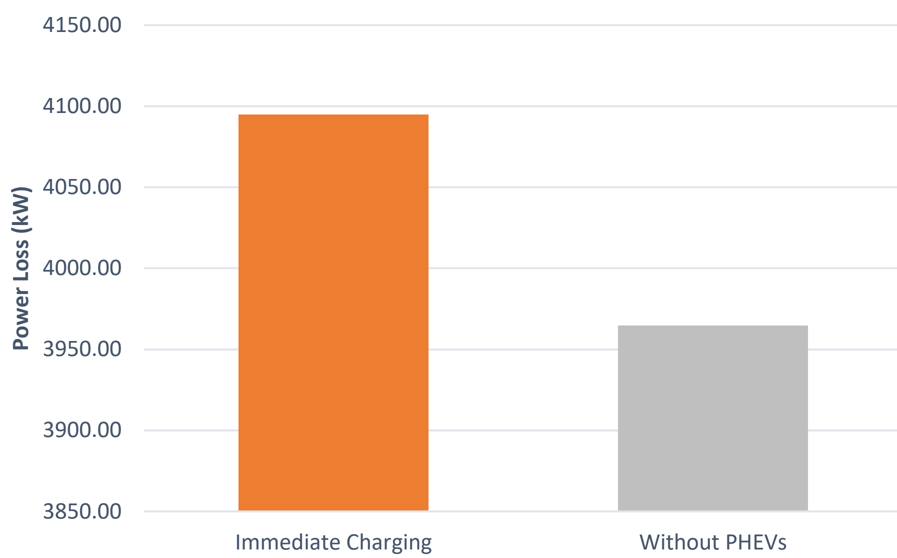


Figure 20. Power losses of the system considering immediate charging scenario.

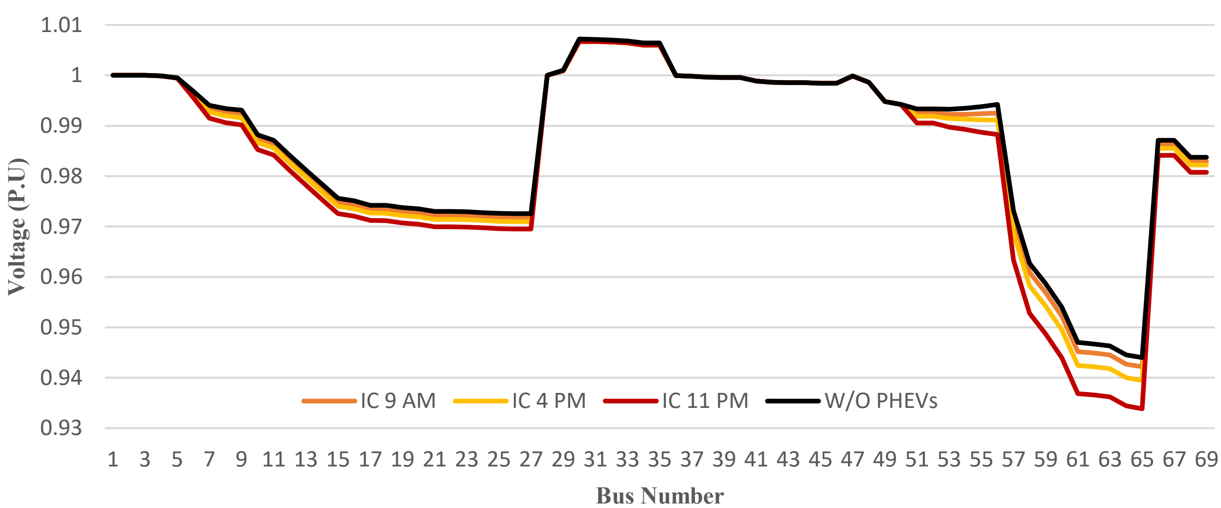


Figure 21. Voltage Profile of the system with and without PHEVs.

As can be seen in Fig. 20, the charging demand of PHEVs, without consideration of the network's load status, has resulted in an increase in power losses within the network. Additionally, Fig. 21 indicates that the PHEV's charging demand in the immediate charging scenario at different hours of the day, including on-peak, Mid-peak as well and off-peak, affects the voltage profile of the system negatively in comparison to the network voltage profile when no PHEVs were present.

To address the issues caused by the uncoordinated charging demand of PHEVs in the network, a smart charging scenario will be introduced. In this scenario, PHEVs can release the power stored in their batteries back into the network by selling it to the grid using the V2G discharging strategy. Several factors influence the decision-making process of PHEV owners in this scenario, including the network's load status (whether it is on-peak or off-peak hours), the price of charging and discharging, and their energy consumption for upcoming trips. By considering these factors, PHEV owners can optimize their charging and discharging schedules to increase their benefits and support the grid. In this regard, Fig. 22 presents the charging and discharging patterns of all travel scenarios considered in this study, along with the SOC of their batteries.

Figure 22. Smart charging scenario for the current number of PHEVs in the city of Montréal under four different travel scenarios.

According to Fig. 22, all the PHEVs contribute to the smart charging strategy by selling back the energy stored in their PHEV batteries to the network to increase their benefit by using the V2G strategy of discharging during the on-peak and mid-peak hours. This behavior not only increases the vehicle owners' profits but also helps the grid manage the electricity demand during peak hours, as outlined in Table 2. Additionally, Fig. 22 shows that the smart charging strategy leads PHEV owners to charge their vehicles more efficiently. Specifically, they tend to charge their PHEVs during the night and off-peak hours, which will allow them to optimize their charging schedules with lower electricity prices.

By using the smart charging scenario, as illustrated in Fig. 22, PHEVs act as portable distributed generators, helping the grid reduce pressure during peak hours. This contribution benefits the grid by positively affecting both power loss and the voltage profile of the system. Figure 23 presents a comparison of the power losses in the network under three different conditions, while Fig. 24 illustrates the comparison of the voltage profile of the network at different hours of the day, including on-peak, mid-peak, and off-peak. These comparisons include three different conditions, including the network without considering PHEVs, the network with PHEVs using only the G2V strategy in the immediate charging scenario, and the network with PHEVs using the smart charging scenario, where both G2V and V2G strategies for charging and discharging are considered.

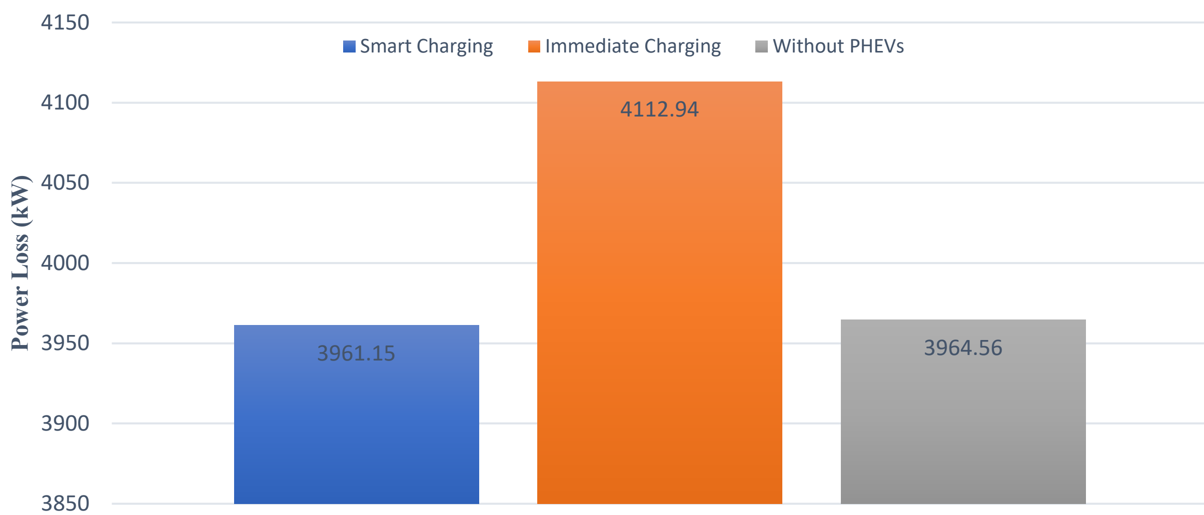


Figure 23. Power losses of the system considering immediate and smart charging network.

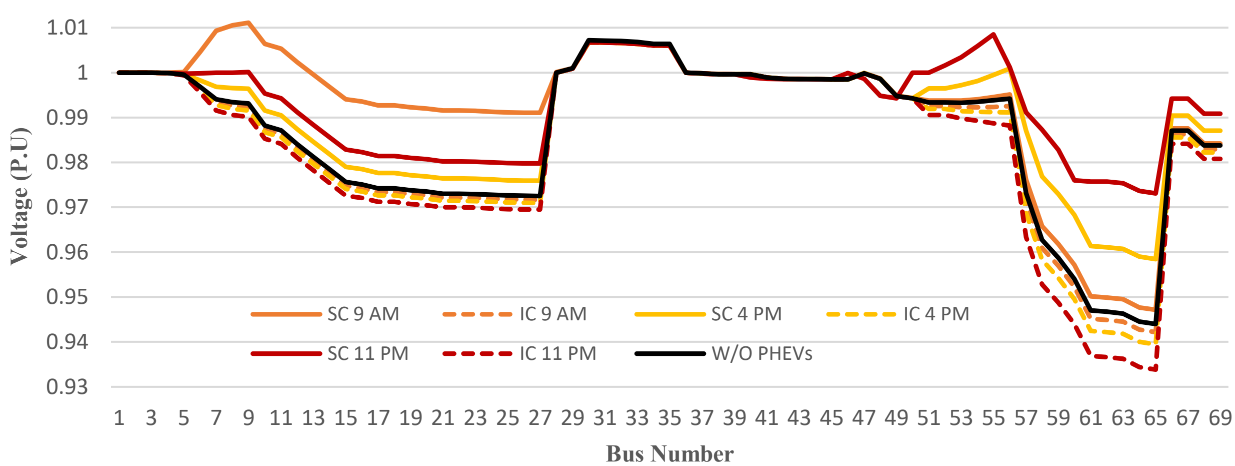


Figure 24. Voltage Profile of the system without PHEVs and with Smart and immediate charging scenarios.

As shown in Fig. 23 and 24, the contribution of PHEVs to the grid by selling back the stored energy from their batteries, particularly during on-peak and mid-peak hours, has a beneficial impact on the electrical network. However, the reason why these effects are not significant is that the number of PHEVs in the three studied areas of Montréal is relatively small compared to the overall load demand of these areas. The positive effect observed highlights the importance and benefits of implementing smart charging with V2G discharging in Montréal. Even with a limited number of PHEVs, the strategy demonstrates potential advantages in reducing grid pressure and improving power system performance, indicating that wider adoption could yield more significant benefits.

In the second phase of the study, the number of PHEVs has been significantly increased to align with Québec's ambitious ZEV goal, which aims to have 2 million electric vehicles on the roads of Québec by 2030. Consequently, the projected number of PHEVs will rise to 692,400. To analyze the impact of this increase on the power grid of Montréal, the number of PHEVs considered in this study will be enlarged from 1,534 to 14,235. This phase will examine the effects of this significant increase in PHEV numbers under both immediate charging and smart charging scenarios. In addition, this phase will compare the outcomes of these two charging strategies by focusing on their consequences for the network's power losses and voltage profile. As a result, this phase aims to provide valuable insights into how large-scale PHEV integration will impact Montréal's power infrastructure and to identify the most effective strategies for managing this transition. Figure 25 demonstrates the comparison between the total energy consumption of the network under two scenarios, including smart charging and immediate charging.

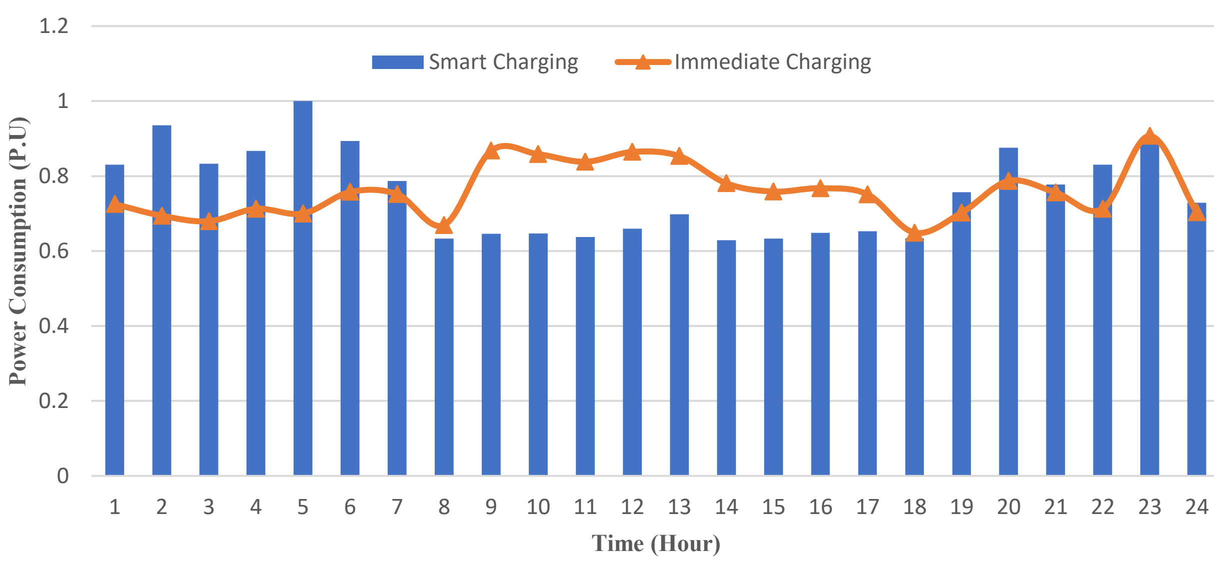


Figure 25. Power Consumption of the network under smart and immediate charging scenarios.

As shown in Fig. 25, the differences in energy usage patterns and the overall efficiency of the network under smart charging and immediate charging scenarios are presented. It can be observed that the implementation of smart charging, along with encouraging PHEV owners to sell back their energy to the grid, can reduce the total energy consumption of the network. This reduction happens because part of the demand is fulfilled by the energy stored in the batteries of the PHEVs, thereby enhancing the overall efficiency of the power grid and shifting the peak load to the off-peak hours during the night.

Figure 26 demonstrates the voltage profile of the system with the increased number of PHEVs, while Fig. 27 shows the power loss of the system under the Québec ZEV plan considering two different scenarios, including immediate charging and smart charging. The results show that the large growth in PHEVs on Montréal's network has a considerable effect on power losses, resulting in a significant rise in overall power loss during a 24-hour period. The problems facing the power grid become even worse with the integration of a significant number of PHEVs into the network, which also weakens the voltage profile. However, when integrating V2G discharging technology and applying coordinated charging and discharging strategies into the network, there is an improvement in the voltage profile and a reduction in power losses. These figures explain the importance of smart charging strategies in managing the increased load from PHEVs and maintaining the stability and efficiency of the power grid as Québec moves toward its ZEV goals.

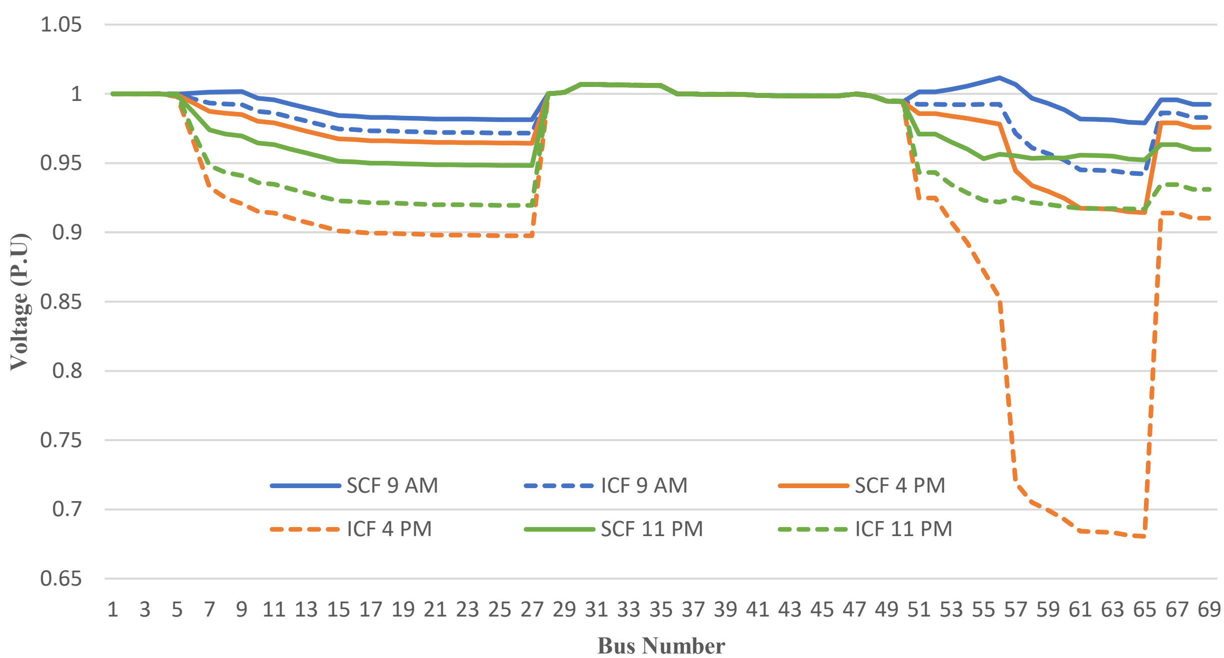


Figure 26. Voltage Profile of the system under the Québec ZEV plan by 2030.

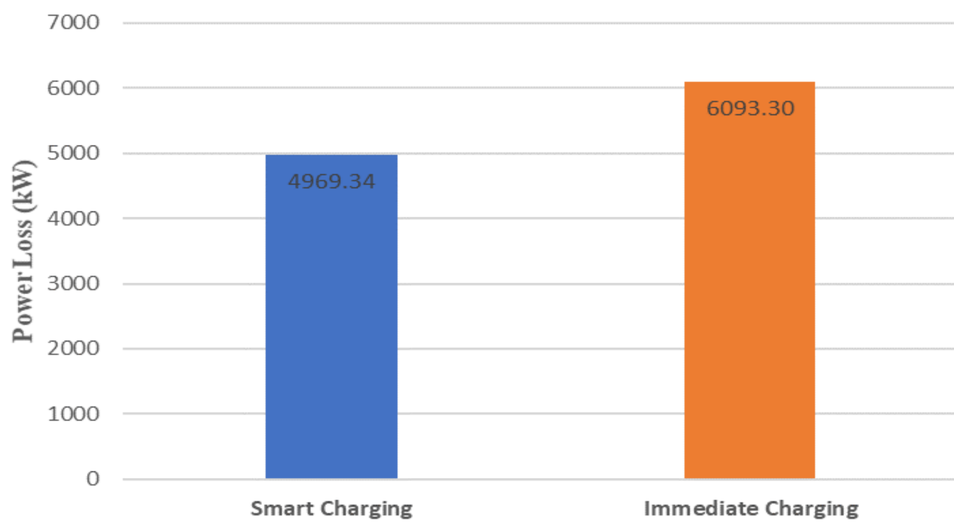


Figure 27. Power losses of the system under the Québec ZEV plan by 2030.

Figure 28 presents the Pareto frontier for the problem under consideration. As shown in this figure, there is a trade-off between the two objective functions. Specifically, as the profit for PHEV owners increases, which acts as the primary objective function, the second objective function tends to decrease, which is considered as the cost associated with system power loss. This inverse relationship highlights the effectiveness of optimizing the system in a way that optimizing for PHEV owner profits can simultaneously contribute to reducing power loss costs within the network and enhancing the efficiency and economic viability of the power grid.

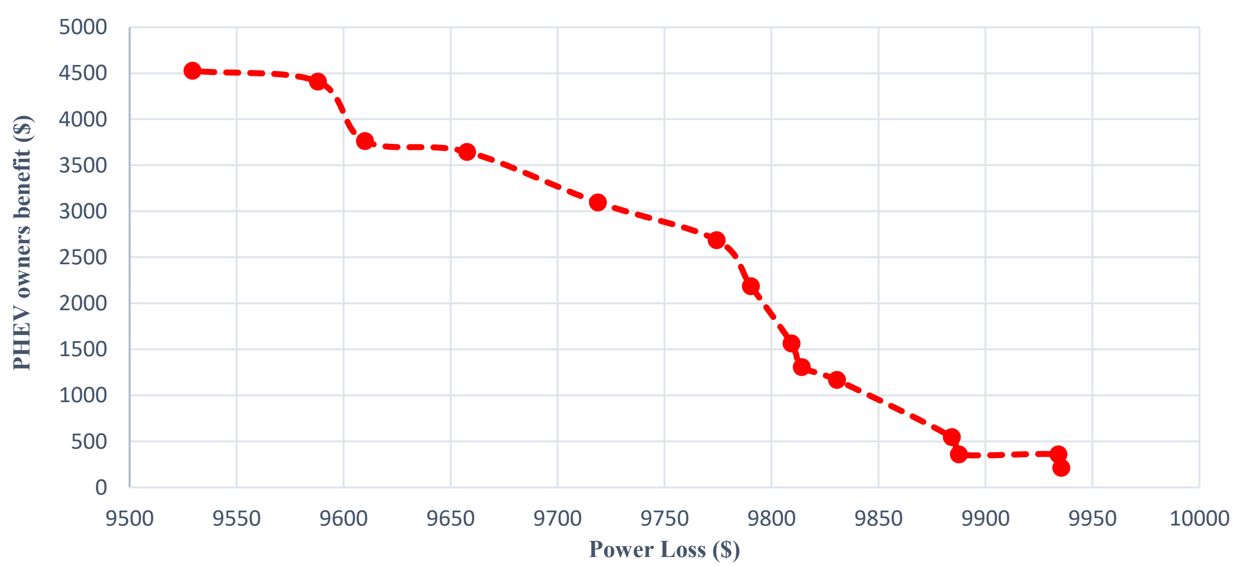


Figure 28. Generated Pareto Frontier using the proposed Epsilon-Constraint method.

Table 7 presents the numerical results of this study, including the PHEV owner's benefit, which has been earned through selling the energy back to the grid, the total cost of PHEV owners which represents the total bill of PHEV owners, the cost of power loss in the network, and the constraints applied to the multi-objective problem. These results provide a quantitative analysis of the trade-offs between maximizing the benefits for PHEV owners and minimizing the costs associated with owners' bills and the power losses in the network.

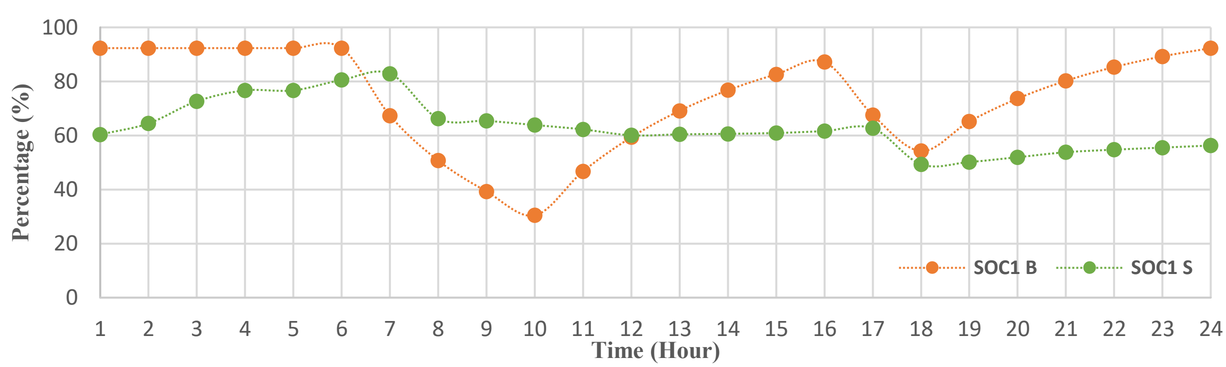
Table 7. Result of the proposed method.

Constraint	Total PHEV owner's cost ($/day)	PHEV owner's benefit ($/day)	Power Loss ($/day)
No	13258.2955	0	10012.3137
13200	13048.2298	210.0657	9935.3888
13000	12901.1226	357.1729	9934.1111
12800	12712.7173	545.5782	9884.3175
12600	12092.3527	1165.9428	9830.623
12000	11952.4079	1305.8876	9814.0826
11800	11695.0213	1563.2742	9809.3789
11600	11072.047	2186.2485	9790.4059
11000	10571.6026	2686.6929	9774.3915
10500	10163.4124	3094.8831	9718.9208
10000	9612.8661	3645.4294	9657.7572
9600	9498.0174	3760.2781	9610.0594
9400	8849.6667	4408.6288	9587.9809
8800	**8732.865**	**4525.4305**	**9529.4435**

As shown in Table 7, the constraint is incrementally decreased with each result iteration. This constraint compels the optimization program to generate numerical results that exceed the specified constraint value. For instance, when the constraint was set at 13200, the algorithm was driven to find a result that exceeded this amount to the benefit of PHEV owners, resulting in a benefit of 210.0657 per day, while the total owner cost was 13048.2298, which is equal to their electricity bill. The constraint is decreased progressively to maximize the first objective function, which is the benefit for PHEV owners. Simultaneously, as the benefit given to PHEV owners increases, the system's power loss decreases. This trend indicates that when PHEV owners actively participate in the proposed coordinated charging and discharging strategy, they not only gain greater financial benefits but also contribute to reducing the power loss in the network. This dual benefit explains the successful use of the smart charging strategy in improving both economic and operational outcomes.

4.3. Method Validation

An alternative V2G approach has been considered to validate the proposed smart charging and discharging method. The purpose of introducing an additional V2G approach is to assess the efficiency of the proposed smart charging and discharging strategy that incorporates V2G in the current problem. In this regard, the aggregator and smart charging and discharging strategies are not considered in this alternate approach. Instead, PHEV owners independently decide when to discharge the stored energy from their PHEV batteries into the grid to earn more profit according to the cost of energy during the day. Additionally, they also have complete control over the time when they want to start charging their PHEVs. In this circumstance, owners typically tend to charge their vehicles during off-peak hours, when electricity prices are lower, rather than during on-peak hours, while selling back their energy to the grid when the energy is at a higher price, which is during the peak hours. However, this approach lacks coordination with the grid, meaning that PHEV owners are unaware of whether the grid will need the energy they attempt to sell or whether the utilities will purchase it. Figure 29 compares the SOC of two proposed approaches, which include V2G with a smart charging and discharging strategy, also known as Smart V2G, and the alternative V2G approach without smart charging/discharging coordination, known as Basic V2G.



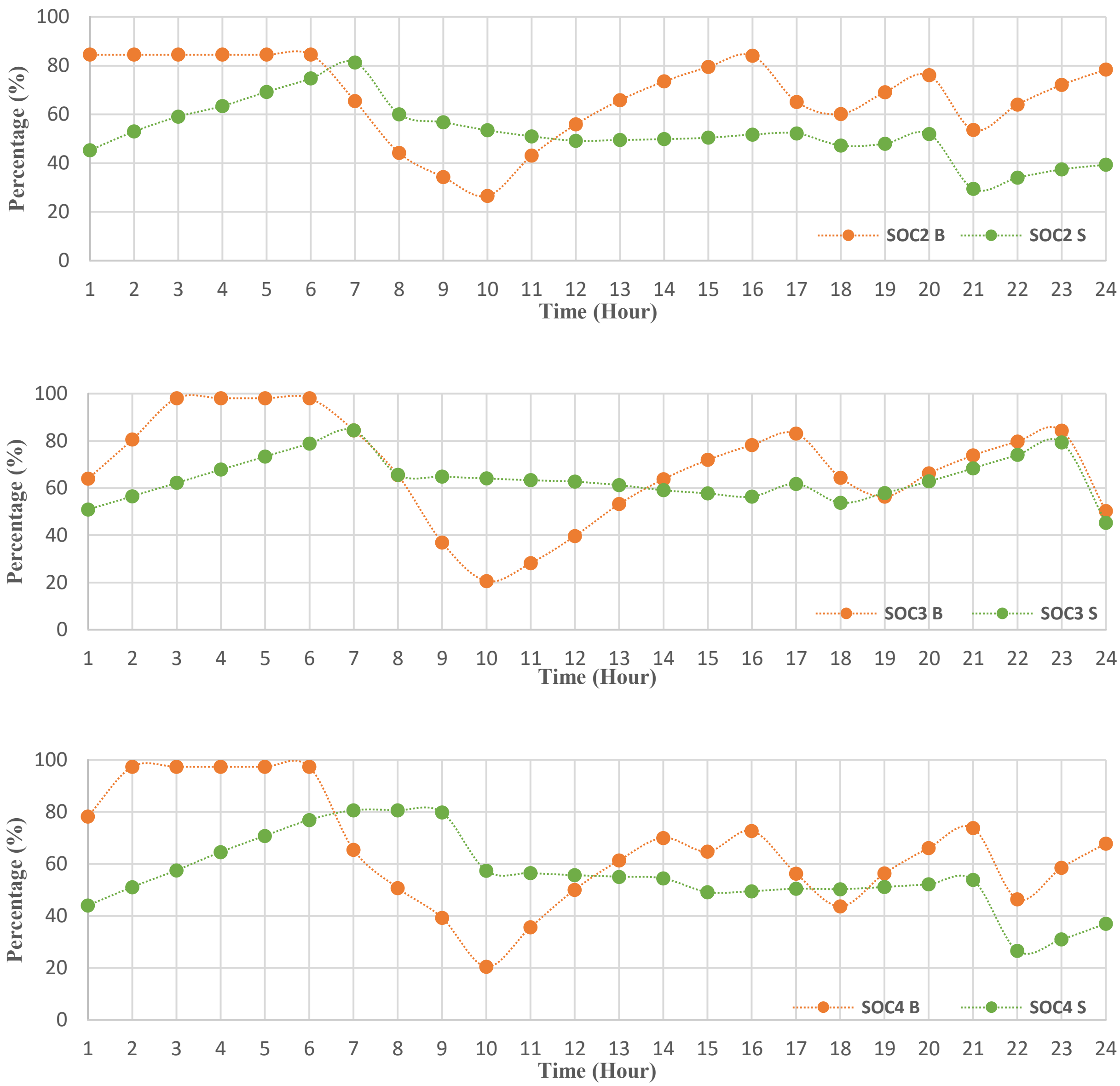
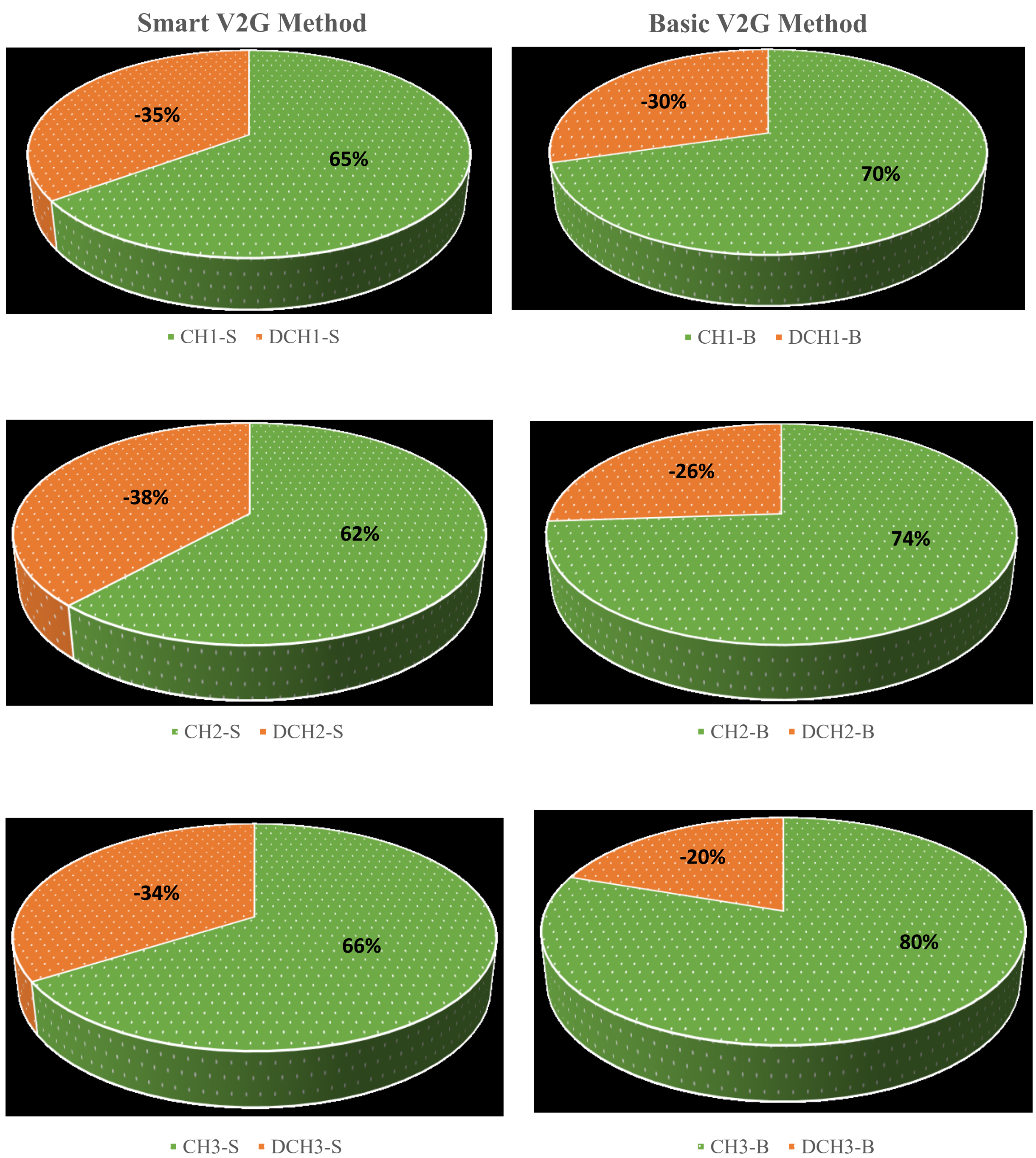


Figure 29. Comparison of SOC of PHEVs in the smart V2G and basic V2G strategies.

As shown in Fig. 29, the SOC for all four types of PHEVs under the smart charging approach follows a smooth and stable pattern. It also indicates that these vehicles primarily charge their batteries during the night and off-peak hours while discharging the stored energy during mid-peak and on-peak hours. In comparison, the SOC of all PHEVs using the basic V2G method without smart charging shows significant fluctuations. PHEV owners who intend to sell energy back to the grid during on-peak and mid-peak hours quickly deplete their battery charge, requiring them to begin recharging during the day when it is either on-peak or mid-peak while the energy prices are high. Furthermore, the SOC of their batteries drops to 20% at certain times, which negatively impacts battery health. These sharp fluctuations in SOC, which are marked by frequent charging and discharging cycles, will raise the risk of accelerated battery degradation. Figure 30 shows a comparison of the charging and discharging patterns for each type of PHEV under both the Smart V2G and Basic V2G approaches.



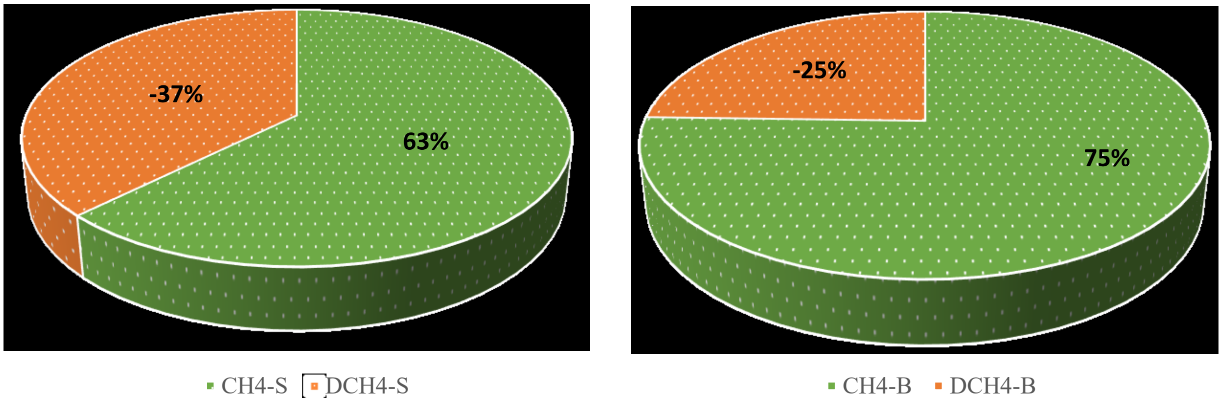


Figure 30. Comparison of charging and discharging patterns in the Smart V2G and Basic V2G strategies.

As shown in Fig. 29, the discharge level or selling back the energy to the grid in the Smart V2G strategy is higher than those in the Basic V2G method for all four types of PHEVs. This indicates that the smart charging and discharging strategy allows PHEV owners to gain more benefits compared to the Basic V2G method. In this regard, Table 7 presents a comparison of the numerical results for these two strategies.

Table 8. Result of the proposed Basic V2G and Smart V2G strategies.

Method	Total PHEV owner's cost ($/day)	Power Loss ($/day)
Basic V2G	10444.1662	44334.26
Smart V2G	8732.865	9529.4435

This table and the results illustrate the advantages of the Smart V2G approach in optimizing both energy usage and financial returns for PHEV owners, as well as benefiting the utilities. The Smart V2G strategy demonstrates its effectiveness in balancing the needs of both individual users and the power grid, making it a superior option compared to more traditional approaches. This comparison also highlights how the Smart V2G strategy not only benefits individual PHEV owners but also contributes to the overall efficiency and stability of the power grid, providing a more balanced and effective solution compared to the Basic V2G method.

Chapter 5: Conclusion

5.1. Conclusion

The rapid increase in the penetration rate of EVs, as well as the rising demand for charging these vehicles and its pressure on the current grid, has highlighted the urgent need for more effective EV charging and discharging strategies. Furthermore, given Canada's policies aimed at accelerating the adoption of EVs and replacing these vehicles instead of cars with combustion engines by 2035, it has become increasingly important to investigate the impact of this growing trend on the electricity network. Therefore, this research study focused on analyzing the impact of EVs on both the current and future power networks of the city of Montréal. For this purpose, three distinct areas of the city, including Downtown, Côte Saint-Luc and Notre-Dame-de-Grâce, and Quartier des Spectacles along with Old Port of Montréal, were selected for analysis. The load profiles for these three zones were provided by Hydro Québec and have been utilized and implemented on the IEEE 69-bus distribution test system in the next steps of this study. The primary goal of this study was to analyze the impact of the presence of PHEVs on Montréal's power grid in accordance with Quebec's ZEV objectives. This goal was successfully implemented in this study by presenting a multi-objective function problem aiming at both increasing the profits of PHEV owners and reducing the power loss within the system. To address the above-mentioned goal, the well-known epsilon constraint method was employed, which allows the transformation of the presented multi-objective function into a single-objective function. Therefore, the current number of PHEVs in the network was considered, and their impact was analyzed using two separate scenarios, including Immediate Charging and Smart Charging. In the Immediate Charging scenario, only G2V technology has been considered. In this regard, the PHEV owners will start to charge their vehicles immediately when they conclude their trips. However, in the Smart Charging scenario, the involvement of an aggregator and the use of coordinated charging and discharging through G2V and V2G strategies enabled vehicle owners to maximize their benefits by optimizing their charging and discharging patterns. In the following step, the future number of PHEVs in the city of Montréal was estimated and considered according to Québec's ZEV goal, which is to have 2 million EVs on Québec roads by 2030. As a result, the number of PHEVs in these three zones was increased to meet this target, while the impact of this increase was assessed and analyzed using the proposed multi-objective problem framework. In this context, an increase in the number of PHEVs from 1,534 to 14,235 resulted in an 18.45% reduction in power loss when utilizing smart charging scenarios. Additionally, smart charging contributed to a more stable voltage profile across the grid, particularly during peak hours, ensuring that the voltage profile remained within 0.95 to 1.05. On the other hand, the Immediate Charging scenario caused significant voltage drops below the 0.95 limit, particularly during peak periods. A notable difference was observed at peak times, such as 4 PM, where the voltage drops in immediate charging scenarios are as large as 30-40% compared to the smart charging scenario at the most unstable buses.

To validate the effectiveness of the proposed Smart Charging strategies, another V2G scenario was implemented. The purpose of this additional scenario was to investigate whether the aggregator and coordinated charging and discharging strategies in the Smart Charging scenarios are effective. The new V2G approach, known as Basic V2G, will allow PHEV owners to have complete control over when they choose to charge and discharge their vehicles. The aim of this approach was that owners could maximize their profits by discharging stored energy into the network during on-peak hours. The results demonstrate that the discharging advantage of Smart V2G ranges between 5-14% higher compared to Basic V2G across different travel patterns; specifically, it is 5% higher for Travel Pattern 1 (35% vs. 30%), 12% higher for Travel Pattern 2 (38% vs. 26%), 14% higher for Travel Pattern 3 (34% vs. 20%), and 12% higher for Travel Pattern 4 (37% vs. 25%). These differences highlight that smart V2G can potentially contribute more to the grid during peak times, while Basic V2G strategies tend to prioritize keeping the vehicles charged rather than optimizing for grid support. In addition, these results also show the importance of coordinated charging and discharging strategies, as implemented in the Smart V2G approach, in order to optimize both financial returns for vehicle owners and the overall performance of the power grid. In this regard, the Smart V2G method provides 16.39% more benefits to PHEV owners than the Basic V2G method. It also reduces power loss by nearly 78.51% compared to the Basic V2G strategy, indicating its better efficiency and economic advantage in regulating energy exchange between vehicles and the grid. Furthermore, the numerical results from both phases of the analysis show that PHEVs with bigger battery capacity, such as the Jeep Wrangler 4Xe, are better suited for people who drive long distances throughout the day. This suitability derives from a bigger battery capacity, which allows these vehicles to go longer distances without the need for frequent recharging during the day. Consequently, they can avoid disruptions to their daily routines and still be able to engage in the smart V2G method, particularly while they are parked at work during peak electricity consumption hours. This capability not only supports the vehicle's extended range but also allows it to contribute to the grid's energy needs, making it an attractive option for drivers who face high commuting demands and want to help with energy management during on-peak or mid-peak hours periods.

Finally, the study's findings express the crucial need for integrating smart charging and discharging management in Montréal's power grid. As the presence of PHEVs on the grid grows, the impact of their uncoordinated charging demand will have a severe effect on the network. In addition, these results illustrate the necessity of smart charging and discharging management to support the successful achievement of Québec's ZEV goals and maintain the power grid's stability and efficiency.

In addition, some of the future works that can be developed from this research study are as follows:

1. Considering the Greenhouse gas emissions.
2. Modeling and considering an individual electricity market.
3. Expand the considered area to the entire city of Montréal.

5.2. Limitation

While this study aims to address several gaps identified in the existing literature concerning the integration of PHEVs into urban power networks, it nonetheless encounters certain limitations that should be acknowledged. First, the geographical scope of the analysis is restricted to three specific regions within downtown Montréal, Côte Saint-Luc, and the Notre Dame-de-Grâce, as well as Quartier des Spectacles and Old Port. While these areas were selected for their relevance to residential, commercial, and recreational activities, they may not comprehensively represent the diverse charging behaviors and infrastructure challenges present in other parts of the city or different urban environments. Thus, the findings may be regionally constrained and could vary if applied to broader contexts.

It is important to emphasize that, in considering the three zones and their respective loads, this study assumed that no PHEVs were present within these loads. This assumption is based on the relatively small number of PHEVs currently operating in the city of Montréal. The decision to exclude them from the load calculations was made to simplify the analysis, as the existing number of PHEVs is not yet significant enough to have a noticeable effect on the overall grid load. Furthermore, the specific demand patterns and detailed data related to these vehicles were not accessible for this research, further justifying their exclusion from the analysis.

Additionally, a significant limitation of this study lies in the exclusion of battery degradation from the analysis. Battery degradation is a critical factor in determining the long-term viability and economic impact of PHEVs, particularly concerning operational costs, vehicle efficiency, and the frequency of battery replacements. By not accounting for this, the results may present an overly optimistic view of the benefits derived from PHEV integration. Furthermore, the PHEVs considered in this research operate exclusively on electric motors, without the use of gasoline, which diverges from conventional hybrid models that utilize both fuel sources. As a result, the findings may not be fully transferable to real-world hybrid vehicles that operate in mixed-mode configurations.

Moreover, this study makes certain assumptions regarding the predictability of PHEV owners' driving and charging patterns, which may not fully capture the complexities of actual human behavior. External variables such as weather conditions, availability of charging stations, and infrastructure changes could all influence charging behaviors in ways that deviate from the patterns assumed in the model. Finally, while the Epsilon-Constraint technique used in this study provides a robust framework for balancing competing objectives, such as minimizing power loss and maximizing benefits for PHEV owners, it does not consider potential technological advancements. Future developments in battery storage technologies, smart grid infrastructures, and renewable energy sources could significantly alter the dynamics of PHEV-grid interactions, suggesting that future studies may need to account for such evolutions.

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