The Development of a Bottom-up Transportation Model for Assessment of Policies on Energy and Emissions

by

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Abstract

The increasing anthropogenic greenhouse gas (GHG) emissions have led to the implementation of various mitigation policies in order to limit the adverse impacts of climate change. However, it becomes challenging as the growth in energy demand outbalances the GHG mitigation measures. The transportation sector is predominantly reliant on fossil fuels and is responsible for 24% of direct GHG emissions globally.

This study assesses low-carbon energy transition pathways for road transport in a fossil fuel-dependent jurisdiction. In this research, a novel assessment framework is developed to analyze long-term energy transitions in the road transport sector considering sectorial activities, vehicle costs, market shares, energy use, and GHG emissions to 2050. The vehicle categories include cars, sport-utility vehicles, pickup trucks, vans, school buses, intercity transit buses, urban transit buses, and light, medium, and heavy freight trucks. Each fuel's full energy supply chain was modelled, including resource extraction, conversion, transmission and distribution, and fuelling, allowing for final and primary energy analysis. The framework was applied to the road transport sector in Alberta, Canada, one of the most emission-intensive regions in Canada. Nine scenarios on the effect of carbon prices, zero-emission vehicle mandates, and financial incentives on vehicle costs and market shares, energy use, greenhouse gas emissions and social costs to 2050 were evaluated. The findings show that carbon price and zero-emission vehicle incentives do not effectively increase the market adoption of zero-emission vehicles on their own; zero-emission vehicle mandates are needed to transition the sector to zero-emission vehicles fully. It was found that the increase in carbon price from $0/tonne to $350/tonne increases the market share of zero-emission vehicles by 11% in 2050 and incentivizing the zero-emission vehicles increases the share by 9% in 2050. Assessing the current policies in Alberta, including $170/tonne carbon price by 2030 and

zero-emission vehicle sales mandate in current policy scenario, it was found that these policy measures resulted in a 67% increase in the share of zero-emission vehicles in 2050. However, when the ZEV sales mandate was applied to all sectors, it resulted in a 90% increase in the market share of zero-emission vehicles in 2050. The market penetration potential for hydrogen fuel cell vehicles is lower than battery electric vehicles in all categories. The system-wide GHG emission footprints of hydrogen and battery electric vehicles are significantly below conventional gasoline and diesel vehicles in all cases. It was found that the GHG emission footprint of hydrogen vehicles supplied by auto-thermal reforming with 91% carbon capture was lower than for battery electric vehicles powered by a primarily natural gas-based power grid (53.6% and 83.2% natural gas-based electricity generation in 2030 and 2050). The findings on the effectiveness of carbon prices vs incentives vs vehicle mandates should be considered by government policymakers who are aiming to reduce GHG emissions from road transport and will inform infrastructure planners and other energy stakeholders.

Preface

This thesis is an original work by Minza Haider under the supervision of Dr. Amit Kumar.

Parts of Chapter 1 and Chapter 2 of this thesis are to be published as Haider M, Davis M, and Kumar A, "A framework to assess the market share of low-carbon road vehicles in a fossil-fuel-dependent jurisdiction" and parts of Chapter 1 and Chapter 3 of this thesis are to be published as Haider M, Davis M, and Kumar A, "Development of a framework to assess the greenhouse gas mitigation potential from the adoption of low-carbon road vehicles in a hydrocarbon rich region" in peer-reviewed journals. I was responsible for the conceptualization, data collection, methodology, validation, and analysis as well as the manuscript composition. Matthew Davis assisted with the conceptualization, methodology, validation, and contributed to manuscript edits. Amit Kumar was the supervisory author and was involved with conceptualization, methodology, validation, analysis, and manuscript review and edits.

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Abbreviations

$	2020 Canadian dollar
AFLEET	Alternative Fuel Life-Cycle Environmental and Economic Transportation
ASEAN	Association of Southeast Asian Nations
ATR	Auto-thermal reforming
BEV	Battery electric vehicle
CAD	Canadian dollar
CARB	California Air Resources Board
CCS	Carbon capture and storage
CCUS	Carbon Capture Utilization and Storage
CER	Canda Energy Regulator
CFS	Clean Fuel Standard
CNG	Compressed natural gas
CNGV	Compressed natural gas vehicles
CP	Current policy scenario
CP0	Carbon price policy of $0/t
CP50	Carbon price policy of $40/t in 2021 and $50/t from 2022 to 2050
CP170	Carbon price policy of $40/t in 2021, $50/t in 2022, rising linearly to $170/t by 2030, then increasing with inflation
CP350	Carbon price policy of $40/t in 2021, $50/t in 2022, rising linearly to $350/t by 2030, then increasing with inflation
DC	Delivery cost
D-ICEV	Diesel internal combustion engine vehicle

ECCC	Environment and Climate Change Canada
EF	Emission factor
EVAFIDI	Electric Vehicle and Alternative Fuel Infrastructure Deployment Initiative
H_2-FCEV	Hydrogen fuel cell electric vehicle
INC	Incentive scenario
GDP	Gross Domestic Product
G-ICEV	Gasoline internal combustion engine vehicle
GJ	Gigajoule
Gt	Gigatonne
HDSAM	Hydrogen delivery scenario analysis model
HEV	Hybrid engine vehicle
ICEV	Internal combustion engine vehicle
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCFS	Low-Carbon Fuel Standard
LEAP	Low Emissions Analysis Platform
MJ	Megajoule
Mt	Megatonne
MW	Megawatt
NEMO	Next Energy Modelling system for Optimization
NEOCC	New Energy and Oil Consumption Credits
NIR	National Inventory Report
NRCan	National Resources Canada

PHEV	Plug-in hybrid vehicles
RC	Refuelling/recharging cost
REF	Reference scenario
RFS	Renewable Fuels Standard
SD	System dynamics
SEI	Stockholm Environment Institute
SMR	Steam methane reforming
StatCan	Statistics Canada
TC	Transmission cost
WTW	Well-to-wheel
ZEV	Zero-emission vehicle
ZEV+	Zero-emission vehicle mandate policy scenario
ZEV+EV	Zero-emission vehicle mandate policy scenario with battery electric vehicle bias
ZEV+H_2	Zero-emission vehicle mandate policy scenario with battery hydrogen vehicle bias
ZEVAI	Zero Emission Vehicle Awareness Initiative
ZEVIP	Zero Emission Vehicle Infrastructure Program

Variables

$\boldsymbol{A}$	annual average distance driven [km per year]
$\boldsymbol{b}$	base year [year]
$\boldsymbol{B}$	biofuel blending percentage [percent]
$\boldsymbol{CI}$	carbon intensity [g CO_2e/MJ]
$\boldsymbol{CC}$	capital cost [$]
$\boldsymbol{d}$	density [kg/gal]
$\boldsymbol{DC}$	delivery cost [$/MJ]
$\boldsymbol{E}$	existing vehicle stock [number of vehicles]
$\boldsymbol{EC}$	energy cost [$/MJ]
$\boldsymbol{ED}$	energy demand [MJ]
$\boldsymbol{TED}$	total energy demand in the road transport sector [MJ]
$\boldsymbol{EI}$	energy intensity [MJ/km]
$\boldsymbol{EF}$	emission factor [g CO_2e/MJ]
$\boldsymbol{ES}$	system-wide emissions [g CO_2e]
$\boldsymbol{EP}$	system-wide energy [MJ]
$\boldsymbol{FC}$	fuel cost [$/year]
$\boldsymbol{FD}$	Feedstock requirement [kilo-tonne]
$\boldsymbol{GE}$	greenhouse gas emissions [CO_2e]
$\boldsymbol{GM}$	greenhouse gas mitigation cost [$/tonne]
$\boldsymbol{i}$	interest rate [fraction]
$\boldsymbol{L}$	average life span of vehicle [years]
$\boldsymbol{LB}$	liquid biofuel [litres]

$\boldsymbol{LHV}$	calorific value of fuel [MJ/kg]
$\boldsymbol{MC}$	maintenance cost [$/year]
$\boldsymbol{MF}$	mass fraction
$\boldsymbol{MS}$	market share multiplier [fraction]
$\boldsymbol{N}$	new vehicle sales [number of vehicles]
$\boldsymbol{P}$	population [number of people]
$\boldsymbol{PC}$	production cost [$/MJ]
$\boldsymbol{RC}$	refuelling/recharging cost [$/MJ]
$\boldsymbol{r}$	retirement rate for existing vehicle stock
$\boldsymbol{S}$	scrappage of vehicles [number of vehicles]
$\boldsymbol{SC}$	scenario cost [$]
$\boldsymbol{SE}$	scenario emissions [tonne]
$\boldsymbol{TCO}$	total cost of ownership [$/km]
$\boldsymbol{V}$	total number of vehicles
$\boldsymbol{W}$	vehicle use rate [number of vehicles per person]
$\boldsymbol{v}$	vehicle adoption sensitivity to cost
$\boldsymbol{y}$	yield of biomass [kg/litre]

Sets

$\boldsymbol{C}$	subsector [cars, sport-utility vehicles, pickup trucks, vans, school buses, intercity transit buses, urban transit buses, light freight trucks, medium freight trucks, heavy freight trucks]
$\boldsymbol{F}$	fuel [diesel, electricity, gasoline, hydrogen, natural gas]
$\boldsymbol{F'}$	biofuel [ethanol, biodiesel, renewable diesel]
$\boldsymbol{S}$	scenario [CP0, CP50, CP170, CP350, CP, ZEV, ZEV+EV, ZEV+H_2]
$\boldsymbol{T}$	year [1990:1:2050]
$\boldsymbol{X}$	vehicle type [BEV, CNGV, D-ICEV, G-ICEV, HEV, H_2-FCEV, PHEV]

1. Introduction[1]

1.1. The global road transportation sector

The transportation sector contributed 24% to global greenhouse gas (GHG) emissions in 2020, or 7 gigatonnes (Gt) carbon dioxide equivalent (CO_2e) [1]. The annual growth rate of transport emissions is 1.7% which is the highest among the end-use sectors [2]. The contribution is expected to reach 9 Gt CO_2e in 2050 because of emerging markets and the absence of net-zero pledges in developing countries [3], preference for larger and heavier vehicles, and gross domestic product growth [1]. All of these increase the challenge of meeting the Paris Agreement target to limit the global temperature rise to 1.5°C [4, 5].

The road transport sector contributes the largest segment of global transport emissions at 74% [6]. Petroleum-based fuels are the bedrock of road transport, but the emergence of zero-emission vehicles (ZEVs) fuelled by electricity and hydrogen has been accelerating in recent years. Still, battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (H_2-FCEVs) only make up 1% of vehicles globally [3]. Decarbonizing the road transportation sector is primarily dependent on the transition to BEVs and H_2-FCEVs [7]; these vehicles have higher fuel efficiency and are

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projected to be cost-effective. Additionally, these vehicles have the potential to achieve zero emissions by decarbonizing the hydrogen and electricity production. Furthermore, the existence of supportive policies facilitates the adoption of these vehicles. At the United Nations Climate Change Conference 2021 (COP26), several countries committed to the ZEV Declaration to accelerate the transition to ZEVs and achieve 100% ZEV sales by 2035 [8].

1.2. The road transportation sector in Canada

Canada ranked 10th in GHG emissions in 2018 and accounted for 1.5% of global emissions [9]. Figure 1.1 shows the emissions from the transportation sector in Canada. In 2019, the Government of Canada mandated that by 2035 all new light-duty passenger vehicles added to the fleet be ZEVs and initiated the 5-year, $280 million Zero Emission Vehicle Infrastructure Program (ZEVIP) to increase the refuelling and charging stations for ZEVs [10]. In 2020, sales of new ZEVs were 2.5% [11]. Initiatives like Electric Vehicle and Alternative Fuel Infrastructure Deployment Initiative (EVAFIDI) are also announced to increase the charging and hydrogen refuelling infrastructure [12]. It also launched the Incentives for Zero-Emission Vehicles (iZEV) Program for light-duty vehicles and Incentives for Medium- and Heavy-Duty Zero-Emission Vehicles (iMHZEV) Program in order to encourage the adoption of zero-emission vehicles [13, 14]. The Government of Canada established The Net-Zero Emissions Accountability Act in 2021 in support of achieving net-zero emissions by 2050 [15]. In 2022, the Government of Canada released the 2030 Emissions reduction plan to achieve to targets of the Paris Agreement and reach net-zero emissions in 2050 [15, 16]. It also launched Zero Emission Vehicle Awareness Initiative (ZEVAI) to increase awareness regarding zero-emission vehicles [17].

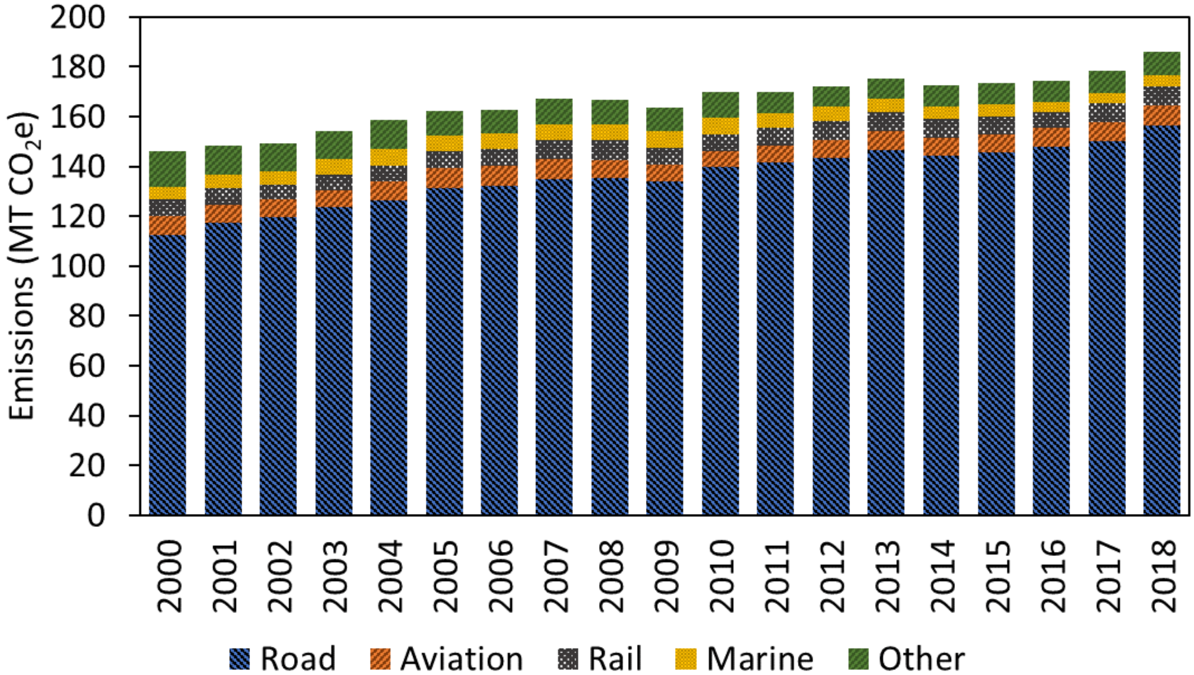

Figure 1.1: Emissions from the transportation sector in Canada [18].

Energy from biofuels can play an important role in achieving net-zero emissions. Canada adopted the Pan-Canadian Framework on Clean Growth and Climate Change in 2016; at that time the development of Clean Fuel Standard (CFS) was identified as a key action to reduce GHG emissions from the transportation sector [19, 20]. The CFS was also identified as a key climate change mitigation action to promote clean technology and create an opportunity for economic growth [21]. The Canadian government set a GHG emissions reduction target of 30% below 2005 levels by 2030, through the transition to a low-carbon economy. The Canadian government has set a goal of reducing 30 million tonnes of GHG emissions annually by 2030. The CFS mandates that low-carbon intensity liquid biofuels be blended with fossil-based liquid fuels in order to reduce the annual carbon intensity of fossil fuels. Fossil-derived fuels include gasoline, diesel, kerosene, and light and heavy fuel oil. The CFS regulations require the transportation sector to reduce the carbon intensity of gasoline and diesel to 84 g CO_2e/MJ by 2030 [22] by fuel blending. The

Government of Canada introduced Renewable Fuels Regulations that require fuel suppliers and importers to have an average of at least 5% renewable fuel in the gasoline produced in or imported to Canada [23]. The regulations also require an average of at least 2% renewable fuel in the diesel and heating oil produced in or imported to Canada.

1.3. The road transportation sector in Alberta

Alberta, a western Canadian province, has the highest emissions in the country [24], with emissions per capita at 64.3 tonnes of CO_2e, more than thrice the national average of 19.6 tonnes per capita, due to the prevalent use of fossil fuels for energy supply, energy export, and demand [25]. Transport is the third-largest GHG-emitting sector in Alberta, accounting for 32.1 Mt CO_2e in 2018 [26, 27]. With the Natural Gas Vision and Strategy, the Government of Alberta aims to produce and deploy hydrogen from natural gas to develop a clean hydrogen economy along with expanding natural gas demand [28]. In 2019/20, the production of natural gas in Alberta was 11.1 billion cubic feet per day [28]. Alberta, moreover, is the largest producer of hydrogen in Canada, producing 2.4 million tonnes of hydrogen per year [29]. It has two world-scale commercial Carbon Capture Utilization and Storage (CCUS) projects for reducing GHG emissions and storage of carbon dioxide [30]. In November 2021, the Government of Alberta released the Hydrogen Roadmap with plans to capitalize on Alberta's natural gas resources and energy infrastructure to become a global centre for clean hydrogen production [30]. Recent studies by our research group – i.e., our comparative techno-economic and GHG emissions analysis of different hydrogen production technologies in Alberta [31], techno-economic assessment of exporting Alberta hydrogen [32], and evaluation of Alberta's hydrogen production potential from wind and solar [33] – contribute to the growing interest in hydrogen production and export to international markets. Based on the federal government's CFS, the Alberta Government's 2020 Renewable

Fuels Standard (RFS) Regulation mandates minimum amounts of renewable fuel content in gasoline and diesel – a minimum 5% ethanol in gasoline and 2% biodiesel in diesel [34].

However, it is not known what the most effective ways to bring about the transition are, considering policy options, consumer costs, emissions, and broader energy system impacts. For instance, the overall GHG reduction effectiveness of battery electric and hydrogen vehicles depends largely on the emissions associated with the production of electricity and hydrogen. If a region is heavily dependent on fossil fuels for energy, will a transition to electric and hydrogen vehicles still offer effective GHG emission reductions? In another instance, what government policy interventions will accelerate the transition to low-carbon transport most effectively, and how much will it cost?

1.4. Transition to ZEVs

Several studies that consider a transition to ZEVs, focusing on the GHG emissions associated with H_2-FCEVs and BEVs were considered. For H_2-FCEVs, Li and Kimura [35] compared the total cost of ownership and emissions of H_2-FCEVs in ASEAN countries. The study was done for mid-size passenger cars, buses, and heavy-duty trucks. The study developed a total cost of ownership (TCO) model for the estimation of the costs and emissions of owning and driving vehicles. The results showed that H_2-FCEVs are not economically competitive at present but are likely to become competitive in the near future because of policies encouraging the transition to ZEVs. The study projected the costs for 2030 and does not incorporate carbon price policy. It considers a simplified factor based on energy consumption for hydrogen supply infrastructure, including transportation, storage, and delivery. The authors built a well-to-wheel (WTW) model to study the energy, costs, and emissions of different powertrains in future scenarios. The results also showed that the emissions from H_2-FCEVs are lower than from other powertrains, except BEVs. The study considered hydrogen production in a mix of pathways and provided the cost and emissions for the present and 2030 scenarios. The hydrogen pathways considered are natural gas reforming, lignite gasification, biomass gasification, solar photovoltaic, and wind. It does not consider hydrogen production by auto-thermal reforming. He et al. [36] studied the emissions and costs for passenger H_2-FCEVs in China. A GREET model was used to estimate the WTW emissions for different hydrogen production pathways. The model compared the levelized cost of driving and WTW GHG emissions for ICEVs, hybrid-electric vehicles (HEVs), BEVs, and H_2-FCEVs. The results showed that H_2-FCEVs have significant emission mitigation potential, and with an anticipated reduction in the capital cost of electrolyzers and hydrogen storage, the levelized cost of driving could become comparable with ICEVs. This study does not consider the entire energy demand and supply system and the analysis is not over a long-term planning horizon. Choi et al. [37] projected the GHG emissions of BEVs, plug-in HEVs, and H_2-FCEVs in the passenger category up to 2030 in South Korea. The authors also used a GREET model to calculate the WTW emissions in different powertrains. The study considered the life cycle emissions of different transport fuels and electricity and hydrogen production by different pathways and their associated emissions. The results showed that H_2-FCEVs have the lowest GHG emissions when hydrogen is produced by naphtha cracking, followed by steam methane reforming (SMR) and electrolysis. The key limitation of this study is that this does not consider the system level assessment. Staffell et al. [38] reviewed the role of hydrogen and fuel cells in a low-carbon energy system. The authors studied the potential of hydrogen in different energy systems including transport, heat and industry, and power, and discussed hydrogen infrastructure from the perspective of hydrogen production processes to distribution and storage. The authors also discussed the social factors and policy drivers for the hydrogen market and concluded that hydrogen can play a major role, along with electricity, in attaining a low-carbon energy system. This study does not consider all the different hydrogen production technologies and focused solely on SMR and electrolysis. Ahmadi and Kjeang [39] studied the life cycle emissions of passenger H_2-FCEVs in four provinces in Canada. They considered hydrogen production by SMR, electrolysis, and thermochemical processes and concluded that greenhouse gases decrease drastically if an internal combustion engine vehicle is replaced by a hydrogen fuel cell vehicle, and the greatest decrease is achieved by thermochemical hydrogen production. The study also showed that H_2-FCEVs considerably decrease the energy cost during the lifetime of a vehicle, which can offset the high capital cost of these vehicles. In this case, hydrogen production through SMR showed the most economic results but the study does not focus on the whole energy system impacts due to the adoption of all the low-carbon vehicles.

For BEVs, Doluweera et al. [40] studied the impact of electric vehicles on emissions in Alberta. The authors developed a hybrid simulation model for the province's electricity system and estimated the emissions for passenger vehicles in six scenarios with different BEV penetration levels. The authors estimated emissions up to 2031 and compared the 2030 results with the policy targets for 2030. One limitation of the analysis is that the level of EV penetration was considered by assuming a constant annual rate for replacing ICEVs with BEVs and neglecting any cost-based market adoption dynamics. The study concluded that the GHG emissions reduction potential of electric vehicles is approximately 9% below Alberta's 2005 GHG emissions. Krause et al. [41] studied energy consumption and CO_2 emissions in the European Union (EU) road transport sector up to 2050. The authors modelled the share of BEVs and H_2-FCEVs and calculated the demand and tank-to-wheel emissions for various scenarios using the DIONE fleet impact model, a road transport fleet projection tool that analyze long-term scenarios for activity, vehicle stock, energy, and emission parameters. The study focused on all sectors of the road transport sector and calibrated the vehicle fleet activity and stock with EU renewable energy and GHG targets for 2020 along with the policies agreed upon until 2014. The authors concluded that electrification has substantial potential to decrease tank-to-wheel emissions and is feasible if combined with measures such as efficiency improvements and annual vehicle activity reductions. Gómez Vilchez and Jochem [42] studied the impact of electric cars on GHG emissions in various countries. The study used a system dynamics (SD) model and developed a Transport, Energy, Economic, Environment (T3E) model that takes variables such as GDP, vehicle stock, policies, infrastructure, and market behaviour into consideration and projects demand and emissions up to 2030. The study considered WTW emissions and showed that electric vehicles have great potential for decreasing GHG emissions. Talebian et al. [43] studied the impact of the electrification of freight transport on GHG emissions up to 2040. The study forecasted the freight vehicle stock using an average increase in GDP and considered the fulfillment of current legislation in British Columbia as a scenario. WTW emissions were considered and a mid-term target of a 64% GHG emission reduction in the freight sector was assumed. The results showed that current policies fail to decrease GHG emissions and that the share of all-electric freight trucks should be more than 65% of the stock to achieve the 64% reduction target in British Columbia by 2040.

The studies that analyze the impact of various policies on GHG emissions were also reviewed. Yan et al. [44] studied the impact of various policies in Ireland on the freight transportation sector through 2050. The study developed a framework to assess the energy and emissions considering four different policy scenarios. The results show that carbon pricing results in a moderate decline in total energy and GHG emissions from the freight transportation sector. The study did not assess the different fuel technology vehicle options in the freight sector, and they also did not consider higher levels of carbon prices. Axsen et al. [45] compared the policy pathways to reach the goal of 100% ZEV sales by 2035 for light-duty vehicles in Canada. The study used the AUtomaker-consumer Model (AUM), a simulation model which assesses the impact of various policy options for light-duty vehicles. The study modelled various policy options in the baseline scenario and considered 9 different scenarios. The results conclude that the ZEV mandate is the most cost-effective way to reach the target of 100% ZEV sales by 2035. However, the study did not consider the market penetration of hydrogen fuel cell electric vehicles. It also considered an average WTW emissions which does not does not account for the possible transition of electricity to renewables over the long-term. Sykes and Axsen [46] modelled the light-duty passenger vehicles in British Columbia to assess the effects of regional spillover in the adoption of ZEVs and the impact of ZEV and other climate policies in the province. The study uses a simulation model, CIMS-ZEV that assesses the market share, costs, and GHG emissions from the sector and simulated five policies in different combinations and stringencies in different scenarios. The results show that corporate average fuel economy (CAFÉ) and low-carbon fuel standard (LCFS) policies have a very low impact on the market share of ZEVs. The ZEV shares, in a combination of CAFÉ and LCFE policies, in medium and high stringency scenarios will reach 8.5% and 7.9% by 2050. The results conclude that ZEV sales mandate is a stronger policy needed to achieve the GHG emission reduction targets of 2050. Without ZEV sales mandate, CAFÉ, LCFS and carbon tax policies achieve the 2050 GHG emission target only in 25% of the simulations.

Studies that consider a transition to ZEVs, focusing on the market share of the H_2-FCEVs and BEVs were also reviewed. Lepitzki and Axsen [47] modelled the road transportation sector in British Columbia and assessed the impacts of various policies on the vehicle market shares for passenger and freight sectors using the CIMS energy economy model in different scenarios. It is a hybrid bottom-up/top-down model that calculates the impact of energy and climate mitigation policies on technology adoption, costs, energy, and emissions across energy-intensive sectors [48]. The results showed that in the moderate policy scenario, the market share of passenger BEVs and freight H_2-FCEVs reaches 52% by 2050. However, the results also consider more stringent LCFS along with other policies. The study provides a less-comprehensive categorization of the transport sector and does not take into consideration the infrastructure for the recharging/refuelling of the zero-emission vehicles. Krause et al. [41] studied road transport energy and emissions in the European Union (EU) up to 2050. The study calculated the market share potential of various fuel technology vehicles in different scenarios using the DIONE fleet impact model reference scenario along with the assumptions derived from expert group discussions. DIONE is a bottom-up optimization model used to assess the implications of vehicle fleet composition, vehicle activity, cost of ownership, and energy consumption using a scenario-based approach. The results showed that in a combined high electrification and hydrogen scenario, the market share of the H_2-FCEVs and BEVs reaches 9.4% and 78.5% respectively in 2050. The study is limited to assessing tank-to-wheel energy consumption and CO_2 emissions of passenger vehicles and it focuses solely on the examination of three electrification scenarios with only one of them considering hydrogen fuel cell electric vehicles. Ou et al. [49] studied the number of BEVs in China up to 2050 in various technology evolution scenarios considering different costs for vehicle technologies. The New Energy and Oil Consumption Credits (NEOCC) model, an optimization-based bottom-up model developed at the Oak Ridge National Laboratory is used to quantify the projections for BEVs between 2020 and 2050. The results show that BEVs will be the dominant vehicle technology in China by 2050 and the market penetration of BEVs will be around 30.4%–64.6% in different scenarios. However, the study focuses on BEVs and restricts its scope to passenger vehicles.

Studies that investigated the costs of H_2-FCEVs and BEVs were also reviewed. Ruffini and Wei [50] studied the costs of H_2-FCEVs and BEVs in California using a top-down model and projected costs to 2050. The vehicle purchase cost, fuel operational cost, non-fuel operational cost, and carbon social cost were considered. The study showed that H_2-FCEVs have the greatest potential for cost reduction, and the technology adoption rate in the initial years plays an important role in their competitiveness relative to ICEVs. The study does not consider any policies in its analysis. Morrison et al. [51] studied the TCO of H_2-FCEVs and BEVs and the competitiveness of light-duty passenger vehicles. The study uses Autonomie, a simulation model developed at the Argonne National Laboratory, to conduct the analysis along with the assumption that United States Department of Energy (US DOE) cost targets are met for both battery and hydrogen vehicles [52]. The result concluded that the BEVs have a great advantage over H_2-FCEVs due to lower costs, but these costs significantly diminish after 2030. The study also shows that SUVs and vans have a relative cost advantage for H_2-FCEVs over BEVs compared to passenger cars. The study does not consider the cost of infrastructure for refuelling and recharging of hydrogen and battery electric vehicles in the TCO analysis. Szumska et al. [53] studied the total cost of ownership of mid-size passenger cars in the EU for various drivetrains including BEVs. The study conducted the TCO analysis using the Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) tool, developed by the Argonne National Laboratory [54] which is used to calculate the lifetime fuel consumption and costs of ownership of the vehicles. The results show that the ownership cost of BEVs is the highest among all drivetrains including conventional and hybrid vehicles due to high purchase costs and additional battery replacement costs. The study does not include hydrogen fuel cell vehicles in its analysis or the infrastructure costs of BEVs. Also, the study does not present TCO projections for the future. Zhou et al. [55] studied the lifetime costs of class-6 medium-duty trucks in Toronto, Canada. The study simulated the fuel consumption of vehicle technologies using Autonomie [52] and calculated the lifetime total cost of ownership of conventional diesel and battery electric trucks. The results show that the battery electric truck has higher TCO than diesel trucks, but the costs can be lower than diesel trucks with more favourable conditions like lower battery and recharging infrastructure costs. The study's scope was limited to a cost comparison for BEV and ICEV class-6 medium-duty trucks for 2014. Ajanovic and Haas [56] studied the barriers to the adoption of hydrogen fuel cell vehicles and focused on economic factors from hydrogen production to infrastructure and vehicle costs. They concluded that hydrogen fuel cell vehicles have great potential to transform the transport system to a more sustainable one. Current barriers such as lack of infrastructure, high costs, and lack of policies are the major risks for this technology, and solving them would increase its competitiveness. The study focused on hydrogen fuel cell electric vehicles and compared the economic factors with ICEVs for passenger cars. Lee et al. [57] performed a techno-economic analysis of hydrogen delivery cost. The authors used the hydrogen delivery scenario analysis model (HDSAM) developed by the Argonne National Laboratory to analyze the hydrogen refuelling station and delivery costs. The model showed that the higher capacity exponentially decreased the cost of the delivery infrastructure. Reddi et al. [58] studied the costs involved in the refuelling of hydrogen using HDSAM. The authors assessed the impact of the high cost of refuelling equipment, station capacity and utilization on the total cost of refuelling and analyzed the potential decrease in refuelling cost in the future. They concluded that although at present a great share in the levelized cost of hydrogen delivery is due to hydrogen refuelling stations, increasing the number of stations and their capacity would significantly decrease the station's cost. The study focused on hydrogen delivery by tube-trailers and does not provide cost projections. The study focused on hydrogen delivery by tube-trailers and does not provide cost projections. Nugroho et al. [59] studied the levelized cost of hydrogen (LCOH) for long-haul heavy-duty vehicles in Germany in 2050. The study uses Node-Capacitated Flow Refueling Location Model (NC-FRLM) to determine optimal locations for hydrogen refuelling stations and calculate the various infrastructure costs. It also compared the costs for on-site and centralized hydrogen production using electrolysis. The results show that the LCOH is €6.50 per kg for on-site hydrogen production. It also slows that there is only a slight decline in the LCOH for centralized hydrogen production and transport of hydrogen using pipelines. The study focused on heavy-duty vehicles and solely considered hydrogen production by electrolysis.

1.5. Knowledge gaps

The literature review suggests there has been limited assessment of the entire road transport sector; instead, studies have mostly focused on a single subsector, such as passenger cars or freight, or a single technology class, such as BEVs. There are no studies assessing the long-term impact of both H_2-FCEVs and BEVs in all categories of the road transport sector in the same analysis. In other words, a study of the transition of the entire road transportation sector has not been done (to the best of my knowledge). The literature review also found that no road transport studies considered hydrogen production by auto-thermal reforming (ATR) with carbon capture and storage (CCS); this gap should be filled since ATR-CCS has among the lowest emissions of any hydrogen production process, according to Oni et al. [31].

A summary of the specific areas of the novelty of this thesis is:

- Many studies compare BEVs and/or H_2-FCEVs with ICEVs based on life cycle GHG footprints. Since the current road transport sector includes several other fuel technologies, it is important to consider the impact of all the fuel technologies on the total GHG emissions from the road transport sector. With my research colleagues, a novel framework was developed to comparatively assess the energy and GHG footprints of a broad range of vehicles (conventional gasoline and diesel ICEVs, HEVs, plug-in HEVs, compressed natural gas vehicles H_2-FCEVs, and BEVs). This provides, for the first time, a holistic GHG impact assessment of all the fuel technologies used in the road transport sector within a consistent analysis framework.

- Most of the reviewed literature focuses on a specific category of the road transport sector; a robust analysis should include the entire sector, but no such analyses were found. This study modelled the entire road transport sector in detail by considering separate categories of cars, sport-utility vehicles, pickup trucks, vans, school buses, intercity transit buses, urban transit buses, light freight, medium freight, heavy freight, as well as each fuel's associated energy supply chain from resource extraction through conversion, transmission and distribution, refuelling, and final consumption. This modelling is important to understand the total impact on the road transport sector.
- While there are studies that assess the impact of various policies, the analysis is limited to a specific sector, policy, or fuel technology vehicle. None of the studies assessed the current and proposed policy options considering both H_2-FCEVs and BEVs single analysis framework so that these options can be compared. There is a knowledge gap in studies that assess the transition to ZEVs in which various policy option scenarios are assessed for the entire road transport sector within the same framework so that the impact of these policy options on the entire sector can be effectively compared.
- None of the studies considered hydrogen production by ATR with CCS fuelling hydrogen vehicles. This study considered hydrogen production from a range of low-carbon technologies,

including ATR with CCS. A comparative analysis of different hydrogen production technologies is important to identify the most favourable technology for effective GHG mitigation (in terms of cost and scale).

1.6. Objectives of the research

The main purpose of this study is to assess the GHG emission mitigation potential of low-carbon vehicle technologies in road transport in fossil fuel-dependent jurisdictions. The study results are important for policymakers to provide insight into the policy frameworks for the transition to ZEVs.

The specific objectives are to:

- Develop a framework to assess the GHG mitigation potential of H_2-FCEVs and BEVs in fossil fuel-dependant jurisdictions;
- Apply the framework to Alberta, Canada, as a case study;
- Project the system-wide energy use and GHG emissions associated with the road transport sector considering all subsectors, vehicle technologies, fuels, and associated energy supply chains; and
- Assess and compare the impact of carbon price, incentives, and zero-emission vehicle policy mandates on vehicle market shares, energy consumption, GHG emissions, and social costs.

1.7. Limitations of research

There are certain challenges in projecting GHG emissions from the road transport sector. The relative cost of the fuel technology is considered as the driving factor in market share projections of different vehicles in a category. The ability to consider factors such as lack of vehicle availability and refuelling/recharging stations as well as intangible determinants is limited given their unpredictable nature.

With respect to the cost analysis of the vehicles, there is limited data available on H_2-FCEV costs in all sectors. Cost parity with ICEVs was assumed for other fuel technologies at different time steps, which might or might not be precise because of the unavailability of low-carbon fuel technology vehicles in various sectors of road transport. H_2-FCEV costs and parity with ICEVs might also be affected by policies encouraging the adoption of such vehicles such as carbon pricing, 100% ZEV sales, and incentivization. The vehicles are assumed to be scrapped after their lifetime, and the present study does not consider a scrappage value for any of the vehicles because of the range of scrappage costs for different vehicle fuel technologies. In any case, the scrappage value after the entire lifetime would not be significant enough to affect the total cost of operation.

Another major challenge is that an annual activity is assumed for the vehicles in each sector. This approach might not be precise for the freight sectors, which have varied duty cycles and might affect the energy intensity of the vehicles and therefore the energy demand and GHG emissions from these sectors.

1.8. Thesis outline

This thesis comprises 4 chapters. Chapter 1 sets the scene for this thesis and describes the energy and emissions from the road transportation sector from provincial and national perspectives. It describes the current and proposed federal and provincial policy mandates for the sector. A detailed literature review of the recent studies on policy mandates, costs, energy demand and emissions is provided. The research questions are then defined, the objectives are provided, and the knowledge gaps that are meant to be filled are outlined. The chapter also discusses the limitations of this study.

Chapter 2 summarizes the method used to achieve the objectives defined in Chapter 1. Further descriptions of the method are included in each of the following chapters as required. Chapter 2 describes the framework used to develop the road transportation model for market share analysis. It examines the various costs used to calculate the total cost of ownership and the energy efficiency of different fuel technology vehicles and provides the market share that is used in the demand side of the LEAP modelling framework in Chapter 3.

Chapter 3 presents the method for developing the bottom-up LEAP model for the road transportation sector. It provides the energy, GHG emissions, and social cost for the study period in different scenarios. It describes the development of the transformation modules of the LEAP framework and the various scenarios that are analyzed in this research. It also examines the infrastructure for the supply of fuels for the zero-emission vehicles.

In the transformation module of the LEAP-Canada model, certain modules are utilized and modified from the previous research in our group. The hydrogen production module was modelled by Davis et al. [60] where all the input data and assumptions can be found. The electricity generation module was modelled by Davis et al. [61]; a modified business-as-usual (BAU) scenario was used in this study. The gasoline and diesel production modules were modelled based on the data obtained from Talaei et al. [62]. Further details of these modules are given in Sections 3.1, 3.2 and 3.4, respectively.

For this study, a new demand module and several transformation modules were developed in the LEAP-Canada model. These include dedicated modules for natural gas production, delivery, and refuelling; biodiesel production and delivery; gasoline delivery and refuelling; diesel delivery and refuelling; and hydrogen delivery and refuelling. Additionally, the ethanol production and delivery as well as electricity transmission and distribution modules were initially developed within the research group and were modified for this study.

Chapter 4 assesses the contributions made with this research, and some overall conclusions are drawn.

Chapter 2, and Chapter 3, are rewritten as two separate papers that will be submitted to different academic journals for publication. Certain sections of Chapter 1 and Chapter 4 are also included in these papers.

2. Total Cost of Operation of Vehicles and Development of Market Share Model[2]

2.1. Methodology

2.1.1. Framework

Figure 2.1 shows the framework developed for the study. The framework comprises five modules: the road transport module and the energy supply modules for hydrogen, electricity, natural gas, and gasoline/diesel. The road transport module models vehicle stocks, costs, adoption, energy, and emissions. The starting point in the framework is to calculate vehicle stocks in each year of the study period. For each subsector, a vehicle stock model projects the demand for vehicles for each year and determines the number of new vehicle sales based on existing stocks and scrappage rates (share of vehicles discarded every year). The number of new vehicle sales is then allocated to available vehicle technologies based on a market share equation using relative costs of ownership. The annual activity of each vehicle creates demand for energy, which is supplied by the energy supply modules (Chapter 3).

2.1.2. Vehicle stock, adoption, and activity modelling

The stock turnover model computes the number of vehicles in use each year. The total number of vehicles ($\boldsymbol{V}$) in a subsector ($\boldsymbol{C}$) each year ($\boldsymbol{t}$) is given by the product of population ($\boldsymbol{P}$) and vehicle use rate ($\boldsymbol{W}$) in vehicles per person (Equation 2.1). The number of scrapped vehicles ($\boldsymbol{S}$) is calculated by Equation 2.2, where $\boldsymbol{E}$ is the existing vehicle stock in the base year ($\boldsymbol{b}$), $\boldsymbol{r}$ is the

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[2] A version of this chapter is to be published as Haider M, Davis M, and Kumar A, "A framework to assess the market share of low-carbon road vehicles in a fossil-fuel-dependent jurisdiction."

annual rate of scrappage, and $\boldsymbol{L}$ is the average lifetime of a vehicle. After the existing stock of vehicles is scrapped, the scrapped vehicles equal the new vehicle sales ($\boldsymbol{N}$) $\boldsymbol{L}$ years before $\boldsymbol{t}$. Equation 2.3 gives the new vehicle sales ($\boldsymbol{N}$), given by the growth in the total number of vehicles and the scrappage. New vehicle sales are then allocated to the different vehicle types using a market share multiplier ($\boldsymbol{MS}$) [63] in Equation 2.4, found from the relative total cost of ownership ($\boldsymbol{TCO}$) of each vehicle ($\boldsymbol{X}$). The parameter $\boldsymbol{v}$ determines the shape of the market share function. A high value means that the market shares bias towards the technology with the lowest operation cost. A lower value means that the market shares are distributed more evenly between all the competing technologies. So, $\boldsymbol{v}$ can denote the sensitivity of technology choice to the relative cost of options. Equation 2.5 calculates the $\boldsymbol{TCO}$ ($/km) based on the annualized capital cost ($\boldsymbol{CC}$), maintenance cost ($\boldsymbol{MC}$), fuel cost ($\boldsymbol{FC}$), and annual average distance driven ($\boldsymbol{A}$). The $\boldsymbol{FC}$ is calculated with vehicle energy intensity ($\boldsymbol{EI}$) and energy cost ($\boldsymbol{EC}$) in Equation 2.6, and energy cost ($\boldsymbol{EC}$) is given in Equation 2.7 and comprises energy production costs ($\boldsymbol{PC}$) for each fuel ($\boldsymbol{f}$), energy delivery costs ($\boldsymbol{DC}$), refuelling/recharging costs ($\boldsymbol{RC}$), and externality cost ($\boldsymbol{EX}$) (price on carbon).

For the case study, the indicator for vehicles per person ($\boldsymbol{W}$) for each subsector was derived using annual stock data from National Resources Canada (NRCan) [27] and population data from the Canada Energy Regulator (CER) [64]; historical annual stock data for vehicles in each subsector was used up to 2018 and the 2018 value for $\boldsymbol{W}$ was used with population projections [64] for future years. An average annual distance travelled for each vehicle type was used [27]. An average vehicle lifetime ($\boldsymbol{L}$) of 10 years was assumed for new vehicles. It was assumed that existing vehicle stocks ($\boldsymbol{E}$) in the base year ($\boldsymbol{b}$), 2019, are scrapped at a rate ($\boldsymbol{r}$) of 10% per year. Values of 2.9 for $\boldsymbol{v}$ and 22.6% for $\boldsymbol{i}$ were used [65].

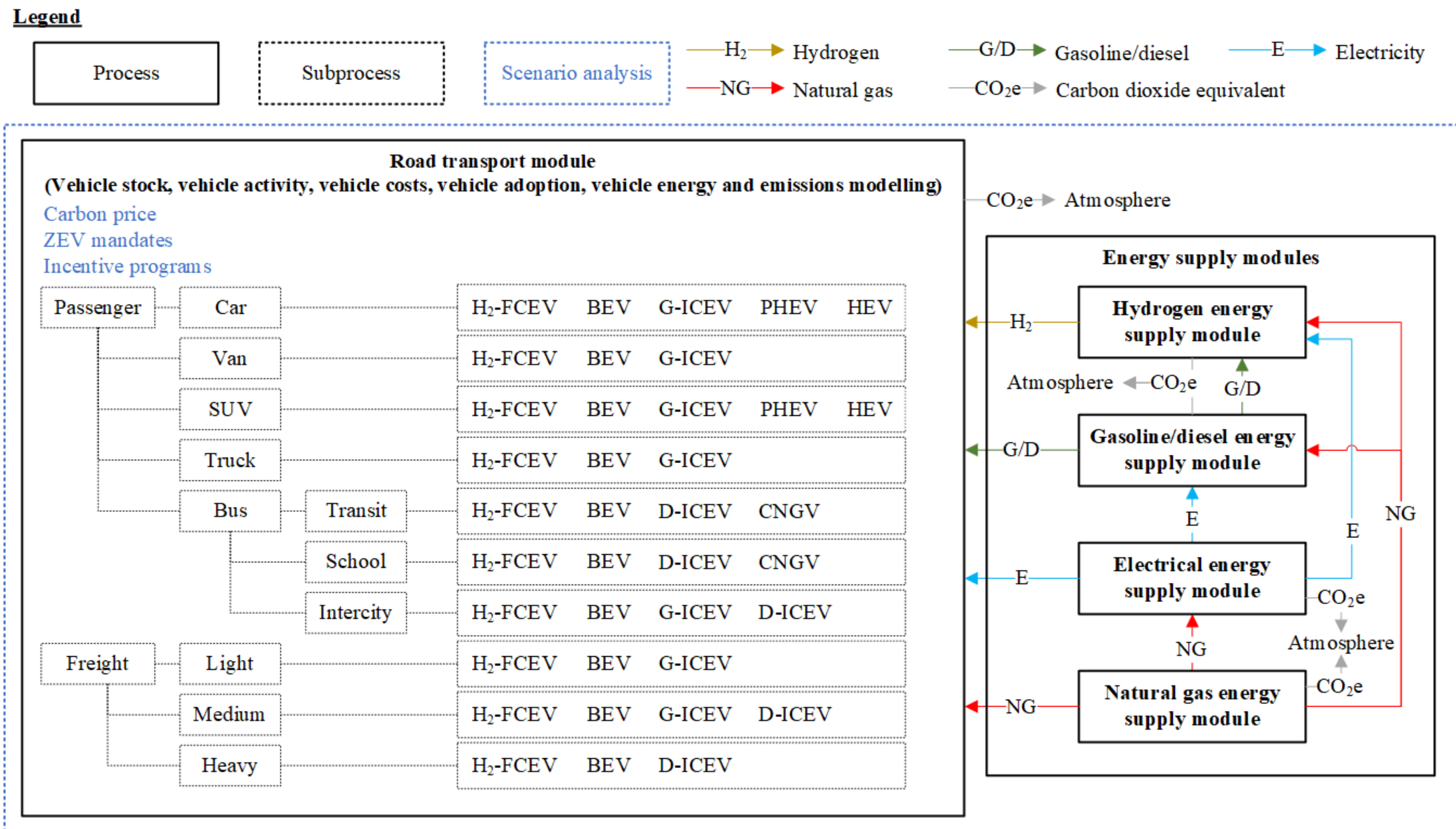

Figure 2.1: A framework to assess the GHG mitigation potential from the adoption of low-carbon road vehicles in a fossil-fuel-dependent jurisdiction.

$$\boldsymbol{P * W_{c,t}} \qquad \boldsymbol{c \in C, t \in T} \qquad \text{Equation 2.1}$$

$$\boldsymbol{S_{c,t} = \begin{cases} E_c * r, t \leq b + L \\ N_{t-L}, t > b + L \end{cases}} \qquad \boldsymbol{c \in C, t \in T} \qquad \text{Equation 2.2}$$

$$\boldsymbol{N_{c,t} = \ (V_{c,t} - V_{c,t-1}) \ + \ S_{c,t}} \qquad \boldsymbol{c \in C, t \in T} \qquad \text{Equation 2.3}$$

$$\boldsymbol{N_{c,t,x} = N_{c,t} * MS_{c,t,x} = N_{c,t} * \left[{TCO_{c,t,x}}^{-v} \Big/ \sum_{x}^{X} [{TCO_{c,t,x}}^{-v}] \right]} \qquad \boldsymbol{c \in C, t \in T, x \in X} \qquad \text{Equation 2.4}$$

$$\boldsymbol{TCO_{c,t,x} = \ \left[\left(CC_{c,t,x} * \frac{i \times (1+i)^L}{(1+i)^L \ - 1} \right) + MC_{c,t,x} \ + FC_{c,t,x} \right] \Big/ A_{c,t}} \qquad \boldsymbol{c \in C, t \in T, x \in X} \qquad \text{Equation 2.5}$$

$$\boldsymbol{FC_{c,t,x} = \ \sum\nolimits_{f}^{F} \left[EI_{c,t,x,f} * EC_{c,t,x,f} \right] * A_{c,t}} \qquad \boldsymbol{c \in C, t \in T, x \in X} \qquad \text{Equation 2.6}$$

$$\boldsymbol{EC_{c,t,f} = PC_{t,f} + \ DC_{t,f} + RC_{c,t,f} + EX_{t,f}} \qquad \boldsymbol{c \in, t \in T, x \in X, f \in F} \qquad \text{Equation 2.7}$$

2.1.3. Vehicle costs, energy, and GHG emissions modelling

The total annual distance travelled for each vehicle technology and its energy intensity was used to calculate the final energy demand. As mentioned in the framework section, Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Tier 1 emission factors were applied to the energy consumption to calculate GHG emissions. Vehicle purchase and maintenance costs were approximated from values of existing vehicles and their projections are based on recent reports and publications. All costs were calculated per vehicle-km for passenger transport and vehicle-km (and average tonnage) for freight transport. All costs are in 2020 CAD.

Table 2.1 shows the breakdown of costs and energy intensities for the passenger category in 2020 and 2050. The capital cost of a H_2-FCEV car is assumed to start at $65,000 in 2020. The capital cost is assumed to decline and reach parity with an ICE ($30,000) by 2040. Our starting values are approximated from those reported by others $57,215 – $82,800 [66-68]. The current price of H_2-FCEV cars is $54,990-$76,750 ($49,500-$66,000 USD) [69]. The IEA and two studies have reported maintenance costs of $0.04-$0.19 per km [67, 70, 71]; a maintenance cost of $0.085 per km was assumed. The capital cost of a BEV car is assumed to be $50,000 on average and to reach parity with gasoline cars by 2030; the capital cost range is large as there is already a variety of BEV cars in the market [72-76]. The values were approximated from the peer-reviewed studies [68, 77, 78]. The maintenance cost is assumed to be $0.042 per km; this value is considered from the range of $0.04-$0.08 reported by other peer-reviewed studies [67, 68, 71, 78]. The capital cost of the PHEV car is assumed to be $39,000; it is assumed from the values used by others in the range of $36,857-$57,999 [53, 68, 79]. The maintenance cost is assumed to be $0.07 per km; this value is approximated from a range of $0.08-$0.11 [67, 78]. For the HEV car, the capital cost is assumed to be \$34,500; this value is assumed from values used by others in the range of \$35,526-\$48,498 [53, 68, 78, 79]. The maintenance cost is assumed to be \$0.07 per km; a comparable range of \$0.08-\$0.11 was found [67, 78].

The capital cost of a H_2-FCEV SUV is assumed to be \$75,000 and to reach parity with ICEVs by 2040; the value is approximated from the values of \$51,147-\$78,345 reported by others [80, 81]. The maintenance cost is assumed to be the same as the H_2-FCEV car, \$0.085 per km. For BEVs, the capital cost is assumed to be \$75,000; a comparable value of \$85,909 was found in a paper by Burnham et al. [80]. The cost of the Tesla Model X is \$158,310 [82]; this is at the higher end of the cost range. The maintenance cost is assumed to be \$0.07 per km; a comparable range was found in the literature [80, 83]. The capital cost of HEVs is assumed to be \$45,000; the value is approximated from a comparable range of \$45,106-\$69,970 found in other studies [80, 83]. The maintenance cost is assumed to be \$0.09 per km; studies show comparable values [80, 83]. The capital cost of PHEVs is assumed to be \$55,000; studies report a range of \$66,695-\$101,614 [80, 83] and are used to approximate the value for this study. The maintenance cost is assumed to be \$0.09 per km; studies show comparable values [80, 83].

The costs for the van and passenger truck are assumed to be the same. The capital cost of a H_2-FCEV is assumed to be \$65,000; it is assumed from a range of \$65,167-\$87,209 provided by automobile manufacturers [84, 85]. The maintenance cost is assumed to be the same as the H_2-FCEV car, \$0.085 per km. The capital cost for a BEV is assumed to be the same as a H_2-FCEV. The maintenance cost is assumed to be the same as an SUV, \$0.07 per km.

The energy intensity of vehicles is taken from approximate values of existing vehicles and their projections are based on recent reports and publications. The efficiency of hydrogen fuel cell vehicles is 40-60%; a gasoline vehicle drivetrain's efficiency is ~20% [39]. The fuel economy of a H_2-FCEV car is assumed to be 97.63 km per kg H_2 (the current fuel economy of available H_2-FCEVs in North America) and to improve over time [86]. The International Energy Agency [67] provides a comparable value. The fuel economy of a BEV car is assumed to be 0.57 MJ/km; the value is assumed from studies that provide comparable values [77, 87, 88]. The efficiency of a PHEV car is assumed to be 1.42 MJ/km gasoline and 0.45 MJ/km electricity; Kamiya et al. [87] provide a comparable value. The efficiency of an HEV car is assumed to be 1.69 MJ/km; similar values were reported in peer-reviewed studies that are used to assume the value for this study [87, 88]. Among SUVs, the fuel efficiency of a H_2-FCEV is assumed to be 1.23 MJ/km; the International Energy Agency [67] provides a comparable value. The fuel economy of a BEV SUV is assumed to be 0.57 MJ/km; studies have provided comparable values [77, 87, 88]. The efficiency of a PHEV SUV is assumed to be 1.27 MJ/km for gasoline and 0.60 MJ/km for electricity; Cihat Onat et al. [83] provide a comparable value. The efficiency of an HEV SUV is assumed to be 2.08 MJ/km; it is considered from studies that provide similar values [80, 83, 89]. Among vans and passenger trucks, the fuel efficiency of H_2-FCEVs is assumed to be 9.45 MJ/km; a comparable value was found in a study by Lee et al. [90]. The efficiency of BEVs is assumed to be 0.85 MJ/km; Burke and Miller [91] provides a similar value.

Table 2.2 shows the breakdown of costs and energy intensities for the competing vehicles for the bus category in 2020 and 2050. The capital cost of a bus is assumed to be $1,500,000; it is approximated from studies that reported a range of $620,778-$1,413,430 [91, 92]. The maintenance cost is assumed to be $0.47 per km and to decline to $0.3 per km by 2040; this is comparable to values found in peer-reviewed studies [71, 93]. The capital cost of a BEV is considered to be $1,300,000; a comparable range of $705,304-$1,357,858 was found in several studies [91, 92, 94-97]; our value is assumed from this range. The capital cost of a trickle-charged transit bus in Edmonton is ~ \$1,146,639 [98]. The maintenance cost of an urban transit bus is assumed to be \$0.09 per km; it is assumed from studies that show a comparable range, \$0.04-\$0.3 per km [71, 95, 97]. The capital cost of compressed natural gas (CNG) buses is assumed to be \$1,000,000; it is considered from studies that provide a comparable range of \$477,143-\$528,056 [92, 94]. The maintenance cost is assumed to be \$0.31 per km; Lajunen and Lipman gives a comparable value [92].

The fuel efficiency of a H_2-FCEV bus is assumed to be 9.2 MJ/km. The value is comparable to values given in other studies [99, 100] and were used to assume this value. The fuel efficiency of a BEV bus is assumed to be 4.41 MJ/km. It is approximated from other studies that show a comparable value [88, 91, 95, 97, 100].

Table 2.3 shows the breakdown of costs and energy intensities for the competing vehicles for the freight category in 2020 and 2050. The capital cost of a heavy-duty H_2-FCEV truck is assumed to be \$287,500; this value is approximated from those reported in other studies (\$237,223-\$444,799) [91, 101-103]. There is very limited data available for fuel cell freight trucks. Most studies speculate the costs and therefore the range is very wide. The cost of the Nikola H_2-FCEV truck is expected to be \$188,174 [104]. The maintenance cost is considered to be \$0.15 per km; a comparable range was found in a white paper [101]. The capital cost of a BEV heavy-duty freight truck is assumed to be \$235,000, considered from other estimates [101-103, 105]. The cost of a Tesla Semi truck is expected to be ~ 180,000 USD [106]. The maintenance cost is assumed to be \$0.19 per km; published studies provide a comparable value [101, 105].

The capital cost of a medium-duty H_2-FCEV truck is assumed to be $200,000; our value is assumed from the value given by Burke and Miller [91]. The maintenance cost is assumed to be the same as heavy-duty trucks, $0.15 per km; a comparable range was found in a study by Moultak et al. [101]. The capital cost of medium-duty BEV trucks is assumed to be 165,000. The maintenance cost is assumed to be the same as that of heavy-duty trucks, $0.19 per km. The capital cost of light-duty H_2-FCEV trucks is assumed to be $164,000; Burke and Miller give a comparable value [91]. The maintenance cost is assumed to be the same as heavy-duty trucks, $0.15 per km; a comparable range was found in the literature [101]. The capital cost of a light-duty BEV is assumed to be $134,000; value is assumed from the value provided by Burke and Miller [91]. The maintenance cost is assumed to be the same as heavy-duty trucks, $0.19 per km.

For the freight sector, hydrogen fuel energy is within 53-81% of diesel energy per distance travelled depending on the duty cycle. The fuel efficiency is considered to be 9.45, 5.74, and 3.93 MJ per km, for heavy, medium, and light trucks, respectively; the value is approximated from values found in two studies [91, 107]. The fuel efficiency of BEV trucks is assumed to be 5.08, 3.18, and 1.43 MJ per km for heavy, medium, and light trucks, respectively; a comparable value is found in two studies [55, 91].

2.2. Results and discussion

2.2.1. Vehicle costs

The ownership cost of vehicles per km for the passenger sector is shown in Figure 2.2 and for bus and freight sectors is shown in Figure 2.3. In all cases, H_2-FCEV and BEV ownership costs decrease from 2021 to 2050. At present, the fuel cell stack and battery costs are very high, which leads to the high capital cost of these vehicles. There is no established infrastructure for the delivery and refuelling of electric and hydrogen vehicles, thus the energy cost of these vehicles is also high. These costs decline as the technology becomes established. Improvements in the energy efficiency of the battery also decrease vehicle energy costs. Conventional vehicle costs decline as well following the decline in purchase costs and energy efficiency improvements. Carbon pricing has the greatest impact on conventional vehicles. As carbon pricing increases, it increases the total cost of these vehicles.

The ownership cost of a H_2-FCEV car in 2021 is calculated to be \$1.58/km. This includes capital, maintenance and operation, energy, and carbon costs. The energy cost includes the cost of energy production, storage, delivery/transmission, and the refuelling station. The International Energy Agency [108] gives a value of \$1.13/km (\$0.85/km USD). The H_2-FCEV cost will decline to \$0.77/km in 2050. The International Energy Agency [108] gives a long-term (for the years after 2030) value of \$0.66/km (\$0.5/km USD). The ownership cost of a BEV car in 2020 was \$1.08/km in 2021 and will decline to \$0.70/km in 2050. The International Energy Agency [108] gives comparable values of \$0.80/km and \$0.64/km for 2021 and 2050.

The ownership cost of a H_2-FCEV SUV is calculated to be \$1.74/km and \$0.86/km in 2021 and 2050. The ownership cost of the BEV SUV is \$1.60/km and \$0.83/km in 2021 and 2050. The ownership cost of the H_2-FCEV van and passenger truck was found to be \$2.82/km in 2021 and to decline to \$1.41/km in 2050. The ownership cost of a BEV van is \$1.41/km and \$0.93/km in 2021 and 2050.

Table 2.1: Data inputs for passenger vehicles

		Cars		SUVs		Van/Passenger truck	
Technology	**Variable**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**
H_2-FCEV	Capital cost ($)	65,000	30,000	75,000	35,000	65,000	40,000
	Maintenance cost ($/km)	0.09	0.09	0.09	0.09	0.09	0.09
	Energy intensity (MJ/km)	1.23	1.19	1.23	1.19	9.45	8.90
BEV	Capital cost ($)	50,000	30,000	75,000	35,000	65,000	40,000
	Maintenance cost ($/km)	0.04	0.04	0.07	0.07	0.07	0.07
	Energy intensity (MJ/km)	0.57	0.57	0.85	0.85	0.85	0.85
G-ICEV	Capital cost ($)	30,000	30,000	35,000	35,000	40,000	40,000
	Maintenance cost ($/km)	0.07	0.07	0.10	0.10	0.10	0.10
	Energy intensity (MJ/km)	2.83	2.59	2.70	1.47	5.51	5.19
PHEV	Capital cost ($)	40,000	30,000	55,000	35,000	-	-
	Maintenance cost ($/km)	0.07	0.07	0.09	0.09	-	-
	Energy intensity (Gas) (MJ/km)	1.42	1.29	1.27	1.09	-	-
	Energy intensity (Electric) (MJ/km)	0.45	0.45	0.60	0.60	-	-
HEV	Capital cost ($)	35,000	30,000	45,000	35,000	-	-
	Maintenance cost ($/km)	0.07	0.07	0.09	0.09	-	-
	Energy intensity (MJ/km)	1.69	1.55	2.08	1.78	-	-

Table 2.2: Data inputs for buses

		Urban transit		School buses		Intercity buses	
Technology	**Variable**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**
H_2-FCEV	Capital cost ($)	1,600,000	820,000	1,600,000	820,000	1,600,000	820,000
	Maintenance cost ($/km)	0.47	0.3	0.47	0.3	0.47	0.47
	Energy intensity (MJ/km)	9.2	8.66	9.2	8.66	9.2	8.66
BEV	Capital cost ($)	1,300,000	820,000	1,300,000	820,000	1,300,000	820,000
	Maintenance cost ($/km)	0.09	0.09	0.09	0.09	0.09	0.09
	Energy intensity (MJ/km)	4.41	3.07	4.41	3.07	4.41	3.07
G-ICEV	Capital cost ($)	-	-	-	-	850,000	820,000
	Maintenance cost ($/km)	-	-	-	-	0.31	0.31
	Energy intensity (MJ/km)	-	-	-	-	14.21	14.21
D-ICEV	Capital cost ($)	850,000	820,000	850,000	820,000	850,000	820,000
	Maintenance cost ($/km)	0.31	0.31	0.31	0.31	0.31	0.31
	Energy intensity (MJ/km)	19.66	15.45	34.47	34.47	14.21	14.21
CNGV	Capital cost ($)	1,000,000	820,000	1,000,000	820,000	-	-
	Maintenance cost ($/km)	0.31	0.31	0.31	0.31	-	-
	Energy intensity (MJ/km)	18.42	18.42	18.42	18.42	-	-

Table 2.3: Data inputs for freight vehicles

		Heavy freight		Medium freight		Light freight	
Technology	**Variable**	**2020**	**2050**	**2020**	**2050**	**2020**	**2050**
H_2-FCEV	Capital cost ($)	287,500	152,000	205,000	140,000	164,000	85,000
	Maintenance cost ($/km)	0.15	0.14	0.15	0.14	0.15	0.14
	Energy intensity (MJ/km)	9.45	8.90	5.74	5.74	3.93	3.48
BEV	Capital cost ($)	235,000	162,000	168,000	115,000	134,000	92,000
	Maintenance cost ($/km)	0.19	0.19	0.19	0.19	0.19	0.19
	Energy intensity (MJ/km)	5.08	4.14	3.18	2.66	1.43	1.30
G-ICEV	Capital cost ($)	-	-	125,000	137,000	100,000	110,000
	Maintenance cost ($/km)	-	-	0.20	0.20	0.20	0.20
	Energy intensity (MJ/km)	-	-	6.97	5.82	4.3	3.7
D-ICEV	Capital cost ($)	175,000	192,000	125,000	110,000	-	-
	Maintenance cost ($/km)	0.20	0.20	0.20	0.20	-	-
	Energy intensity (MJ/km)	11.08	9.82	7.73	6.65	-	-

For passenger vehicles, the TCO of H_2-FCEVs is higher than BEVs largely due to higher capital cost of these vehicles. The decline in capital costs rapidly decreases the TCO of both H_2-FCEVs and BEVs by 2050. The difference in the TCO of these vehicles also decreases as they reach cost parity; this difference is driven by the greater decline in the capital cost of H_2-FCEVs. Hydrogen delivery and refuelling infrastructure is currently very limited and comparatively have higher costs than electricity transmission and recharging. The decline in the delivery and refuelling/recharging infrastructure cost for both H_2-FCEVs and BEVs due to economies of scale also declines the TCO of these vehicles.

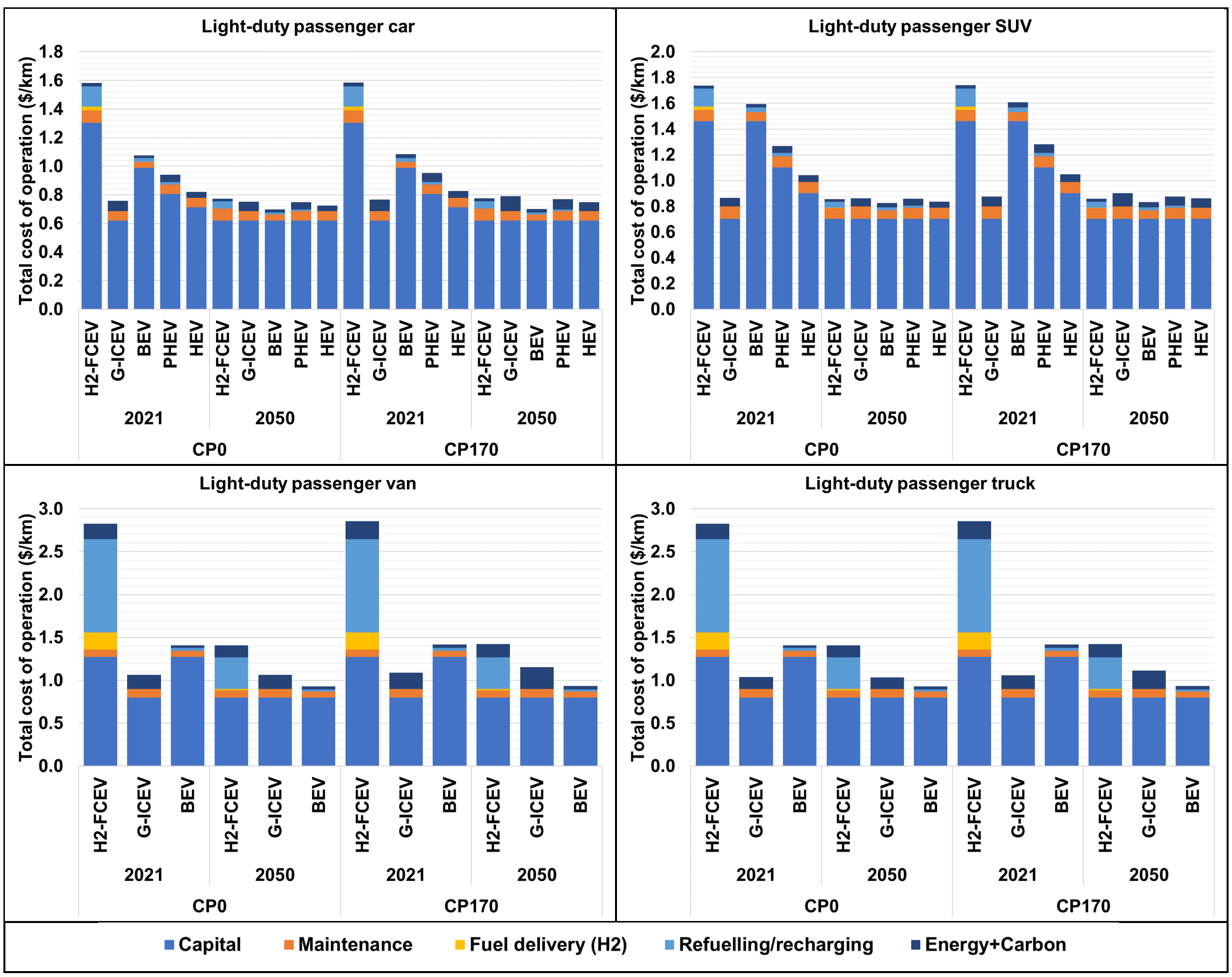

Figure 2.2: The total cost of operation for passenger sector.

The ownership cost of the H_2-FCEV urban transit was found to be \$8.48/km in 2021 and to decline to \$4.26/km in 2050. The ownership cost of BEV urban transit is \$5.87/km and \$3.75/km in 2021 and 2050. The ownership cost of a H_2-FCEV school bus was found to be \$14.21/km in 2021 and will decline to \$7.28/km in 2050. The ownership cost of a BEV school bus was found to be \$10.58/km and \$6.76/km in 2021 and 2050. The ownership cost of a H_2-FCEV intercity bus was found to be \$9.66/km in 2021 and to decline to \$5.06/km in 2050. The ownership cost of a BEV intercity bus was found to be \$6.79/km and \$4.37/km in 2021 and 2050.

For buses, due to higher capital cost, H_2-FCEVs have higher TCO than BEVs, both of which decline over the study period. However, the difference in the capital cost of H_2-FCEVs and BEVs is less than that in the passenger vehicles. Higher delivery and infrastructure cost for H_2-FCEVs than transmission and recharging cost for BEVs increases the difference in TCO of these vehicles. The higher maintenance cost of H_2-FCEV buses also increases the TCO of these vehicles. These costs are expected to decline with the advancement of technology but remain higher than BEV buses.

The ownership cost of a H_2-FCEV light-duty fright truck is \$3.49/km and \$1.81/km in 2021 and 2050. The ownership cost of a BEV light-duty fright truck is \$2.65/km and \$1.86/km in 2021 and 2050. The ownership cost of a H_2-FCEV medium-duty freight truck was found to be \$2.78/km in 2021 and decline to \$1.70/km in 2050. The ownership cost of a BEV medium-duty freight truck was found to be \$1.89/km and \$1.37/km in 2021 and 2050. The ownership cost of a H_2-FCEV heavy-duty freight truck was found to be \$2.37/km in 2021; the International Energy Agency [108] gives a comparable value (\$2.23/km). In 2050, the cost will decline to \$1.08/km; a comparable value of \$1.62/km is provided by the International Energy Agency [108]. The ownership cost of a BEV heavy-duty freight truck was found to be \$1.24/km and \$0.91/km in 2021 and 2050.

Comparable values of $1.53/km and $1.26/km in 2021 and 2050 are given by the International Energy Agency [108].

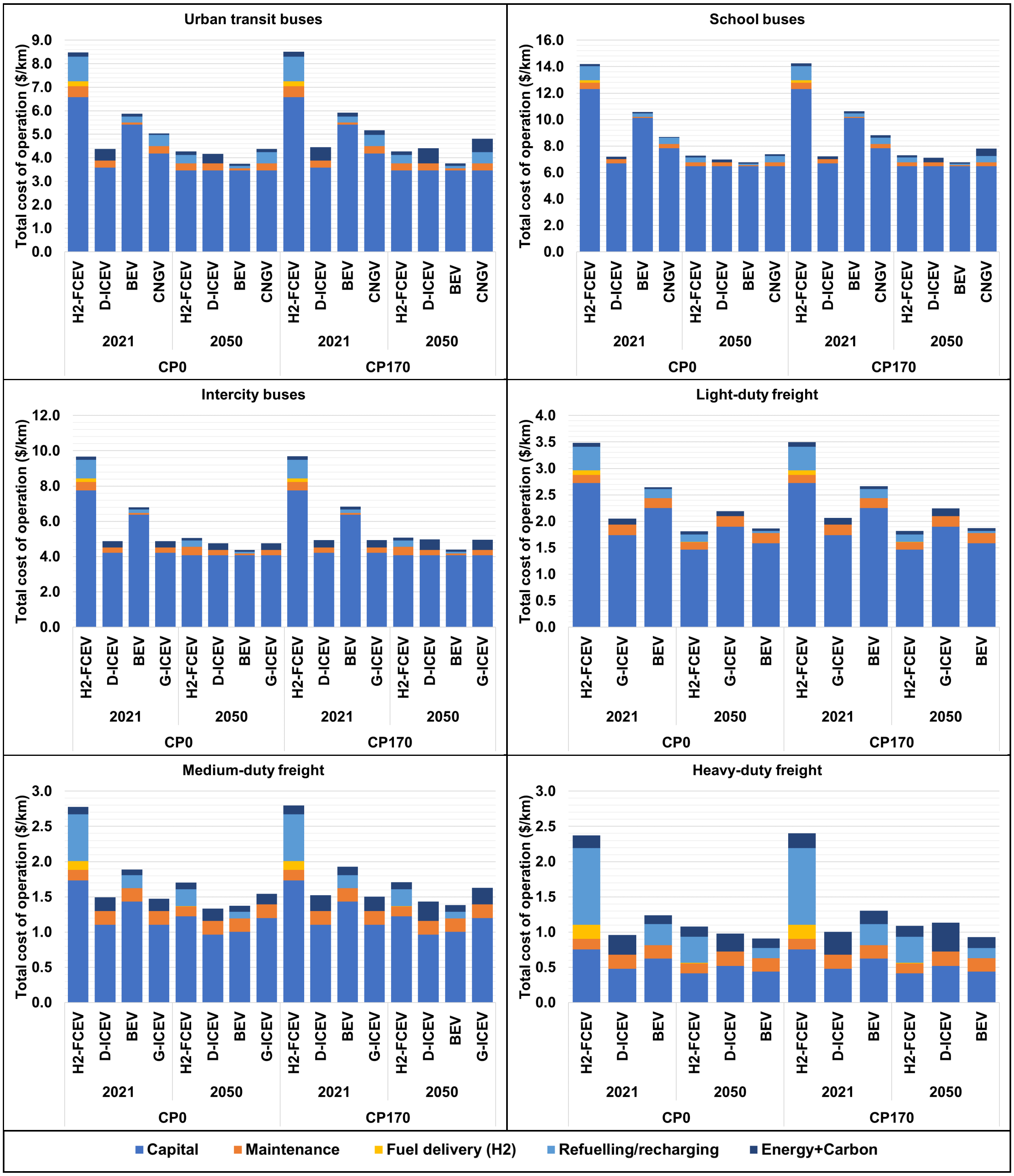

Figure 2.3: The total cost of ownership for bus and freight sectors.

For freight vehicles, The TCO of H_2-FCEVs is higher than BEVs due to higher capital cost and hydrogen delivery and refuelling cost. The capital cost of H_2-FCEVs, although currently higher than BEVs, is expected to reach parity with BEVs in 2030s. This declines the TCO of H_2-FCEVs by 2050. The delivery and infrastructure cost for H_2-FCEVs is higher than transmission and recharging costs for BEVs; which along with the activity and energy consumption of H_2-FCEVs increases the difference in the TCO of these vehicles. All these costs are expected to decline by 2050, but the TCO of H_2-FCEVs remains higher than that of BEVs.

2.2.2. Market shares

2.2.2.1. Market shares in different scenarios

Figure 2.4 to Figure 2.6 shows the market share of the different fuel technology vehicles in different sectors. The REF scenario charts show the baseline results. A “no carbon price” policy is assumed for the reference scenario. BEVs and H_2-FCEVs are introduced into the fleet in 2023 and 2026, respectively. H_2-FCEV and BEV shares of passenger vehicles are 2% and 15%, respectively, by 2030. The H_2-FCEV share reaches 16% by 2050; the BEV has a larger share (31%) by 2050. H_2-FCEV buses have a share of 4% by 2030 that increases to 23% by 2050. BEVs grow from 13% in 2030 to 27% by 2050. H_2-FCEV freight trucks have a share of 6% in 2030 that increases to 27% by 2050. BEVs have a share of 22% in 2030 and grow to 36% by 2050. As the share of ZEVs increases, ICEVs decrease to 24%, 30%, and 37% in the passenger vehicle, bus, and freight categories, respectively, by 2050. The shares of other fuel technologies are limited as the ZEV becomes economical in the later years.

Figure 2.4 shows the market share in carbon price scenarios. The increase in carbon price increases the shares of H_2-FCEVs and BEVs. This is because as the carbon price increases, the total cost of ownership of conventional and hybrid fuel technology vehicles experience a greater increase compared to H_2-FCEVs and BEVs. As a result, H_2-FCEVs and BEVs become more competitive, leading to a higher market share of these vehicles. The TCO of ICEVs, PHEVs, and HEVs increases at a greater rate because carbon price increases the direct carbon cost for these vehicles due to tailpipe emissions along with the increase in fuel production and delivery costs. In H_2-FCEVs and BEVs, the increase is seen solely due to an increase in the cost of fuel production and delivery processes. At a \$50/t carbon price, H_2-FCEVs increase by 3.2%, 3.3%, and 2.4% from the baseline in the passenger vehicle, bus, and freight categories by 2030. The H_2-FCEV growth rate slackens because the ownership cost of BEVs is lower; the increase in shares due to carbon price are 2.3%, 2.4% and 1.7%, respectively, by 2050. The impact of the carbon price on BEVs is comparatively lower; vehicle shares increase by 1.8%, 2.1% and 1.2% by 2050. At a \$170/t carbon price, the growth rate has the same trend. The H_2-FCEV shares increase by 7.5%, 8.4%, and 5.2% from the baseline by 2030 and decline slightly to 6.0%, 6.8%, and 4.4% by 2050. BEV shares increase by 6.2%, 6.5%, and 3.1% by 2030 and 6.0%, 6.7%, and 4.6% by 2050. At a \$350/t carbon price, H_2-FCEV shares increase by 14.2%, 16.3%, and 9.3% from the baseline compared to BEVs, which increase by 12.5%, 13.0%, and 7.0% in the passenger vehicle, bus, and freight categories by 2030. Post 2030, H_2-FCEVs grow at a lower rate than BEVs and increase by 11.4%, 13.1%, and 7.9%, whereas BEVs increase by 12.5%, 13.7%, and 10.1% by 2050.

The results show that BEV and H_2-FCEV passenger vehicle shares increase to 35% and 18% by 2050 with the increase in carbon price from \$0/t to \$350/t. Plug-in hybrid and hybrid vehicle shares decline with the increase in carbon price and have shares of 13% and 14% by 2050; ICEVs make up a 20% share by 2050 at a \$350/t carbon price. BEV and H_2-FCEV buses increase to 30% and 26% by 2050 at a \$350/t carbon price. CNGVs and ICEVs have shares of 15% and 29% by 2050.

In freight, BEV and H_2-FCEV shares increase to 40% and 29% with only a 31% share remaining of ICEVs by 2050 at a $350/t carbon price.

Figure 2.5 shows the market share in incentivization and current policy scenarios. The impact of incentivization by considering rebates on the capital cost of the vehicles as incentives for ZEVs, thereby decreasing the TCO of these vehicles, resulting in an increase in the market share. Incentives of 10% for BEVs and H_2-FCEVs and 5% for PHEVs, HEVs, and CNGVs were considered. The results show increases of 10.8% and 6.8% in BEV and H_2-FCEV passenger vehicles by 2050. In buses, increases of 12.7% and 9.0% are seen and in freight vehicles, 8.4% and 6.1% by 2050.

The shares of BEV and H_2-FCEV passenger vehicles reach 35% and 17% by 2050 in an incentivized scenario at the same carbon price. BEV and H_2-FCEV buses reach shares of 30% and 25% by 2050 and freight, shares of 39% and 29% by 2050.

A current policy scenario is considered with a $170/t carbon price and 100% sales of ZEV passenger vehicles after 2035. ICEVs remaining after 2035 retire at the end of their lifetimes. The results show increases of 7.5% and 6.2% in H_2-FCEV and BEV passenger vehicles from the baseline by 2030. This is because of the increase in carbon price from $0/t to $170/t, which leads to an increase in the market share of H_2-FCEVs and BEVs. By 2050, shares of other fuel technologies are zero and shares of H_2-FCEVs and BEVs increase by 125.7% and 102.7% from the baseline and make up 36% and 64% of the shares, respectively. In buses, the shares increase by 6.8% and 6.7% for H_2-FCEVs and BEVs, whereas in freight the shares increase by 4.4% and 4.6%, respectively, by 2050.

Figure 2.6 shows the market share in ZEV+ scenarios. The ZEV sales policy is extended to all the sectors and the results show that BEVs will have a higher share than H_2-FCEVs by 2050 in all categories because of lower TCO of these vehicles. By 2050, H_2-FCEV shares increase to 36%, 47%, and 41% in the passenger, bus, and freight categories. The BEV shares will be 64%, 53%, and 59%, respectively.

The ZEV sales policy was modified to consider electric and hydrogen bias scenarios in which BEVs and H_2-FCEVs are incentivized by 30% across the road transport sector. In the ZEV+EV scenario, capital cost of EVs declines by 30% that decreases the TCO of BEVs. Due to cost competitiveness, the shares of H_2-FCEVs increase by 22.8% and 8.5% in the passenger and bus categories and decrease by 8.5% in the freight category from the baseline by 2050. On the other hand, shares of BEVs increase by 156%, 181%, and 109%, respectively, by 2050. Shares of H_2-FCEV and BEV passenger vehicles increase to 20% and 80%; bus shares to 25% and 75%; and freight shares to 25% and 75%, respectively, by 2050. In the ZEV+H_2 scenario, the capital cost of H_2-FCEVs declines by 30%, and decreases the TCO of H_2-FCEVs, resulting in an increased market share. In this scenario, BEV shares increase by 51.2%, 78.4%, and 15.8% in the passenger, bus, and freight categories by 2050. H_2-FCEV shares increase by 226.0%, 126.8%, and 116.4%, respectively, by 2050. The shares of H_2-FCEV and BEV passenger vehicles and buses increase to 53% and 47% in both categories and freight to 58% and 42% by 2050.

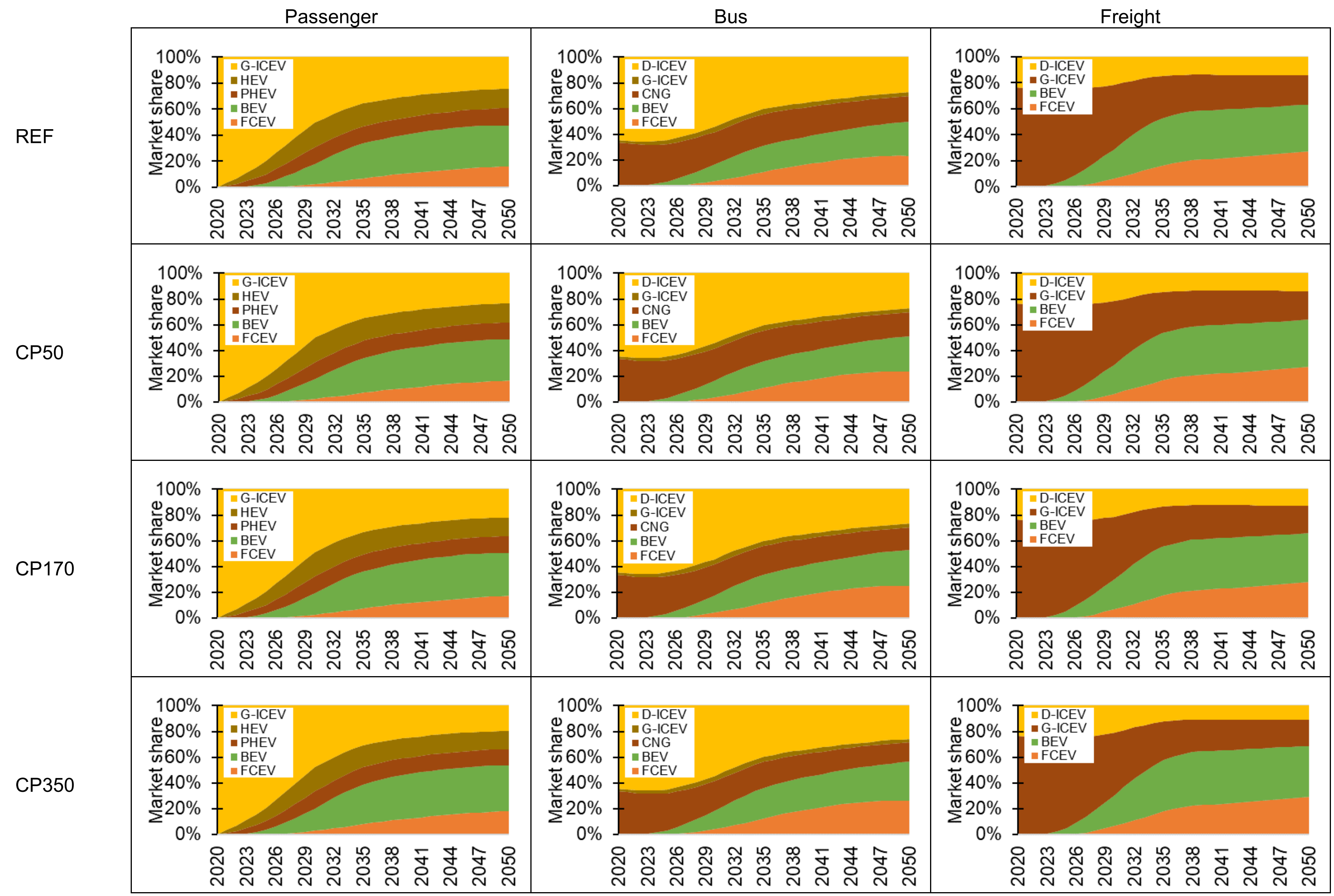

Figure 2.4: REF shows market shares in a "no carbon price" scenario. CP50 shows market shares in a $50/t carbon price scenario wherein the applied carbon price is $40/t in 2022, $50/t in 2023, and increases with inflation beyond 2023. CP170 shows market shares

in a \$170/t carbon price scenario wherein the applied carbon price is \$40/t in 2021, \$50/t in 2022, increases linearly to \$170/t by 2030, and increases with inflation beyond 2030. CP350 shows market shares in a \$350/t carbon price scenario wherein the applied carbon price is \$40/t in 2021, \$50/t in 2022, increases linearly to \$350/t by 2030, and increases with inflation beyond 2030.

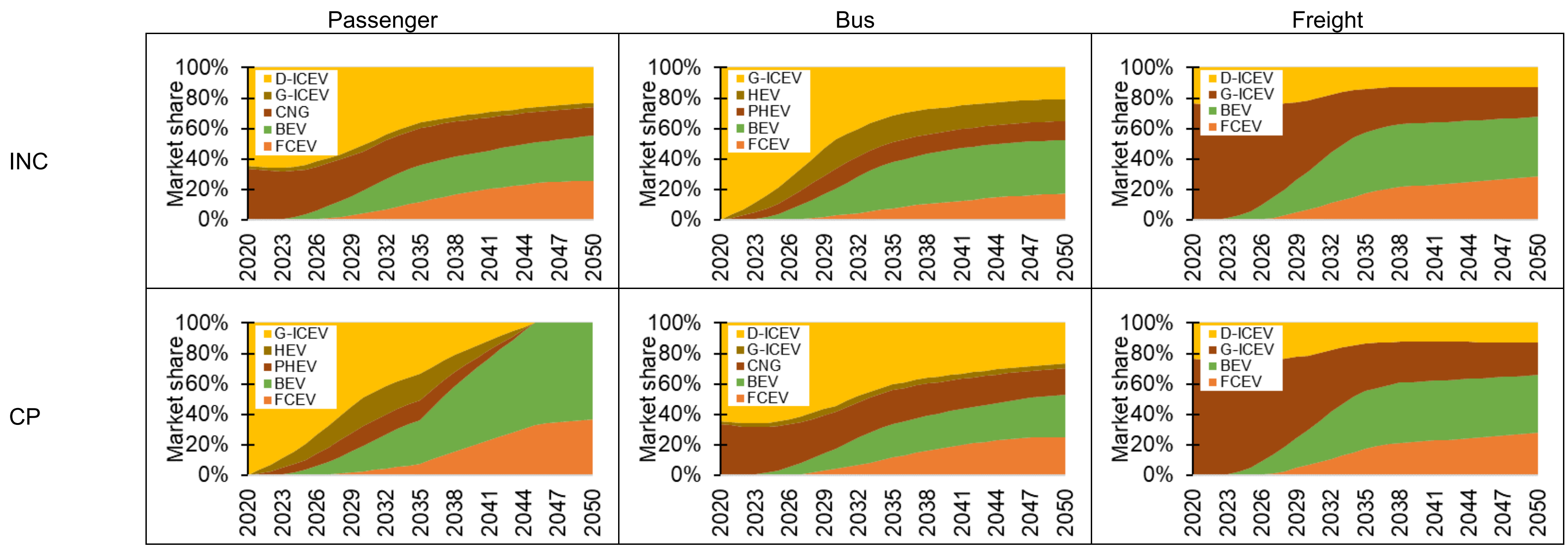

Figure 2.5: INC shows market shares in a “no carbon price and incentivized” scenario wherein low-carbon vehicles are incentivized for all the sectors. Incentives of 10% for ZEV and 5% for HEV, PHEV and CNGV were assumed. CP shows market shares in the current policy scenario wherein the applied carbon price policy is \$170/t along with the ZEV sales policy that mandates that all passenger vehicles be zero-emission by 2035. After 2035, battery electric and H_2-FCEVs are added to the fleet and existing vehicles will retire after their lifetime.

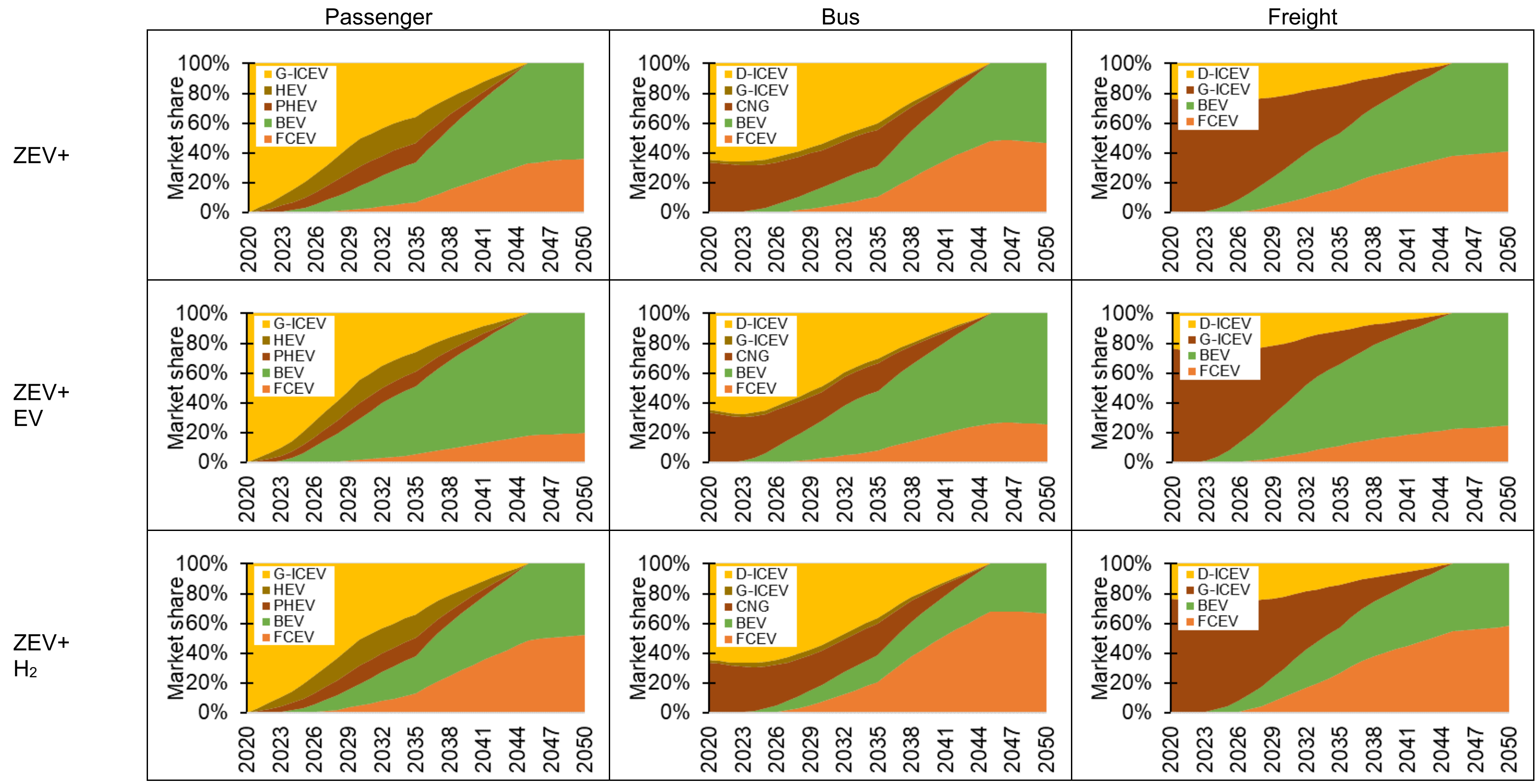

Figure 2.6: ZEV+ shows market shares in a "no carbon price" environment with a ZEV policy applied to all the categories. ZEV+EV shows market shares in a "no carbon price" environment with a ZEV policy applied to all the categories combined with a 30% incentive on capital cost for BEVs. ZEV+H_2 shows the market share in a "no carbon price" environment with a ZEV policy applied to all the categories combined with a 30% incentive on capital cost for H_2-FCEVs.

2.2.2.2. Market shares of passenger vehicles

Figure 2.7 shows the market shares of light-duty passenger cars, light-duty passenger SUVs, light-duty passenger vans, and light-duty passenger trucks for REF, CP, and INC scenarios. The TCO of H_2-FCEVs will consistently remain higher than that of BEVs, and therefore, the market share of H_2-FCEVs will always be higher than BEV in all categories and scenarios. In the REF scenario, shares of H_2-FCEV and BEV passenger cars are found to be 17% and 24% by 2050. Low-carbon technology options like PHEVs and HEVs are found to have lower TCO than H_2-FCEVs and BEVs. Due to cost competitiveness, they will have significant shares, PHEVs and HEVs have shares of 19% and 21% by 2050. The H_2-FCEV and BEV SUVs have shares of 20% and 23% by 2050. The shares of BEV vans and passenger trucks are 53% and 52%; while the shares of H_2-FCEV vans and passenger trucks are 11% by 2050. G-ICEVs will still have a considerable share in all categories of passenger vehicles.

In the CP scenario, H_2-FCEV and BEV passenger cars have shares of 41% and 59% by 2050. All other fuel technology vehicles have phased out and all new vehicle sales post 2035 are of ZEVs. SUVs have relatively similar shares (47% H_2-FCEVs and 53% BEVs) by 2050. By 2050, BEV vans and passenger trucks have the same shares of 17% and H_2-FCEV vans and passenger trucks have shares of 83% by 2050.

In the CP scenario, shares of both H_2-FCEVs and BEVs increase by 2.5 in passenger cars and 2.3 times in SUVs from the REF scenario by 2050. This is because of the combined influence of $170/t carbon price and ZEV sales mandate after 2035. In vans, H_2-FCEVs increase by 1.5 times and BEVs increase by 1.6 times from the REF scenario by 2050. In passenger trucks, both H_2-FCEVs and BEVs increase by 1.6 times from the REF scenario by 2050.

In the INC scenario, H_2-FCEV and BEV passenger cars have shares of 18% and 26% by 2050. Similarly, H_2-FCEV and BEV SUVs have shares of 22% and 26% by 2050. The shares of G-ICEVs are found to be 16% and 18% in passenger cars and SUVs by 2050. H_2-FCEVs have shares of 11% in vans and passenger trucks, while BEVs have shares of 59% and 57% in vans and trucks by 2050.

In the INC scenario, incentives for the H_2-FCEVs and BEVs increase the cost competitiveness of these vehicles, therefore, increasing their share. The shares of H_2-FCEVs and BEVs increase by 1.08 and 1.12 times from the REF scenario in passenger cars by 2050. In SUVs, the shares increase by 1.09 and 1.10 times for H_2-FCEVs and BEVs by 2050. The increase in the shares of H_2-FCEVs from the REF scenario is found to be insignificantly small (less than 1%) for both vans and passenger trucks by 2050 while the BEV shares increase by 1.10 and 1.11 times from the REF scenario by 2050. This is due to the cost competitiveness of BEVs in these categories.

2.2.2.3. Market shares of buses

Figure 2.8 shows the market shares of urban transit, school, and intercity buses for REF, CP, and INC scenarios. In the REF scenario, H_2-FCEV and BEV urban transit buses have shares of 23% and 29% by 2050. D-ICEVs have lower TCO and therefore, still have a considerable share (26%) in the REF scenario. In school buses, the shares of H_2-FCEVs and BEVs are found to be 24% and 25% by 2050. Comparatively, shares of H_2-FCEVs are slightly less than urban transit and school buses because the other fuel technology vehicles in intercity buses demonstrate greater cost competitiveness than H_2-FCEVs. The H_2-FCEV and BEV intercity buses have shares of 20% and 27% by 2050.

In the CP scenario, H_2-FCEVs have the same share of 25% for urban transit and school buses by 2050. BEV urban transit buses have a share of 32% and BEV school buses have a share of 26% by 2050. Intercity buses have shares of 22% and 29% for H_2-FCEVs and BEVs by 2050.

In the CP scenario, shares of both H_2-FCEVs and BEVs increase by 1.1 in urban transit buses and 1.05 times in school buses from the REF scenario by 2050. In intercity buses, the shares increase by 6% for both H_2-FCEVs and BEVs by 2050. This is because of increase in carbon price from $0/t to $170/t in CP scenario, which leads to an increase in TCO of ICEVs, and makes H_2-FCEVs more economically competitive.

In the INC scenario, H_2-FCEV and BEV urban transit buses have shares of 25% and 32% by 2050. By 2050, the shares of H_2-FCEV and BEV school buses are found to be 26% and 28% whereas the shares of H_2-FCEV and BEV intercity buses are found to be 23% and 31%, respectively.

In the INC scenario, incentives provided in the form of rebates for the capital cost of vehicles, decline the TCO of H_2-FCEVs and BEVs, consequently leading to an increase in their market share. H_2-FCEV shares increase by 1.07 times and BEV shares increase by 1.12 times from the REF scenario for urban transit buses by 2050. In school buses, the shares increase by 1.1 and 1.13 times for H_2-FCEVs. and BEVs by 2050. And in intercity buses, the shares increase by 1.11 and 1.16 times for H_2-FCEVs. and BEVs by 2050.

2.2.2.4. Market shares of and freight vehicles

Figure 2.9 shows the market shares of light-duty, medium-duty, and heavy-duty freight trucks. In the REF scenario, the shares of H_2-FCEV and BEV light-duty freight trucks are found to be 35% and 39% by 2050. The higher annual activity of freight trucks decreases the relative difference in the TCO of different fuel technology vehicles in the freight category. This thus increases the share of H_2-FCEVs and BEVs in freight vehicles. The H_2-FCEV and BEV medium-duty freight trucks have shares of 15% and 30% whereas H_2-FCEV and BEV heavy-duty freight trucks have shares of 20% and 43% by 2050.

In the CP scenario, shares of H_2-FCEV and BEV light-duty freight trucks are found to be 36% and 39% by 2050. The shares of medium-duty freight trucks are 17% and 33% and the shares of heavy-duty freight trucks are 23% and 48% for H_2-FCEVs and BEVs by 2050.

In the CP scenario, shares of both H_2-FCEV and BEV light-duty freight trucks increase by 1.02 times from the REF scenario by 2050. Similarly, from the REF scenario, the shares of H_2-FCEV and BEV medium-duty freight trucks increase by 1.1 and 1.09 times and the shares of H_2-FCEV and BEV heavy-duty freight trucks increase by 1.16 and 1.12 times by 2050. This is solely because of the increase in carbon price from \$0/t to \$170/t.

In the INC scenario, H_2-FCEV and BEV light-duty freight trucks have shares of 37% and 41% by 2050. The shares of H_2-FCEV medium-duty and heavy-duty freight trucks are found to be 17% and 20% and the shares of BEV medium-duty and heavy-duty freight trucks are found to be 34% and 46%, respectively, by 2050.

In the INC scenario, the shares of both H_2-FCEV and BEV light-duty freight trucks increase by 1.02 times from the REF scenario by 2050. The shares of H_2-FCEV and BEV medium-duty freight trucks increase by 1.1 and 1.09 times and the shares of H_2-FCEV and BEV heavy-duty freight trucks increase by 1.16 and 1.12 times from the REF scenario by 2050. This is because of 10% incentives for H_2-FCEVs and BEVs that decrease the TCO of these vehicles, consequently increasing the market share.

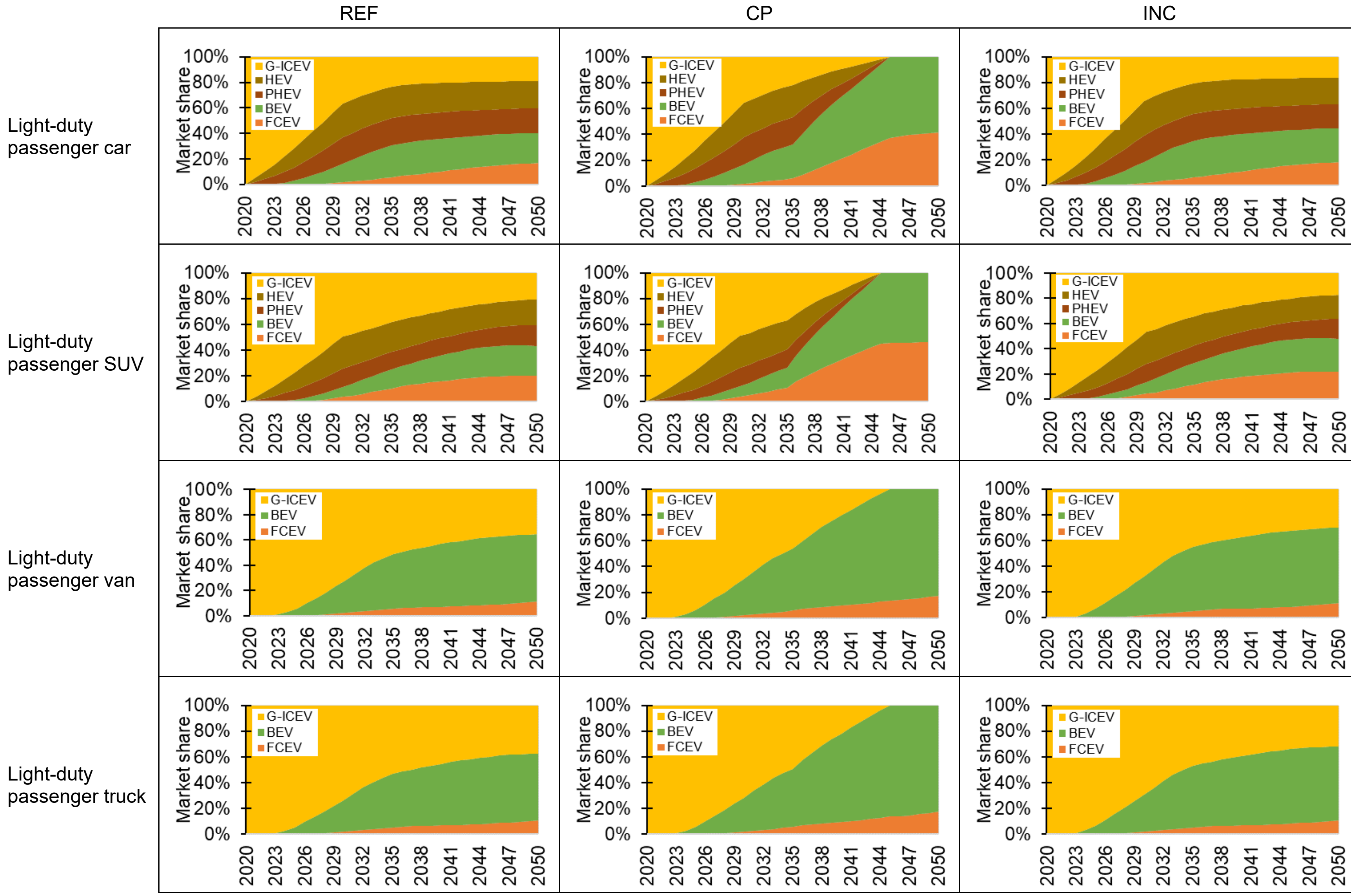

Figure 2.7: Market shares of light-duty passenger car, light-duty passenger SUV, light-duty passenger van, and light-duty passenger truck for REF, CP, and INC scenarios.

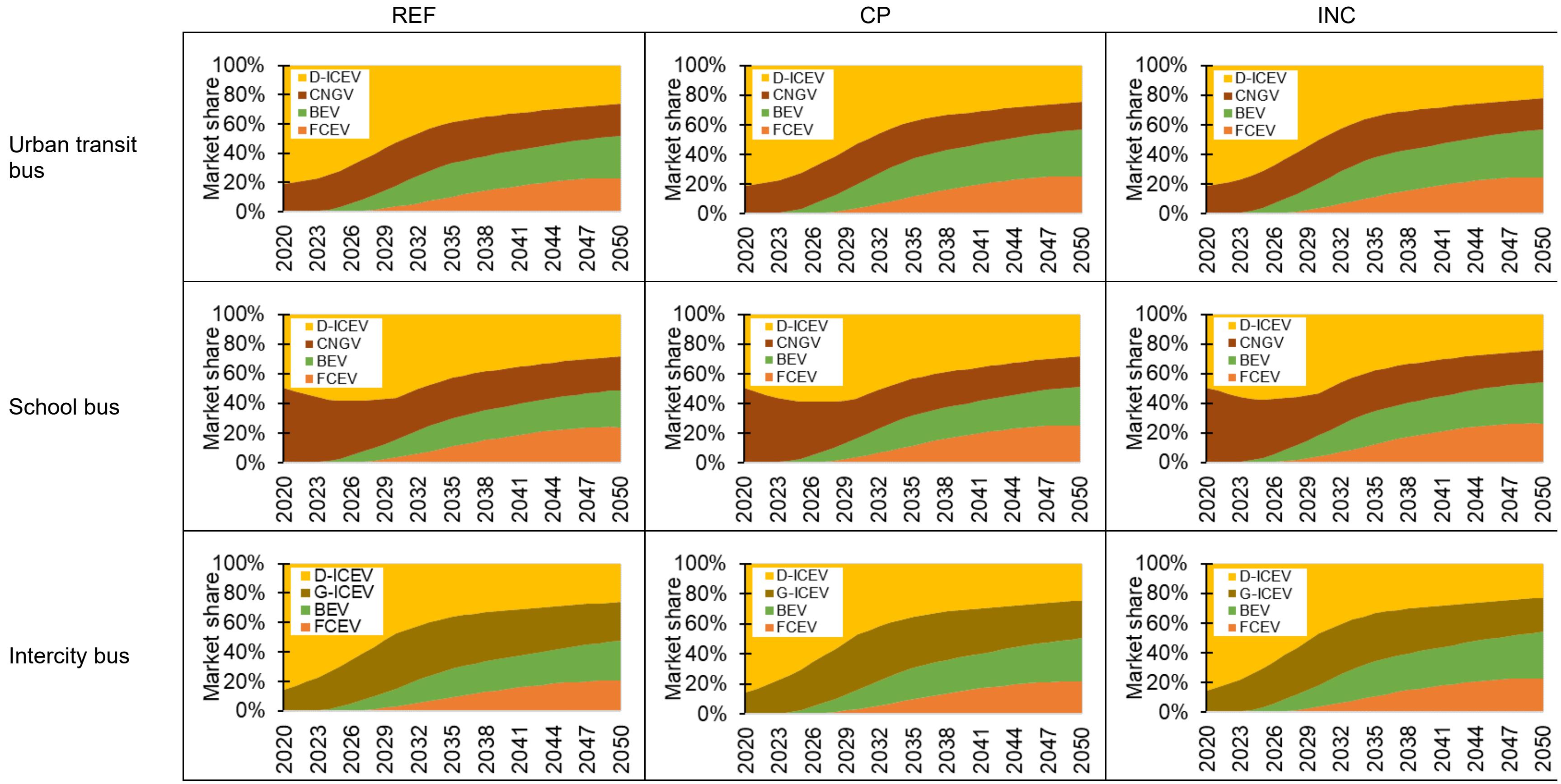

Figure 2.8: Market shares of urban transit, school bus, and intercity bus for REF, CP, and INC scenarios.

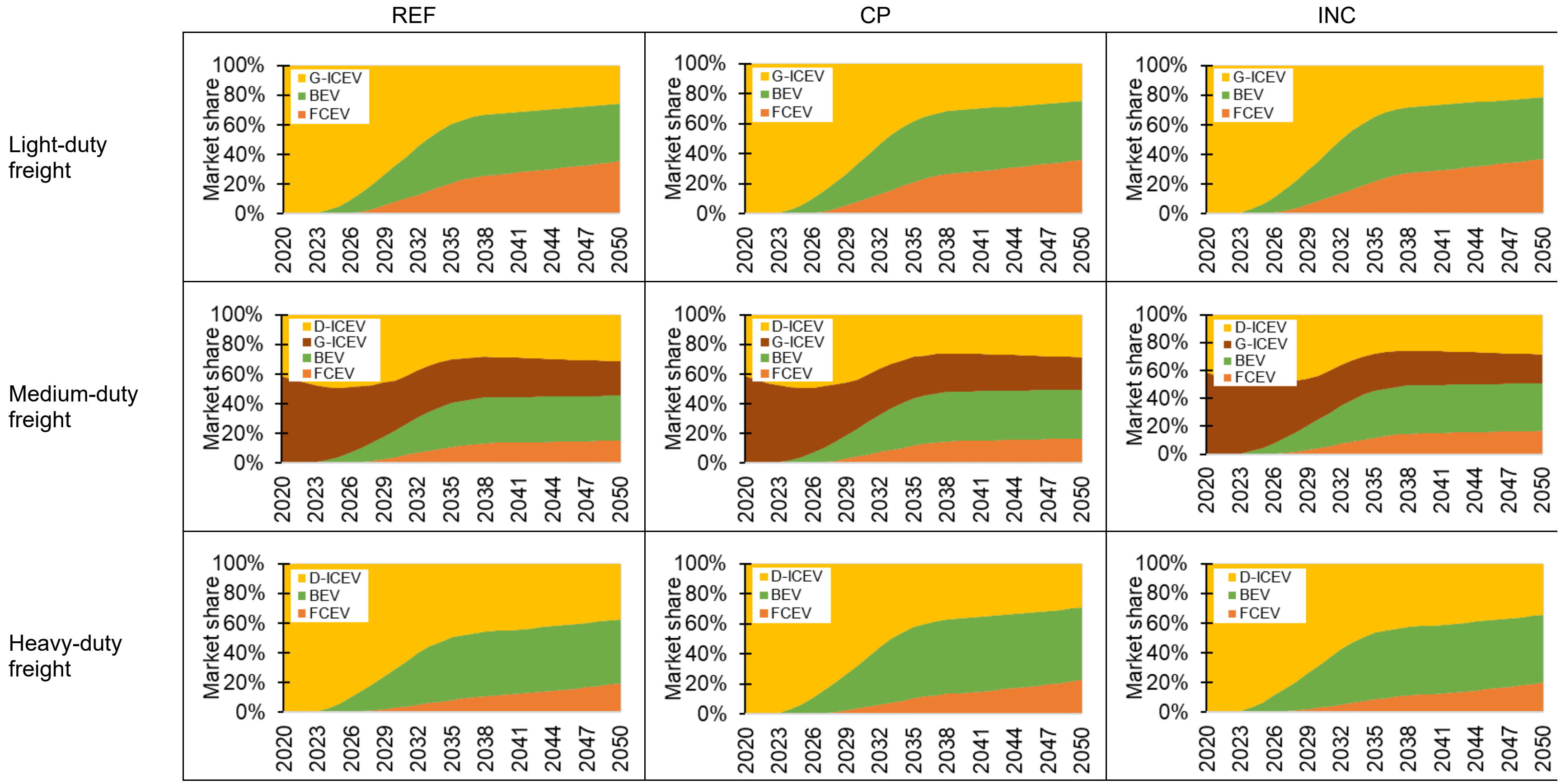

Figure 2.9: Market shares of light-duty freight, medium-duty freight and heavy freight for REF, CP, and INC scenarios.

3. Development of LEAP Model for Transport Sector and System-Wide Energy and GHG Emissions[3]

LEAP is an energy-environment modelling tool developed by the Stockholm Environment Institute (SEI) [109]. LEAP was chosen because it allows the user to model integrated energy systems from the bottom-up and has a built-in scenario analysis capability. The work done for this study is an extension of a previously developed LEAP model of Canada (LEAP-Canada) [26, 61, 110]. New transport demand module and associated energy supply systems were developed for this study. The road transport module (Chapter 2) was implemented in LEAP-Canada's demand module. The energy supply modules (Chapter 3) were implemented in LEAP-Canada's transformation module. The IPCC's Fifth Assessment Tier 1 emission factors were applied to the consumption of energy in the LEAP-Canada model [111]. The time scale is 1990-2050, with 1990-2018 as the model validation period and 2019-2050 as the projection period for scenario analysis. Nine scenarios were developed to investigate the effect of carbon prices, zero-emission vehicle mandates, and financial incentives on vehicle costs and market shares, energy use, and GHG emissions to 2050; these scenarios are described in Section 3.5 of this chapter.

The energy supply modules consider the energy and emissions associated with the upstream processes required to supply each fuel. A detailed description of the supply chain modelling of the fuels is described in Sections 3.1-3.4 of this chapter.

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[3] A version of this chapter is to be published as Haider M, Davis M, and Kumar A, "Development of a framework to assess the greenhouse gas mitigation potential from the adoption of low-carbon road vehicles in a hydrocarbon rich region."

3.1. Hydrogen energy supply chain modelling

Figure 3.1 shows the framework developed for the hydrogen supply chain. Hydrogen production was assumed to be from SMR-85%-CCS, an established technology, until 2030 and from ATR with 91% CCS from 2030 to 2050, allowing time for the commercial scale-up of ATR-CCS. The hydrogen production module was modelled in one of our previous studies, where all the input data and assumptions can be found [60].

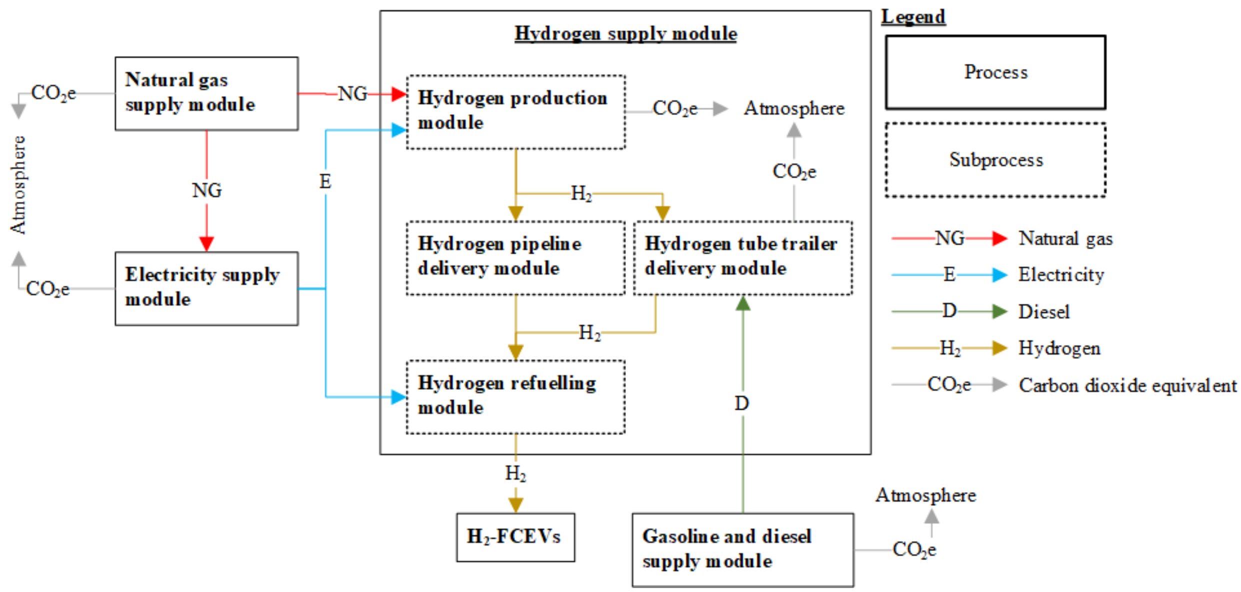

Figure 3.1: Hydrogen energy supply framework.

Table 3.1 shows the inputs used to model hydrogen delivery and refuelling. Hydrogen transportation from the production site to refuelling stations is assumed to be with 100% high-pressure tube-trailer transportation in 2020 and to transition linearly to 100% pipeline delivery by 2050 at an average distance of 100 km. Yang and Ogden [112] shows that pipeline delivery is a more cost-effective and less GHG-intensive mode for transporting larger amounts of hydrogen. The tube-trailer delivery cost was modelled using the HDSAM, a bottom-up model that focuses on the delivery and refuelling of hydrogen [113]. HDSAM inputs were modified to use Alberta-specific values for population, geographical area, total stock, and annual activity of delivery trucks. Population data is from the CER [64]. The urban scenario was used with a 50% hydrogen vehicle market. Hydrogen is dispensed using the 70 MPa dispenser and a high production volume was selected for the cost estimates. HDSAM provides the costs in 2016 USD, therefore the costs are converted to 2020 CAD at a conversion rate of 1.3 CAD/USD and inflation of 2.15%. All the other inputs use default HDSAM values. The delivery cost is assumed to be $2.67/kg in 2020 and $0.14/kg in 2050; our value is considered from similar values that were found in other studies [114, 115]. The resulting delivered costs are in Table 3.2.

Table 3.1: Input data for hydrogen refuelling stations and delivery

Refuelling and delivery inputs	**2020**	**2050**	**unit**
Tube-trailer hydrogen delivery cost	2.67	2.67	$/kg
Fuel delivery energy consumption (diesel)	0.027	0.006	MJ/km
Pipeline hydrogen delivery cost	0.14	0.14	$/kg
Refuelling station capital cost	8.15	2.72	$/kg
Refuelling station operating cost (non-energy)	0.05	0.019	$/MJ
Refuelling station operating energy (electricity)	0.10	0.10	MJ/MJ H_2

The refuelling station capacity is assumed to be 200 kg/day in 2020 and increases to 1,000 kg/day by 2050. The capital cost of the hydrogen refuelling station is assumed to be $8.15/kg of H_2 delivered for 2020 and decline to $2.72/kg in 2050; it is approximated from similar values found in other studies [116, 117]. The operating cost of the hydrogen refuelling station is assumed to be

$0.05/MJ in 2050 and decline to $0.019/MJ in 2050; several studies have provided similar values [114, 116-118]; the values provided by these are used to approximate value for this study.

Table 3.2: Endogenous hydrogen supply costs ($/GJ$_{LHV}$)

	Hydrogen production						Total cost			
Year	**CP0[1]**	**CP50[2]**	**CP170[3]**	**CP350[4]**	**DC**	**RC**	**CP0[1]**	**CP50[2]**	**CP170[3]**	**CP350[4]**
2020 (SMR85%CCS)	19	20	22	25	20	118	157	158	160	163
2025 (SMR85%CCS)	19	20	22	25	17	105	141	142	144	147
2030 (ATR91%CCS)	16	17	18	19	14	92	122	123	124	125
2035 (ATR91%CCS)	16	17	18	19	11	80	106	107	108	109
2040 (ATR91%CCS)	16	17	18	19	7	67	90	91	92	93
2045 (ATR91%CCS)	16	17	18	19	4	54	75	76	77	78
2050 (ATR91%CCS)	16	17	18	19	1	42	59	60	61	62

[1] Carbon price policy of $0/t
[2] Carbon price policy of $40/t in 2021 and $50/t from 2022 to 2050
[3] Carbon price policy of $40/t in 2021, $50/t in 2022, rising linearly to $170/t by 2030, then increasing with inflation
[4] Carbon price policy of $40/t in 2021, $50/t in 2022, rising linearly to $350/t by 2030, then increasing with inflation

3.2. Electricity energy supply chain modelling

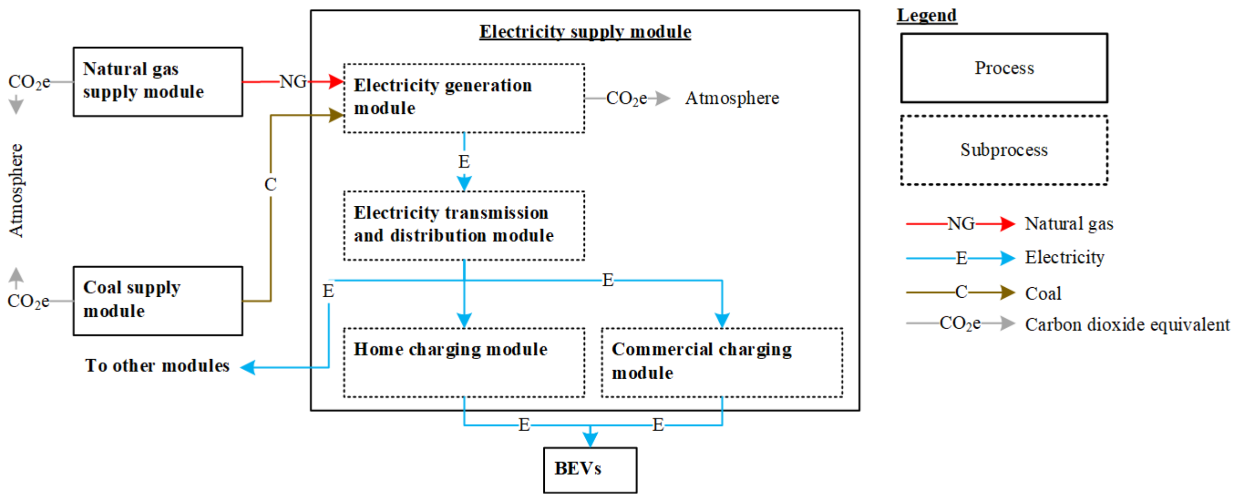

Figure 3.2: Electrical energy supply framework.

Figure 3.2 shows the framework developed for the electricity supply chain. The electricity supply modules comprise the electricity generation module, electricity transmission and distribution module, and charging modules. The electricity generation module was developed in previous work by Davis et al. [61]; it is a detailed representation of Alberta's electricity sector.

For the present study, the electricity generation module is modified. This study uses the business-as-usual (BAU) scenario from Davis et al. [61] with the wind maximum annual capacity additions changed to 1,000 MW for CP0 and 4000 MW for CP50, CP170, and CP350. The model is solved using the Next Energy Modelling system for Optimization (NEMO) (version 1.9.0) [119] and CPLEX solver (version 20.1.0) [120]. The transmission cost of electricity is assumed to be \$0.011/MJ and losses to be 8.7%. The cost value is from the Alberta Electric System Operator [121]. The inputs for modelling electricity transmission, distribution, and recharging are given in Table 3.3.

Table 3.3: Input data for battery charging and electricity transmission and distribution

Recharging and transmission and distribution inputs		2020	2050	unit
Recharging station capital costs	H*	0.025	0.013	$/MJ
	W*	0.040	0.020	$/MJ
	DCFC*	0.050	0.025	$/MJ
Recharging station operating costs (non-energy)		0.01	0.01	$/MJ
Transmission and distribution costs		0.011	0.011	$/MJ
Losses		8.7	8.7	Percent

* (H) home charging; (W) work charging; (DCFC) Direct current fast charging/commercial charging station

Table 3.4: Endogenous electricity supply costs for mix charging ($\$/GJ_{LHV}$)

	Electricity production						Total cost			
Year	**CP0**	**CP50**	**CP170**	**CP350**	**TC**	**RC**	**CP0**	**CP50**	**CP170**	**CP350**
2020	30	42	42	44	11	45	86	98	98	100
2025	40	53	58	67	11	42	93	106	111	120
2030	41	50	49	50	11	39	92	100	99	100
2035	41	48	48	49	11	36	88	95	95	97
2040	40	46	47	49	11	33	85	90	92	93
2045	40	44	46	48	11	30	81	85	88	89
2050	40	43	45	47	11	28	78	82	84	85

The electricity prices were taken considering 50% residential and 50% commercial sector prices for passenger transport. For battery charging, passenger car transport is assumed to have 50%, 25%, and 25% charging at home, work, and commercial charging stations, respectively. The electricity prices were taken considering the commercial sector prices for bus and freight transport. For electric freight and bus transport, DC fast charge is considered at commercial charging stations. Commercial charging station costs decline over time as the availability of charging stations increases. The delivered costs for mixed charging are given in Table 3.4 and commercial charging in Table 3.5.

The capital costs of electric recharging stations are assumed to be \$0.025/MJ, \$0.04/MJ, and \$0.05/MJ for home, work, and commercial charging stations for 2020. A range of \$0.023-\$0.041 per MJ was found in several studies [122-124] and used to approximate the values for this study. The capital costs are assumed to decline to \$0.013/MJ, \$0.02/MJ, and \$0.025/MJ by 2050.

Table 3.5: Endogenous electricity supply costs for commercial charging (\$/GJ_{LHV})

	Electricity production						**Total cost**			
Year	**CP0**	**CP50**	**CP170**	**CP350**	**TC**	**RC**	**CP0**	**CP50**	**CP170**	**CP350**
2020	24	34	35	36	11	60	95	105	106	107
2025	32	43	48	54	11	56	99	110	114	121
2030	34	41	40	41	11	52	96	104	103	104
2035	33	39	39	40	11	48	92	97	98	99
2040	33	38	39	40	11	43	87	92	93	94
2045	32	36	38	39	11	39	83	86	88	89
2050	32	35	37	38	11	35	78	81	83	84

The operating cost of an electric charging station is assumed to be \$0.01/MJ. It is considered based on a similar value found in a National Renewable Energy Laboratory study [117]. The transmission and distribution cost is assumed to be \$0.011/MJ. Rahman et al. [125] provide a value of \$0.09/MJ. The levelized cost of charging when the electricity grid is supplied with hydro and wind energy was found to be \$0.31/MJ and \$1.55/MJ [126].

3.3. Natural gas energy supply chain modelling

Figure 3.3 shows the framework for the natural gas supply chain. The natural gas supply module comprises the natural gas generation module, natural gas distribution module, and recharging station module. The inputs for modelling natural gas delivery and refuelling are given in Table 3.6. The natural gas prices are taken considering the commercial sector prices. The CER provides annual end-use prices projected up to 2050 [64]. Natural gas station refuelling costs for CNGVs were added considering large-scale station costing.

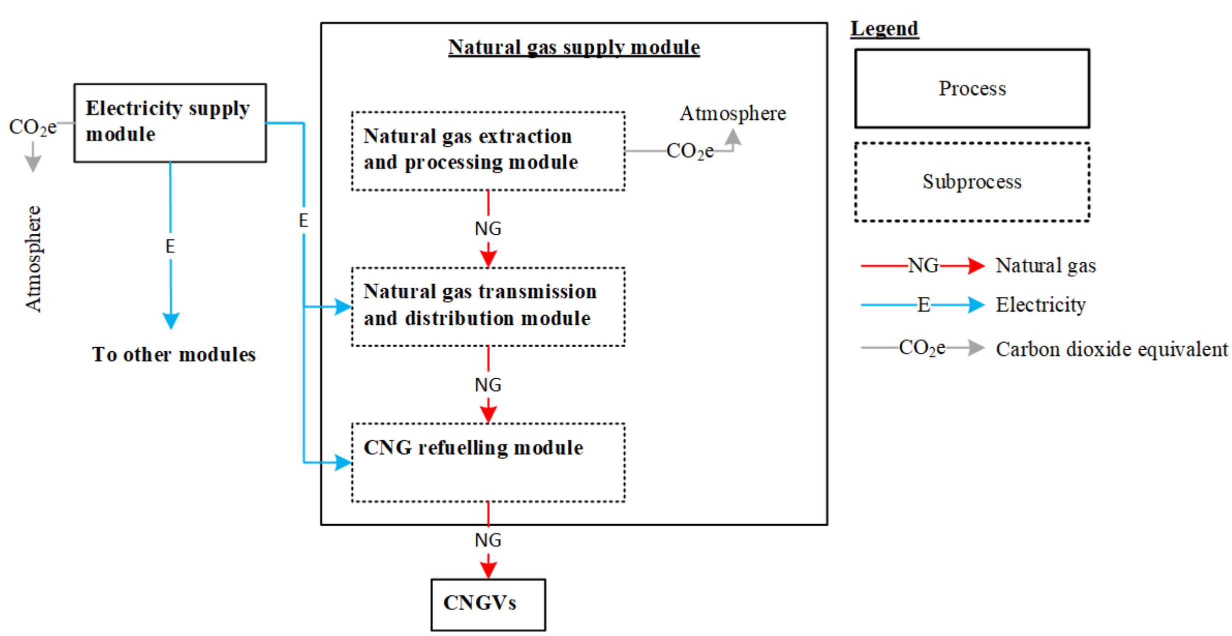

Figure 3.3: Natural gas energy supply framework.

Table 3.6: Input data for natural gas refuelling station and delivery

Refuelling and delivery inputs	**2020**	**2050**	**unit**
Refuelling station costs (non-energy)	26	26	$/GJ
Refuelling station operating energy (electricity)	0.10	0.10	MJ/MJ
Fuel delivery energy (diesel)	0.0025	0.0022	MJ/MJ

The capital cost of natural gas refuelling stations is assumed to be $26 per GJ of natural gas delivered. It is assumed from a similar value reported by the US Department of Energy [127]. The delivered costs are given in Table 3.7.

Table 3.7: Endogenous natural gas supply costs ($\$/GJ_{LHV}$)

	Natural gas production					**Total cost**			
Year	**CP0**	**CP50**	**CP170**	**CP350**	**RC**	**CP0**	**CP50**	**CP170**	**CP350**
2020	4	6	6	6	26	30	32	32	32
2025	5	8	10	15	26	31	34	37	41
2030	5	8	14	24	26	31	35	41	50
2035	5	8	14	24	26	31	34	41	50
2040	5	8	14	24	26	31	34	41	50
2045	5	8	14	24	26	31	34	41	50
2050	5	8	14	24	26	31	34	40	50

3.4. Gasoline and diesel energy supply chain modelling

Figure 3.4 shows the framework for the gasoline and diesel supply chain. The gasoline and diesel modules include crude oil extraction, bitumen extraction, bitumen upgrading, petroleum refining, and delivery and refuelling. The inputs used to model gasoline and diesel are given in Talaei et al. [62]. For the present study, the modules were modified to include the delivery and refuelling of gasoline and diesel. The inputs are provided in Table 3.8. The CER provides annual end-use prices projected up to 2050 [64]. The gasoline prices used for the transport sector are \$27.73/GJ and \$30.74/GJ for 2020 and 2050. The diesel prices used are \$27.84/GJ and \$31.53/GJ for 2020 and 2050. The delivered costs of gasoline and diesel are given in Table 3.9 and the inputs for modelling gasoline, diesel and biofuels are given in Table 3.10.

Table 3.8: Input data for gasoline and diesel refuelling station and delivery

Refuelling and delivery energy	**2020**	**2050**	**unit**
Gasoline			
Refuelling station operating energy (electricity)	0.025	0.025	MJ/MJ
Fuel delivery energy (diesel)	0.0013	0.0011	MJ/MJ
Diesel			
Refuelling station operating energy (electricity)	0.025	0.025	MJ/MJ
Fuel delivery energy (diesel)	0.0012	0.0010	MJ/MJ

Table 3.9: Endogenous gasoline and diesel supply costs ($/GJ$_{LHV}$)

Year	Total cost*				Total cost*			
	Gasoline				Diesel			
	CP0	CP50	CP170	CP350	CP0	CP50	CP170	CP350
2020	28	31	31	31	28	31	31	31
2025	35	40	44	49	36	40	44	50
2030	35	39	48	62	35	40	49	63
2035	34	38	47	61	34	39	47	61
2040	33	37	46	60	33	38	46	60
2045	32	36	45	59	32	37	46	60
2050	31	35	44	58	32	36	45	59

* Includes refuelling and delivery costs

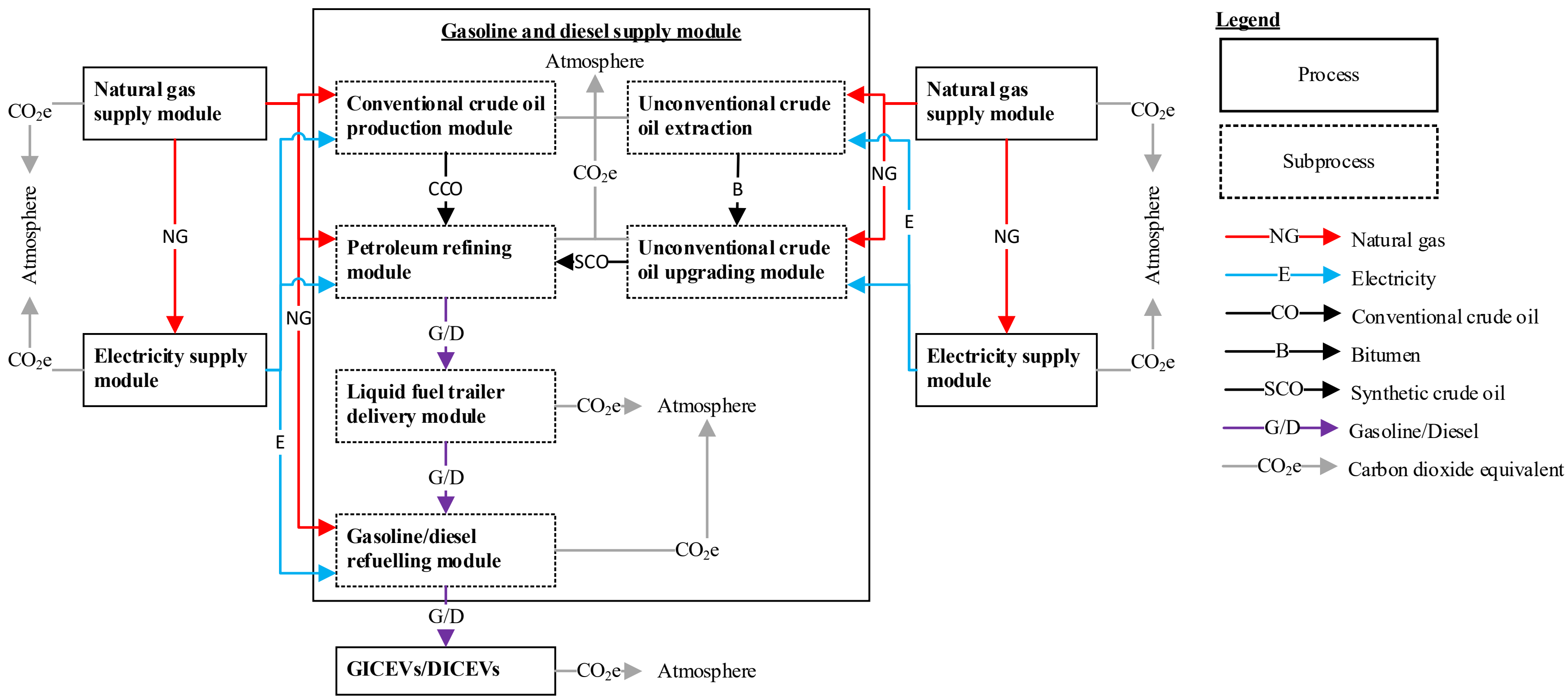

Figure 3.4: Gasoline and diesel energy supply framework.

Table 3.10: The input data for conventional fuels and biofuels production

Fuel	**Processes**	**Process efficiency (%)**	**Auxiliary fuel use (GJ fuel/GJ production)**		**Output fuel**	**Emission source**	**Emission factor (g CO_2e/MJ/Source)**
	Wheat grain harvest and transport	100	Diesel	6.13E-04	Wheat		
Ethanol	Conversion to ethanol	80	Electricity	6.12E-04	Ethanol	Auxiliary	All auxiliary EFs are from IPCC 2014 [111]
			Natural gas	3.85E-01			
	Transport and delivery	100	Diesel	8.04E-04	Ethanol		
Biodiesel	Canola conversion to biodiesel	100	-		Biodiesel		31 Heaps 2022 [109]
Natural gas	Production and processing	99.34	Natural gas	9.34E-02	Natural gas		
Gasoline /Diesel	In situ extraction	100			Bitumen	Fugitive	25.68
			Electricity	8.79E-03		Auxiliary	
			Natural gas	1.43E-01			
			Diesel	5.29E-04			

Fuel	Processes	Process efficiency (%)	Auxiliary fuel use (GJ fuel/GJ production)		Output fuel	Emission source	Emission factor (g CO_2e/MJ/Source)
			Produced gas	2.37E-02			
	Surface mining	100			Bitumen	Fugitive	14.43
			Electricity	8.79E-04			
			Natural gas	4.60E-03		Auxiliary	
			Diesel	2.57E-03			
	Bitumen upgrading	100			Bitumen	Fugitive	1.65
			Electricity	9.65E-03			
			Natural gas	1.01E-01		Auxiliary	
			Produced gas	4.04E-02			
	Petroleum refining	99.3			Synthetic crude oil		
					Light-medium crude oil	Fugitive	0.74
					Heavy crude oil		

Fuel	Processes	Process efficiency (%)	Auxiliary fuel use (GJ fuel/GJ production)		Output fuel	Emission source	Emission factor (g CO_2e/MJ/Source)
					Bitumen		
					Pentanes plus		
			Electricity	3.72E-03			
			Natural gas	1.40E-02		Auxiliary	
			Still gas	2.46E-02			
	Crude oil extraction	100			Light-medium crude oil	Fugitive	2.15
					Heavy crude oil		5.41
			Electricity	3.69E-03			
			Diesel	2.99E-02			
			Produced gas	1.08E-01			
	Pentanes plus and condensates production	100	-				

3.5. Scenario analysis

A reference scenario and eight alternative scenarios were assessed and compared; they are listed in Table 3.11. The reference scenario (REF) serves as a baseline to compare the scenarios. Alternative scenarios allow us to investigate the impacts of carbon price and ZEV policies. For carbon price policies, a wide range of carbon prices is considered, since applied carbon prices can vary widely depending on the policy and jurisdiction. The four carbon price scenarios were labelled CP0, CP50, CP170, and CP350. The impacts of a ZEV sales policy and incentivization were assessed based on current and proposed policies [128, 129]. A scenario examining the effect of low-carbon vehicle incentives (INC) considers rebates on the purchase price of ZEV and hybrid vehicles. A CP scenario replicates Canada's current policy framework, which uses CP170 and a mandate that all personal passenger vehicle sales starting in 2035 are ZEVs. The ZEV+ scenario considers a policy mandate for ZEVs only by 2035 across all sectors. The ZEV+EV and ZEV+H_2 combine the ZEV+ with a 30% purchase rebate incentive for BEVs and H_2-FCEVs.

Table 3.11: Scenario descriptions

Scenario name	Description
CP0 (REF)	The reference scenario, no carbon price policy.
CP50	Carbon price policy: \$40/t in 2022, \$50/t in 2023, then increases with inflation beyond 2023.
CP170	Carbon price policy: \$40/t in 2021, \$50/t in 2022, increases linearly to \$170/t by 2030, then increases with inflation.
CP350	Carbon price policy: \$40/t in 2021, \$50/t in 2022, increases linearly to \$350/t by 2030, then increases with inflation.

Scenario name	Description
CP	Current policy scenario includes a ZEV mandate policy for all personal passenger vehicle sales to be ZEVs by 2035 and CP170.
INC	10% and 5% purchase price rebate for ZEVs and hybrid vehicles, respectively.
ZEV+	ZEV mandate policy for all vehicle sales to be ZEVs by 2035.
ZEV+EV	ZEV mandate policy for all vehicle sales to be ZEVs by 2035 combined with 30% purchase price rebate for BEVs.
ZEV+H_2	ZEV mandate policy for all vehicle sales to be ZEVs by 2035 combined with 30% purchase price rebate for H_2-FCEVs.

To analyze the scenarios, the market shares, annual final and primary energy use, annual GHG emissions, and primary energy footprints and GHG footprints were calculated and compared. LEAP's energy analysis results were used to calculate the final and primary energy requirements and associated GHG emissions for each scenario to develop the results shared in Section 3.7.1.

3.6. Cost analysis

The social costs for all nine different scenarios were assessed and compared. Marginal cost of the scenarios for the study period was calculated, to show the increase or decrease in the total cost between 2020 and 2050 for decreasing one tonne of GHG emissions during the period. The GHG mitigation cost ($\boldsymbol{GM}$) was calculated by Equation 3.1 where $\boldsymbol{SC}$ is the scenario cost and $\boldsymbol{SE}$ is the scenario emissions of the scenario ($\boldsymbol{s}$).

$$\boldsymbol{GM_s = \frac{SC_{s,2050} - SC_{s,2020}}{SE_{s,2050} - SE_{s,2020}}} \qquad \boldsymbol{s \in S} \qquad \text{Equation 3.1}$$

The scenario costs include all the costs for the road transportation sector in the particular scenario. It includes the capital costs, maintenance costs, and fuel costs of all the vehicles in the road transportation sector. The fuel costs include the costs of fuel production, delivery, refuelling/recharging, and carbon costs. These costs are calculated by Equation 3.2 based on capital cost ($\boldsymbol{CC}$), maintenance cost ($\boldsymbol{MC}$), fuel cost ($\boldsymbol{FC}$), of the vehicles and the total number of vehicles ($\boldsymbol{V}$). The fuel cost is calculated using Equation 2.6 and Equation 2.7.

$$\boldsymbol{SC_{s,t}} = \sum_{\boldsymbol{c,x}}^{\boldsymbol{C,X}} \left[\boldsymbol{CC_{c,t,x,s}} + \boldsymbol{MC_{c,t,x,s}} + \boldsymbol{FC_{c,t,x,s}}\right] * \boldsymbol{V} \qquad \boldsymbol{c} \in \boldsymbol{C}, \boldsymbol{t} \in \boldsymbol{T}, \quad \boldsymbol{x} \in \boldsymbol{X}, \boldsymbol{s} \in \boldsymbol{S} \qquad \text{Equation 3.2}$$

The scenario emissions include the emissions from the demand and transformations. The demand emissions are direct tailpipe emissions from the vehicles and the transformation emissions include the upstream processes emissions from fuel production, delivery and recharging/refuelling.

3.7. Results and discussion

3.7.1. Energy and emission results

3.7.1.1. Energy and GHG emission projections

Figure 3.5 shows the energy and emissions for the reference scenario. The freight sector is the largest contributor to emissions and energy demand; system-wide emissions from the sector are 66% in 2020 and 74% in 2050, and corresponding system-wide energy requirements are 67% and 74%. In the freight sector, heavy trucks contribute to ~30% of energy demand and emissions in 2020 and ~28% of energy and emissions in 2050. The freight sector accounts for 33% of the total vehicles in road transport. But the sector's energy demand is exceptionally high due to significant annual activity and fuel consumption of the freight trucks. System-wide emissions from the passenger sector decline from 30% in 2020 to 24% in 2050; corresponding system-wide energy requirements are 31% in 2020 and 23% in 2050. In passenger vehicles, cars are the largest contributor with ~11% of energy and emissions in 2020 and ~8% of energy and emissions in 2050. Buses contribute to 2% of system-wide emissions and energy requirements in 2020 and 2050.

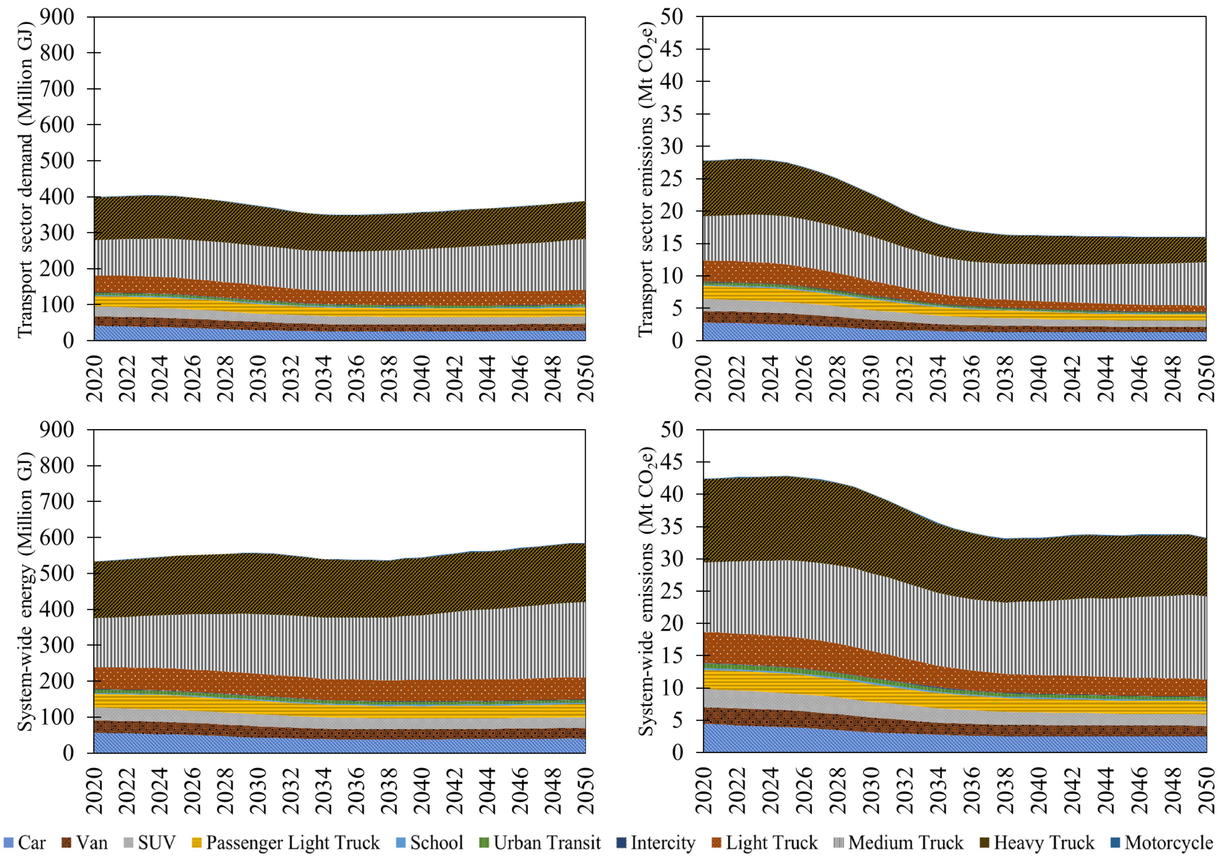

Figure 3.5: Energy demand (top left) and GHG emissions (top right) from the road transport sector, and system-wide energy (bottom-left) and system-wide emissions (bottom-right) from the transport sector for reference scenario in Alberta.

The passenger sector accounts for 67% of the total vehicles, but these vehicles are comparatively more fuel efficient and have significantly lower annual activity than the freight sector, leading to lower energy demand requirements as compared to the freight sector. A comparatively higher fuel consumption and vehicle activity is seen in the buses, but they account for only 0.7% of the total vehicles and do not have a significant impact on the energy demand and GHG emissions.

Figure 3.6 and Figure 3.7 show the total and incremental energy and GHG emissions in the different scenarios. The top left chart shows the energy demand from the road transport sector. In the carbon price scenarios, the change in energy demand from the baseline was found to be no more than 5.9% by 2050 when the carbon price increases from $0/t to $350/t. There is an 11% increase in the shares of ZEVs with the increase in carbon price, and this does not change demand significantly. However, emissions decrease by 22.5% as the carbon price increases from $0/t to $350/t, as shown in the top right chart. The ZEVs are more fuel efficient as compared to conventional and hybrid vehicles. Therefore, the adoption of ZEVs will lead to lower energy demand and subsequently lower GHG emissions. In the incentivized scenario, energy demand decreases by 3.3%; this corresponds to a 9% increase in ZEVs by 2050, which leads to a decline in emissions by 10.4%.

In the CP scenario, energy demand decreases by 11.3%, corresponding to a 110.5% increase in ZEV passenger vehicles and a 6.2% and 3.5% increase in ZEV buses and trucks. In this scenario, ZEV sales mandate is applied to passenger vehicles which requires that all new vehicles must be 100% ZEVs, effectively phasing out other fuel technology vehicles after 2035. Since passenger vehicle emissions are zero in 2050 due to 100% ZEVs, this further decreases the emissions by 38.1% by 2050.

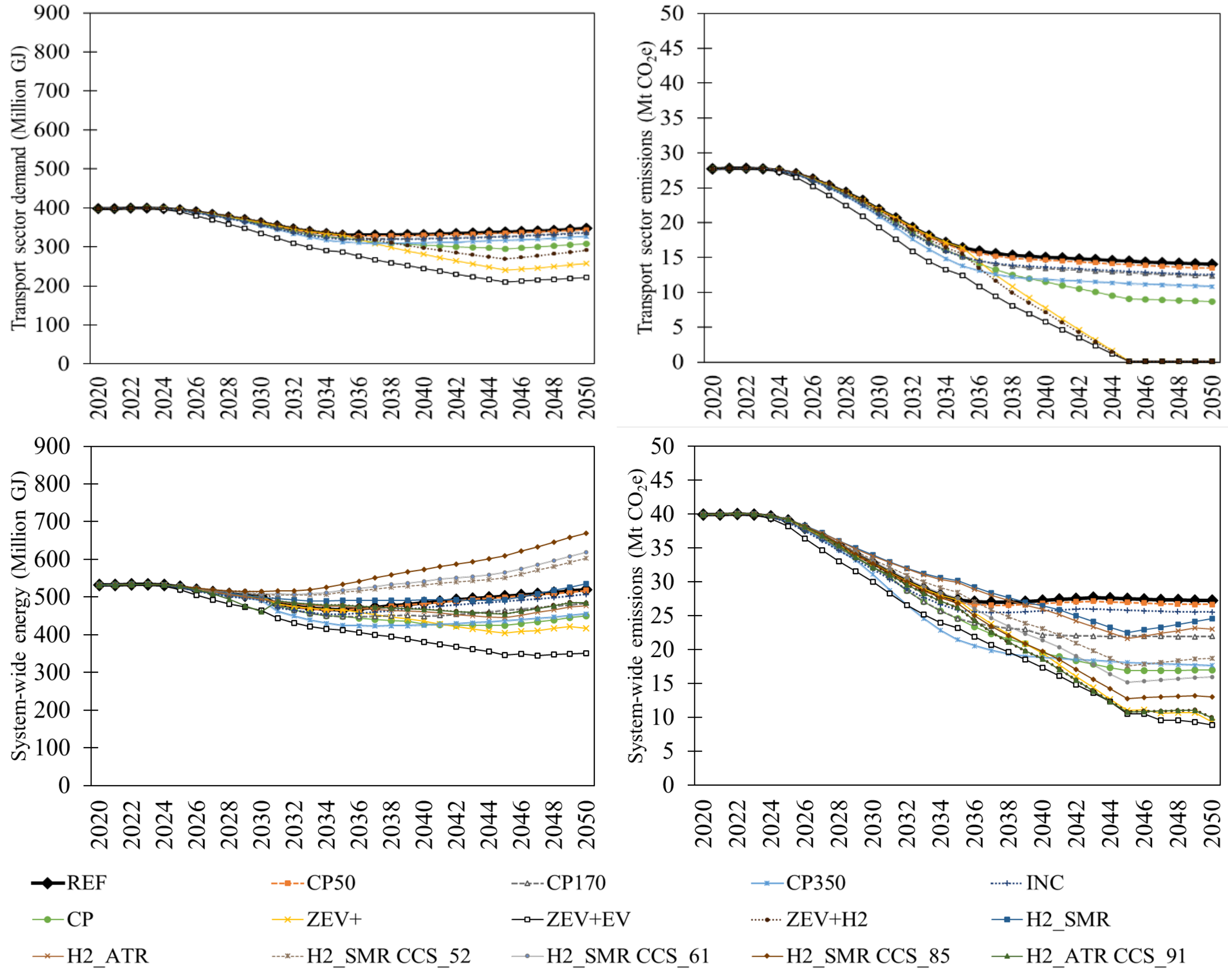

Figure 3.6: Energy demand (top left) and GHG emissions (top right) from the road transport sector, and system-wide energy (bottom-left) and system-wide emissions (bottom-right) from the road transport sector in Alberta.

In the ZEV policy scenarios, the greatest decline was found for ZEV+EV bias scenarios with a 36.1% decrease in demand followed by the ZEV+ scenario and ZEV+H_2 bias scenario with declines of 26% and 16.1%, respectively, by 2050. BEVs are found to have lower energy intensity than H_2-FCEVs and therefore, in ZEV policy scenarios, ZEV+EV bias scenario will have the lowest energy demand. The road transport sector emissions decrease by 99.3% and become insignificant by 2045 in these scenarios because of the 100% transition to ZEVs by 2050.

The bottom-left chart (in Figure 3.6 and Figure 3.7) shows the system-wide energy and the bottom-right chart (in Figure 3.6 and Figure 3.7) shows the system-wide emissions for the different scenarios. These are the energy and emissions associated with the upstream processes of resource extraction, fuel processing, storage, delivery, and refuelling along with the vehicle use energy and tailpipe emissions. The change in system-wide energy demand is greatest in the ZEV+EV bias scenario with a decrease of 32.5% from the baseline by 2050. In this scenario, fuel technology vehicles other than ZEVs have phased out by 2045 due to ZEV sales mandate policy in all sectors. Therefore, this leads to a significant decline in the system-wide energy requirements. In the carbon price scenarios, the change is no more than 12.5% from a carbon price of \$0/t to \$350/t. In the incentivization scenario, the decrease in system-wide energy demand is 2.5% by 2050. This is because in addition to in-use energy demand for vehicles, there is an increase in the natural gas energy for hydrogen and electricity production in these scenarios. Moreover, despite the adoption of ZEVs, a significant share of the road transport sector still comprises conventional and hybrid vehicles, accounting for 47% of the total vehicles by 2050. This limits the decline in overall system-wide energy demand in these scenarios, as these vehicles continue to rely on fossil fuels and have higher energy requirements. The current policy has a greater impact on the system-wide energy demand, which decreases by 13.4% by 2050. The ZEV sales mandate for passenger vehicles increases the number of ZEVs, consequently increasing the demand for natural gas in the hydrogen and electricity production. System-wide energy demand in the ZEV+ policy scenario and the ZEV+H_2 bias scenario declines by 19.8% and 6.9% by 2050. In this study, hydrogen is produced through SMR until 2030 and thereafter, through ATR until 2050. It is important to note that these processes are more energy-intensive compared to electricity production. Therefore, in ZEV+ and ZEV+H_2 scenarios, where H_2-FCEVs have a considerable market share, the system-wide energy demand tends to increase compared to ZEV+EV scenario due to the higher energy requirements associated with hydrogen production.

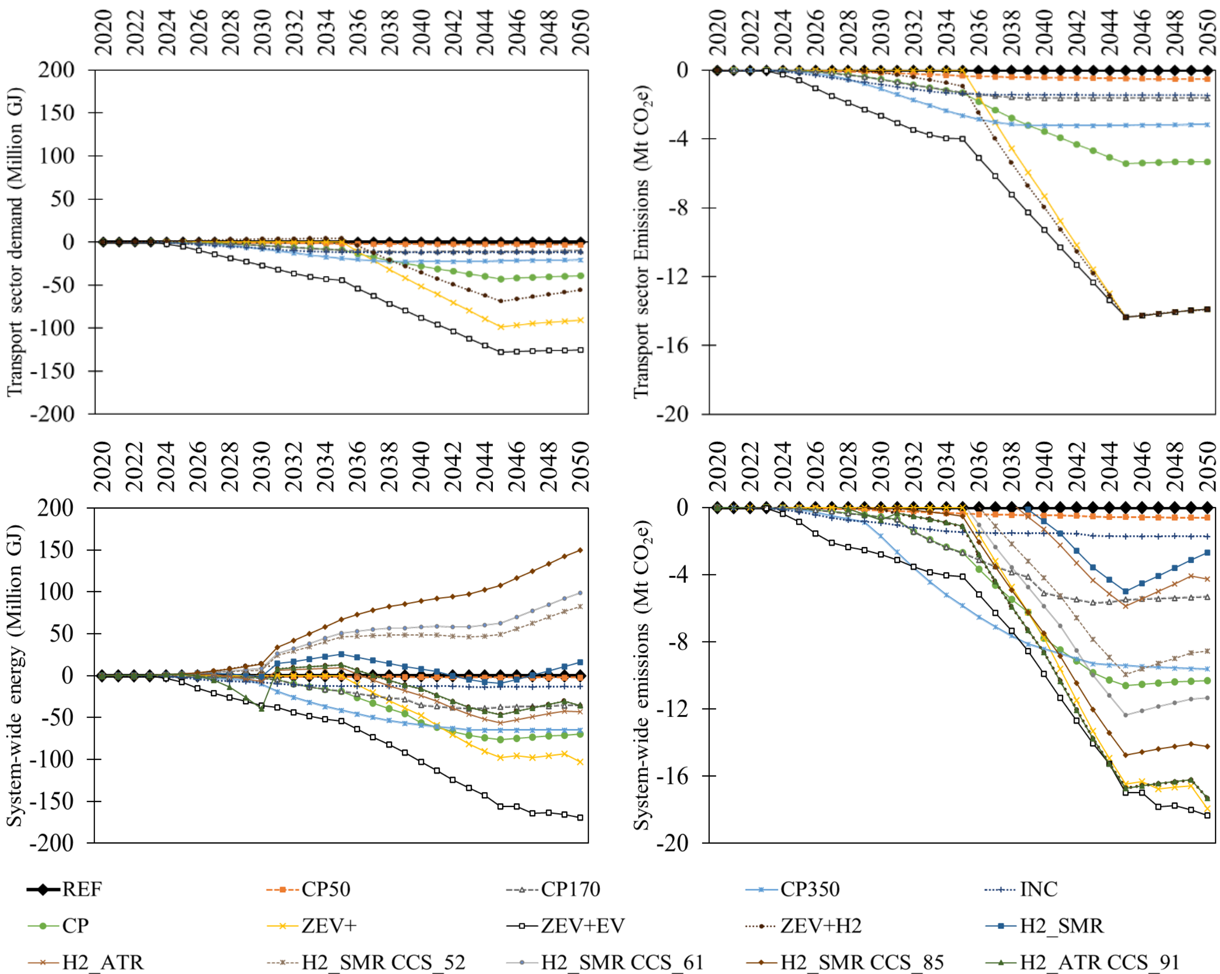

Figure 3.7: Incremental energy demand (top left) and incremental GHG emissions (top right) from the road transport sector, and incremental system-wide energy (bottom-left) and incremental system-wide emissions (bottom-right) from the road transport sector in Alberta.

In the hydrogen production pathway scenarios, system-wide energy demand decreases by 8.3% for ATR and increases by 3.0% for SMR-based hydrogen. In the carbon capture scenarios, energy decreases by 6.9% in ATR-CCS-91%. In the SMR-CCS-52%, SMR-CCS-61%, and SMR-CCS -

85% scenarios, system-wide energy demand increases by 15.9%, 19.0%, and 28.8% from the reference scenario because of high natural gas consumption.

The upstream emissions need to be accounted for to better assess changes in emissions. In the carbon price scenarios, emissions decline by 35.3% as the carbon price increases from $0/t to $350/t by 2050. The adoption of ZEVs declines the system-wide emissions because both hydrogen and electricity production have lower emission intensity compared to gasoline/diesel. Moreover, as the electricity grid transition towards renewable energy sources, it further declines the system-wide energy. In the incentivized scenario, system-wide emissions decrease by 6.3% as there is no significant change in the market share of ZEVs compared to the REF scenario. In the CP scenario, emissions decline by 37.7% because of the 100% transition of passenger vehicles to ZEVs by 2050. In the ZEV policy scenarios, the decrease is greatest in ZEV+EV followed by ZEV+ and ZEV+H_2 scenarios. This is because electricity production is not only less energy-intensive but also generates lower emissions compared to hydrogen production as it transitions to renewables by 2050. Emissions decrease by 67.3%, 65.8%, and 63.5%, respectively, by 2050 in these scenarios. In the hydrogen production pathway scenarios, emissions decrease by 9.8% and 15.6% for SMR and ATR, respectively. Carbon capture decreases emissions to a great extent in both hydrogen production technologies. Emissions decrease by 31.3%, 41.6%, and 52.2%, corresponding to 52%, 61%, and 85% CCS in SMR. The ATR with 91% CCS decreases emissions by 63.5% compared to the baseline.

3.7.1.2. Primary energy consumption by vehicle type

Figure 3.8 and Figure 3.9 show primary energy consumption for passenger cars and heavy freight trucks. These categories were chosen for a comparative assessment because they have the highest GHG emissions and energy demand.

Figure 3.8 shows primary energy consumption for passenger cars in Alberta in 2030, 2040, and 2050. It provides the input energy required by the fuel to drive a unit of km. It includes energy from the upstream processes including resource extraction, conversion to fuel, and delivery/transmission/distribution of the fuels. Values are given for the CP0, CP50, CP170, and CP350 carbon pricing assumptions.

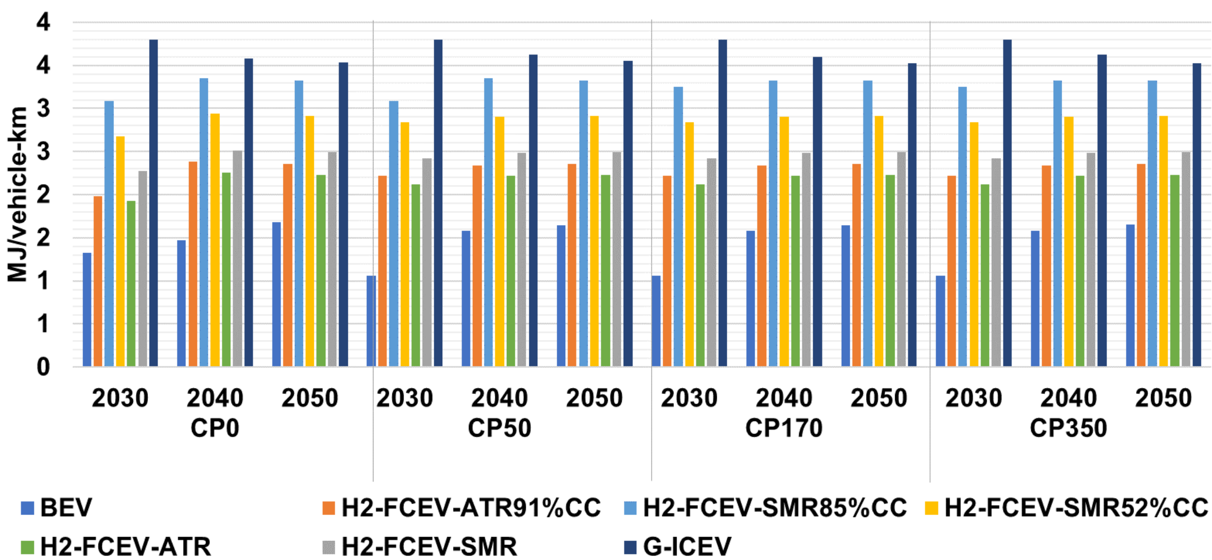

Figure 3.8: Primary energy consumption for passenger cars in Alberta.

For BEV, energy consumption changes drastically year-to-year because of the transition of the Alberta electricity grid from a fossil fuel-based system to a renewable-based system. BEV energy consumption is the lowest of all the fuel technologies (1.3 MJ/veh-km) in 2030 and increases to 1.7 MJ/veh-km in 2050.

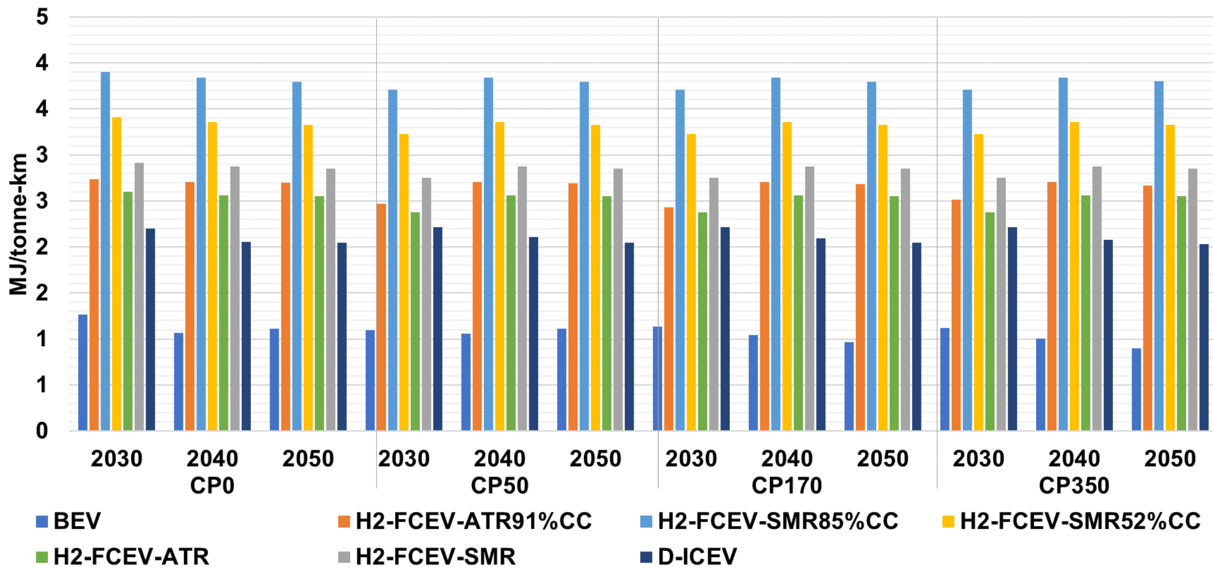

Figure 3.9: Primary energy consumption for heavy-duty freight trucks (class 8) in Alberta.

For H_2-FCEVs, energy consumption is calculated based on different hydrogen production pathways. SMR and ATR have been evaluated without and with carbon capture. H_2-FCEV (SMR) energy consumption was found to be 2.3 MJ/veh-km and 2.5 MJ/veh-km in 2030 and 2050, respectively. Energy consumption increases with the amount of carbon capture due to increased natural gas consumption; H_2-FCEV (SMR 85%CCS) energy consumption was found to be 3.1 MJ/veh-km. Overall, energy consumption in all hydrogen production pathways is lower than ICEV energy consumption at all carbon prices.

Figure 3.9 shows the primary energy consumption for heavy freight trucks (class 8) in Alberta for 2030,2040, and 2050. For BEVs, energy consumption changes drastically in the freight sector as well. Energy consumption in BEVs was found to be 1.3 MJ/tonne-km and 1.1 MJ/veh-km in 2030 and 2050, respectively. H_2-FCEVs (SMR) consume more energy than the ICEVs and the BEVs, 2.9 MJ/tonne-km and 2.8 MJ/tonne-km in 2030 and 2050, respectively. Energy consumption increases with an increase in the amount of carbon capture. Energy consumption in all hydrogen production pathways was found to be higher than for the ICEV at all carbon prices.

3.7.1.3. GHG emission footprints by vehicle type

Figure 3.10 provides the system-wide GHG emission factors for passenger cars in Alberta between 2030 and 2050. These emission factors include the emissions from the full energy chain including resource extraction, resource conversion to fuel, and fuel use in the vehicle. They do not include emissions during vehicle manufacturing or scrappage/recycling. Values are given for the CP0, CP50, CP170, and CP350 carbon pricing assumptions.

For BEVs, the emission factor changes the most drastically year-to-year and across the carbon price assumptions. This is a result of the Alberta electricity grid transitioning from a predominantly fossil fuel-based to a highly renewable-based system if the carbon price is sufficient. For CP0, there are no significant reductions in the electricity grid emissions intensity past 2030 and so the BEV emission factor only reduces slightly. For CP50, the electricity grid emission factor undergoes a steady decline, resulting in the BEV emission factor becoming the lowest value of all vehicle types in 2040 and continuing to decline by 2050. For CP170 and CP350, the BEV emission factor is the lowest among the vehicle types (less than 1.8 g-CO_2e/veh-km) by 2030 and beyond. The emission factors for BEVs and H_2-FCEVs (SMR) were found to be 44.6 g-CO_2e/veh-km and 101.7 g-CO_2e/veh-km, respectively, in 2030. He et al. [36] provide a comparable value of 104.6 g-CO_2e/km for a H_2-FCEV. The relatively higher value of 112 gCO_2e/km was reported when electricity was sourced 49% from coal.

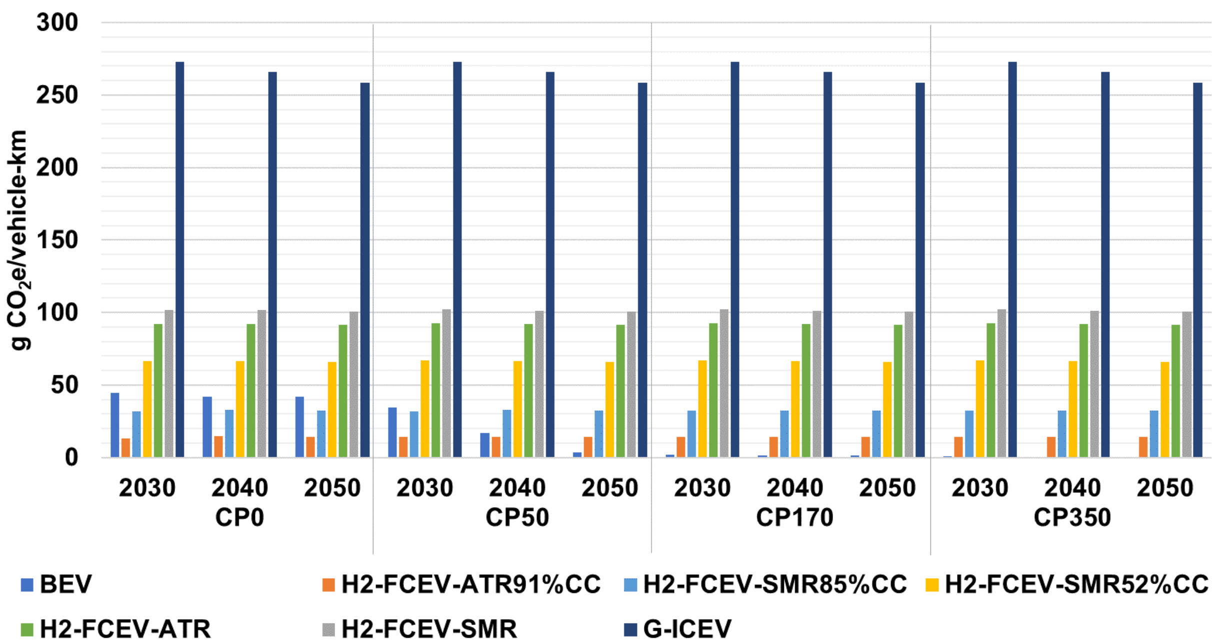

Figure 3.10: Alberta system-wide GHG emission factors for passenger cars in Alberta.

For H_2-FCEVs, the emission factors were calculated based on different hydrogen production pathways. SMR and ATR without and with carbon capture were evaluated as they were found to be the most economical for substantial scale-up in Alberta in the near to medium term. ATR with 91% carbon capture has the lowest emission factor of all vehicles with CP0 assumptions. For CP50, ATR with 91% has the lowest emission factor until it is surpassed by the BEV in the mid-2040s.

All cases with hydrogen have much more favourable emission factors than conventional gasoline and diesel vehicles. Figure 3.11 shows the system-wide GHG emission factors for heavy freight trucks (class 8) in Alberta between 2030 and 2050. The emission factors for BEVs and H_2-FCEVs (SMR) were found to be 53.3 g-CO_2e/tonne-km and 119.4 g-CO_2e/tonne-km, respectively, in 2030.

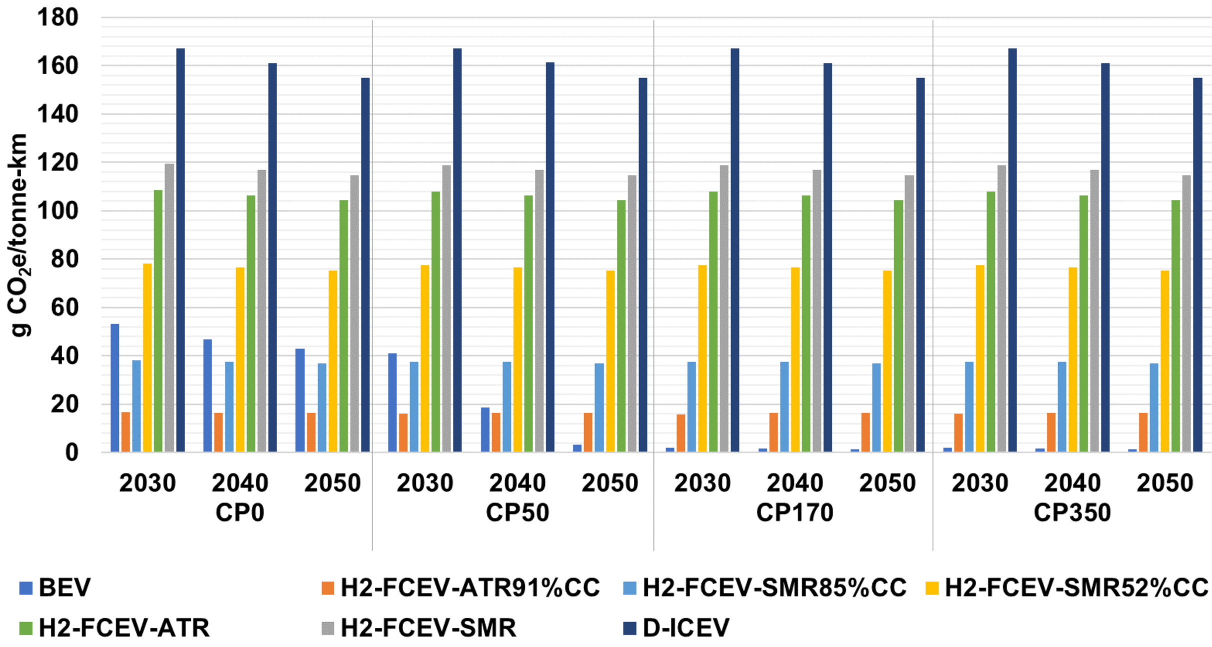

Figure 3.11: Alberta system-wide GHG emission factors for heavy-duty freight trucks (class 8) in Alberta.

The values are comparable to values found in the literature. Sacchi et al. [130] reported values of 70 g-CO_2e/km for BEVs and 110 g-CO_2e/km for H_2-FCEVs in the European electricity mix. For 2050, the emission factors were found to be 43.1 g-CO_2e/tonne-km and 114.8 g-CO_2e/tonne-km for BEVs and H_2-FCEVs, respectively. Sacchi et al. [130] reported comparable values of 40 g-CO_2e/km and 60 g-CO_2e/km for BEVs and H_2-FCEVs, respectively.

3.7.2. Social costs

Figure 3.12 shows the incremental social cost for the transportation sector in different scenarios compared to the reference scenario. For the baseline scenario, the social cost is found to be $88 billion in 2020 and to increase to $119 billion in 2050. This increase can be attributed to several factors. Based on our study, it has been determined that the TCO for both H_2-FCEVs and BEVs will be higher than conventional vehicles in several categories of the road transport. The adoption of these vehicles will increase the social costs of the transport sector. Additionally, the fuel production cost of hydrogen and electricity further contributes to the overall social cost. For the carbon price scenarios, the cost increases by 11% if the carbon price increases to $350 per tonne in 2050. As the carbon price increases, it increases the costs associated with the conventional fuel production due to their energy-intensive processes that incur higher costs with increased carbon pricing. Moreover, increased carbon price leads to an increase in the carbon costs associated with tailpipe emissions. In the CP scenario, the cost increases by 0.5% in 2050, whereas in the INC scenario, the cost decreases by 0.4% by 2050. For passenger vehicles, the TCO of BEVs becomes comparable to that of ICEVs but remains higher for H_2-FCEVs by 2050. As a result, increased number of H_2-FCEVs in the CP scenario leads to a slight increase in the social costs, attributable to an increase in demand cost due to higher TCO of H_2-FCEVs and higher upstream costs. In the INC scenario, the growth in the number of BEVs is more than H_2-FCEVs. Lower TCO of these vehicles declines the social costs in this scenario. In the ZEV+ scenarios, the cost decreases by 0.7% in the ZEV+H_2 scenario followed by 1.9% in the ZEV+ scenario and 3.1% in the ZEV+EV scenario in 2050. In these scenarios, all fuel technology vehicles other than ZEVs have phased out by 2045. The TCO of BEVs becomes lower than that of ICEVs for almost all categories of road transport while the TCO of H_2-FCEVs becomes comparable to that of ICEVs by 2050. This leads to decline in demand costs in these scenarios, and further reduces upstream costs through the exclusive production of hydrogen and electricity.

Figure 3.13 shows the different costs that comprise the total social cost for different scenarios in 2050. For CP0, the demand cost was found to be $103 billion, and the transformation and resources cost was found to be $17 billion in 2050.

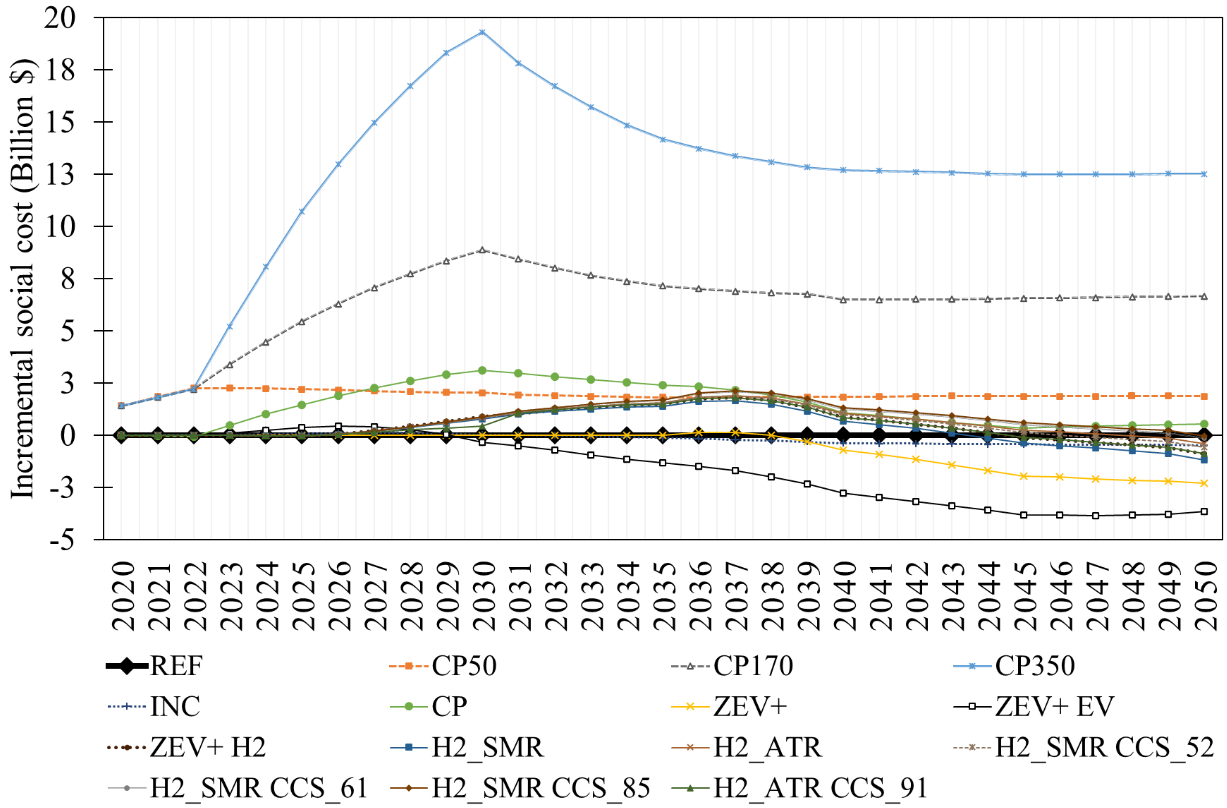

Figure 3.12: Road transport sector incremental social costs in Alberta compared to reference scenario.

The transformation and resource components of the cost comprise natural gas production and delivery (1.4%), gasoline and diesel production and delivery (4.3%), electricity generation (0.9%), transmission and distribution (1.4%), recharging (1.3%), hydrogen production (0.6%), storage (2.5%), delivery by pipelines (0.1%), and the hydrogen refuelling station (1.6%). Demand comprises 87% of the social cost and encompasses the capital and maintenance costs of the vehicles. All the cost components increase with the carbon price. The ZEV+EV scenario costs are the lowest; the demand cost is $102 billion, and the transformation and resources costs are $13 billion in 2050.

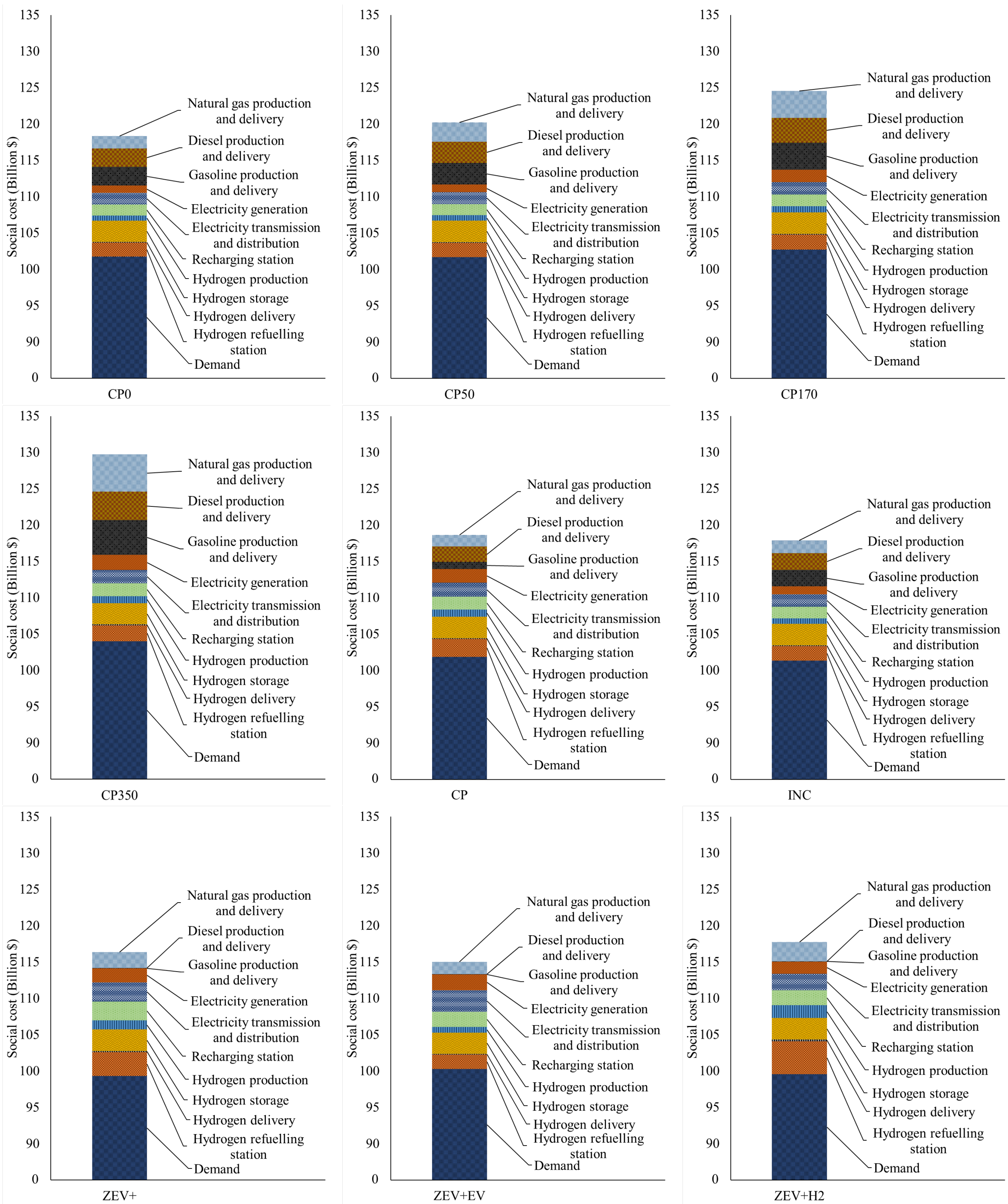

Figure 3.13: Incremental social cost components for different scenarios in 2050 compared to reference scenario.

3.7.2.1. GHG abatement cost curve

Figure 3.14 provides the cost curve comparison for the different scenarios described in Table 3.1. The ZEV sales mandate scenarios had lower mitigation costs whereas the carbon prices had the highest mitigation costs.

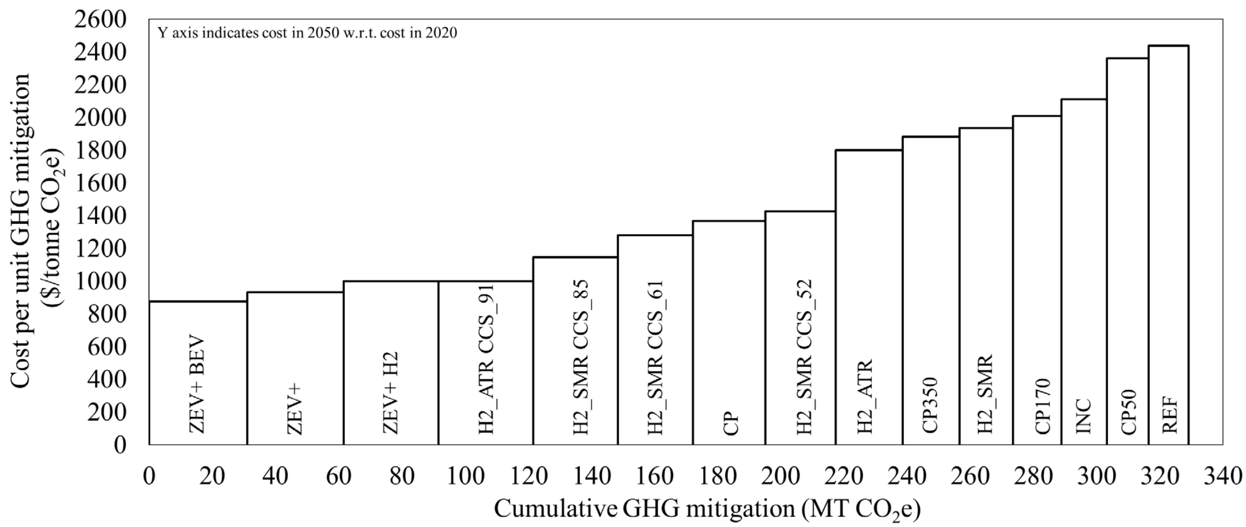

Figure 3.14: Cost curve for different scenarios.

The ZEV+EV could mitigate 31 Mt CO_2e between 2020 and 2050 and the mitigation cost was found to be \$877/tonne-CO_2e. The mitigation costs of ZEV+ and ZEV+H_2 were found to be higher (\$933/tonne-CO_2e and \$999/tonne-CO_2e) and could mitigate 31 Mt CO_2e and 30 Mt CO_2e, respectively. Hydrogen production pathway scenarios with higher carbon capture (ATR-CCS-91%, SMR-CCS-85% and SMR-CCS-61%) had higher mitigation costs (14%, 31% and 46%) than ZEV+EV scenario that could mitigate 30 Mt CO_2e, 27 Mt CO_2e and 24 Mt CO_2e for ATR-CCS-91%, SMR-CCS-85% and SMR-CCS-61% scenarios between 2020 and 2050. The CP scenario was found to mitigate 23 Mt CO_2e at the cost of \$1367/tonne-CO_2e over the study period. Hydrogen production by SMR-CCS-52% was found to mitigate similar amount of emissions (22

Mt CO_2e) at a higher mitigation cost ($1427/tonne-$CO_2$e) than the CP scenario. Hydrogen production by SMR and ATR could mitigate 15 Mt CO_2e and 17 Mt CO_2e between 2020 and 2050. The mitigation costs of these GHG emission reductions were $1935/tonne-$CO_2$e and $1800/tonne-$CO_2$e respectively. The INC scenario has an even higher mitigation cost of $2111/tonne-$CO_2$e for GHG emission reduction of 14 Mt CO_2e. The carbon price scenarios had the highest mitigation costs with the maximum cost for the REF scenario ($2438 /tonne-$CO_2$e) that could mitigate 13 Mt CO_2e over the study period.

4. Conclusions and Recommendations for Future Work

The present study discussed the current energy and GHG emissions from the road transportation sector and assessed the prospects of the sector adopting low-carbon fuel technology vehicles. A novel framework to investigate energy transition in the sector in a fossil fuel-dependent jurisdiction was developed and applied to a case study for Alberta, Canada. The impacts on energy demand and GHG emissions were calculated for nine scenarios with different carbon policies, zero-emission vehicle incentives, and zero-emission vehicle sales mandates. This study analyzed the system-wide energy and GHG impacts associated with each fuel's energy supply chain.

The potential for market shares was the highest for BEVs; H_2-FCEV had fewer shares than BEVs over the study period. Carbon price and incentivization as stand-alone policies were not as effective as zero-emission vehicle sales mandates in decreasing GHG emissions. System-wide GHG emission footprints for all hydrogen and electric vehicles were significantly lower than for gasoline and diesel vehicles. The study is important for policymakers so that they can ensure the stringency required to meet GHG emission standards as well as in the production of alternative low-carbon fuels. It also provides information to energy-producing and vehicle manufacturing industries on the prospects of low-carbon technology vehicles.

The sections below give the key conclusions for market shares of zero-emission vehicles and overall energy transition in the transport sector.

4.1. Market penetration of zero-emission vehicles

The market shares of zero-emission and other fuel technology vehicles in the transport sector were developed for the study period using a market share model. The present research estimated the shares of various fuel technologies in the passenger, bus, and freight sectors for nine scenarios (listed in Table 3.11). The major conclusions are enumerated below:

- The TCO of H_2-FCEVs was much higher than that of BEVs. This difference was mostly influenced by the higher costs associated with the infrastructure, refuelling, and delivery of hydrogen. These costs decline as H_2-FCEVs become established but remain higher than BEVs for the study period.
- The market shares of BEVs were found to be highest in 2050. H_2-FCEV shares were found to be lower than BEVs' for the study period. Figure 4.1 shows the market shares of the road transportation sector for the REF, INC, CP, and ZEV+ scenarios. The relative cost of BEVs is lower than that of H_2-FCEVs, which increases the BEV share. The shares for H_2-FCEVs were found to increase after 2040 as their capital costs decline.
- The adoption of ZEVs was found to be more prominent in the freight sector than the others. According to the literature (discussed in Section 2.2.2), the capital costs of these vehicles will become comparable to those of ICEVs. In addition, the higher fuel costs of ICEV freight trucks will increase the TCO of these vehicles, thereby decreasing their share.
- The carbon price, independently, did not have a significant impact on the TCO of zero-emission vehicles and therefore on their market share. The effect was more prominent on the TCO of the ICEVs than other fuel technology vehicles at higher carbon prices.
- The impact of incentivization as an independent policy in a scenario did not have a significant impact on the TCO of ZEVs, or their market share. The effect of incentivization was analyzed at two values (10% and 30%) and while the increase in incentives slightly increases the shares of ZEVs, the impact is low because the average increase in the TCO due to decreased annualized capital cost is low.

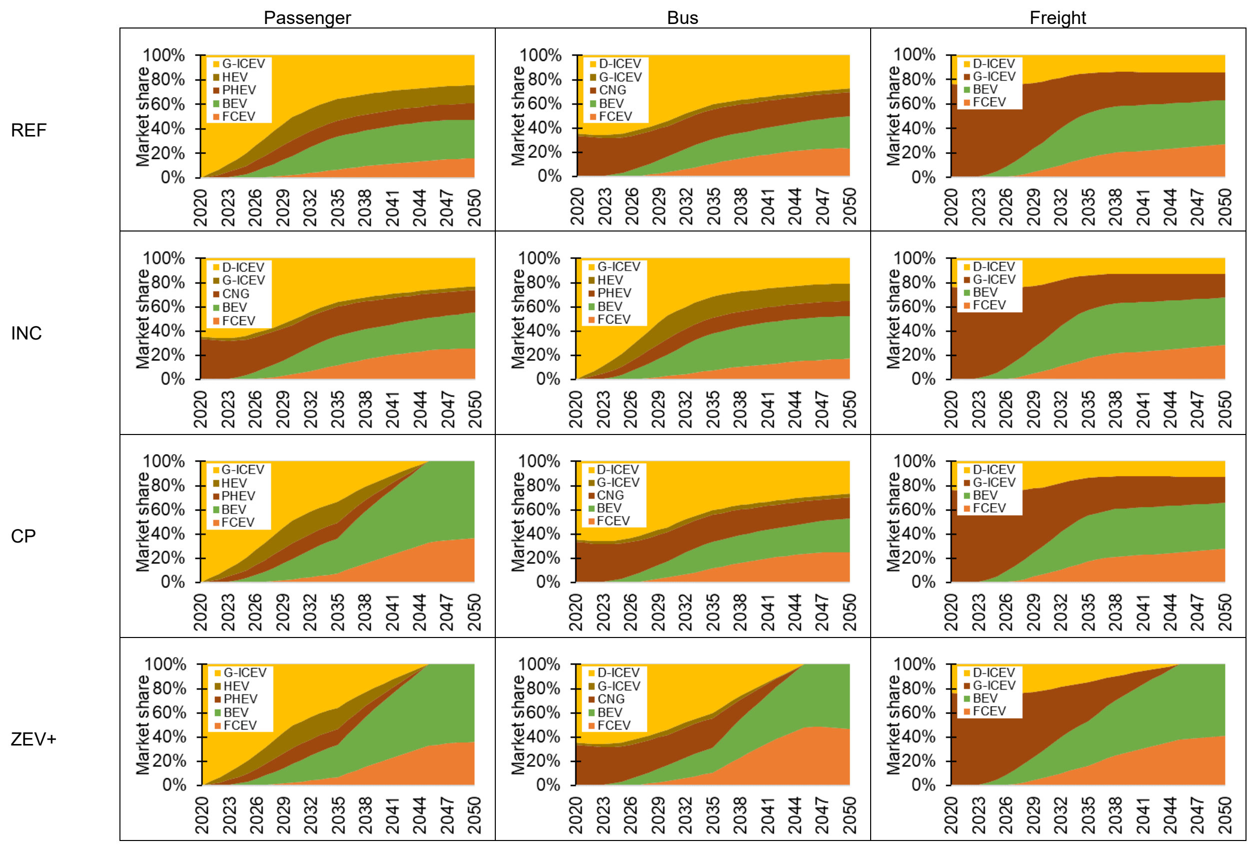

Figure 4.1: Market shares in REF, INC, CP, and ZEV+ scenarios for the passenger, bus, and freight categories up to 2050.

- The ZEV sales mandate was found to be the most effective way of transitioning the road transportation sector to ZEVs. The impact of the mandate in two scenarios was analyzed and found ZEV shares increased by 67% in the CP scenario from the REF scenario. ZEV shares increased another 13% in the ZEV+ scenario from the CP scenario.

4.2. Transportation sector energy transition

This research analyzed the impact of the adoption of ZEVs on the energy demand and GHG emissions from the road transportation sector in Alberta. The system-wide energy requirements and GHG emissions were modelled in LEAP through scenarios that investigated the impact of policies like carbon price, zero-emission vehicle sales mandates, and incentivization on the adoption of ZEVs in the sector and subsequently system-wide energy demand, GHG emission footprints, and social costs. The following major conclusions are drawn:

- Carbon price and incentivization as stand-alone policies are not as effective as zero-emission vehicle sales mandates in decreasing energy demand and GHG emissions. Figure 4.2 shows system-wide energy demand and GHG emissions for different scenarios. Four carbon price scenarios were investigated; the maximum decline in GHG emissions (in the CP350 scenario) is 35% below the REF scenario. The impact of the incentivization scenario is lower than the carbon price scenario and decreased GHG emissions by 6%. The impact of the ZEV sales mandate was analyzed in four scenarios in which the combined effects of the policy with the carbon price and incentivization were assessed. In the CP scenario, the GHG emissions declined by 38%; this is because the ZEV sales mandate was considered for all passenger vehicles and the carbon price of $170 per tonne declined the share of ICEVs as the TCO of these vehicles increased. The ZEV sales mandate was extended to all sectors without a carbon price policy, and GHG emissions declined by 66% in the ZEV+ scenario. The combined effect of the ZEV+ scenario along with 30% incentivization for H_2-FCEVs and another with 30% incentivization for BEVs was analyzed in two different scenarios. It was found that while it impacts vehicle costs and market share, it does not significantly impact the GHG emissions from the sector. The GHG emissions from the ZEV+ H_2-FCEV and ZEV+EV scenarios were 64% and 67% lower than the reference scenario.
- Different hydrogen production technologies were found to impact system-wide energy demand and GHG emissions. GHG emissions decline by 6% when hydrogen is produced

through ATR instead of SMR. Carbon capture has a more significant impact; the maximum decline is 64% from the REF scenario when hydrogen is produced through ATR with 91% carbon capture.

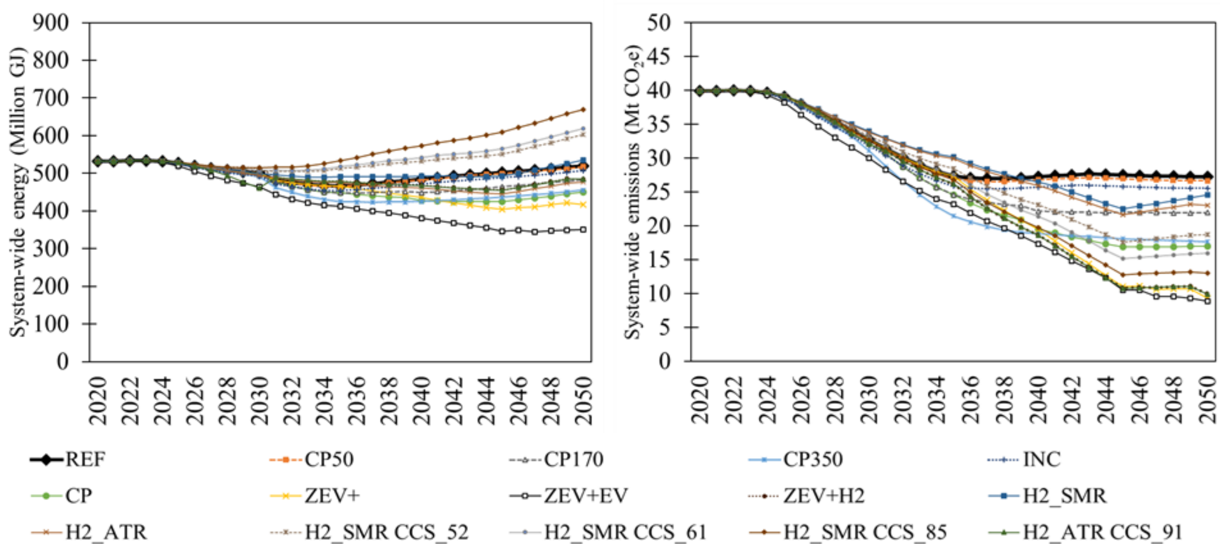

Figure 4.2: System-wide energy and system-wide emissions from the road transport sector in Alberta.

- System-wide energy and GHG emission footprints of H_2-FCEVs and BEVs are significantly lower than ICEVs. The study analyzed the system-wide energy and GHG emissions per km for passenger cars and heavy freight trucks, as shown in Figure 4.3 and Figure 4.4. For H_2-FCEVs, hydrogen production from SMR and ATR was investigated along with the combined impacts of the technologies with carbon capture. The GHG emission factors of H_2-FCEVs when hydrogen is produced through ATR with 91% carbon capture are lowest at lower carbon prices. At higher carbon prices, the emission factors of BEVs are lowest.

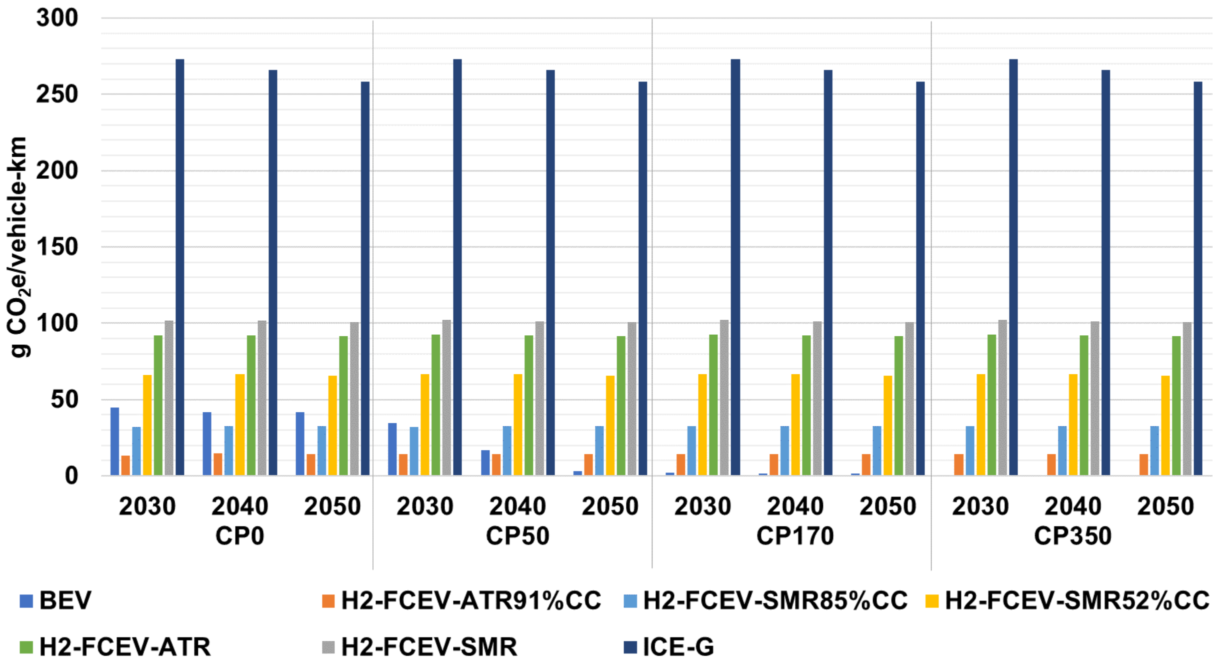

Figure 4.3: Alberta system-wide GHG emission factors for passenger cars in Alberta.

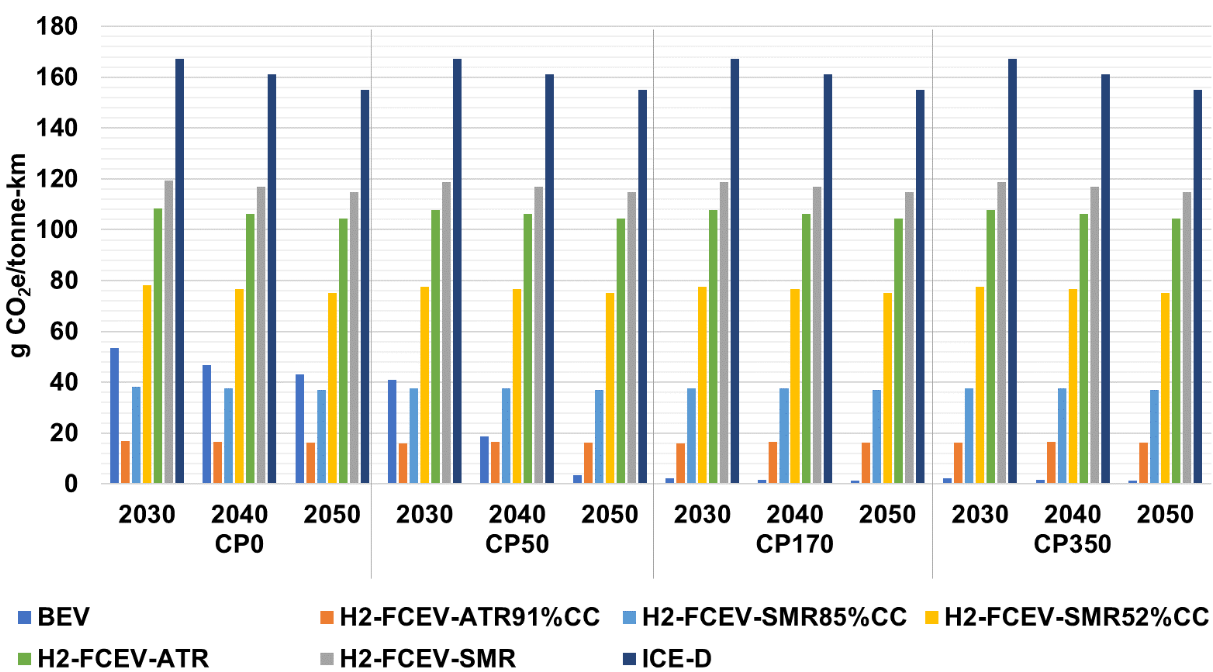

Figure 4.4: Alberta system-wide GHG emission factors for heavy-duty freight trucks (class 8) in Alberta.

- The social costs for the road transportation sector were analyzed for all the scenarios. The carbon price scenarios were found to have the most significant impact of all the scenarios, and the CP350 scenario increased the social costs from the sector by 11% from the REF scenario.
- GHG abatement cost curves were developed for all the scenarios as shown in Figure 4.5. The ZEV sales mandate scenarios have lower marginal abatement costs, and carbon price scenarios have the highest marginal abatement costs. The ZEV+EV scenario could mitigate 31 Mt CO_2e between 2020 and 2050 at a marginal abatement cost of $877/tonne-$CO_2e$. The ZEV+ scenario has a slightly higher marginal abatement cost compared to the ZEV+EV scenario ($933 tonne-$CO_2e$) and could mitigate 31 Mt CO_2e between 2020 and 2050. The ZEV+H_2 and hydrogen production pathway scenarios with higher carbon capture (ATR-CCS-91%, SMR-CCS-85%, and SMR-CCS-61%) have higher mitigation costs (14%-46%) than the ZEV+EV scenario. The CP scenario was found to mitigate 23 Mt CO_2e at a marginal abatement cost of $1261/tonne-$CO_2e$ over the study period. Hydrogen production by SMR and ATR could mitigate 15 Mt CO_2e and 17 Mt CO_2e between 2020 and 2050. The marginal abatement costs of these GHG emission reductions are $1935/tonne-$CO_2e$ and $1800/tonne-$CO_2e$, respectively. The INC scenario has a comparatively higher marginal abatement cost of $2111/tonne-$CO_2e$ for a GHG emission reduction of 14 Mt CO_2e. The carbon price scenarios have the highest marginal abatement costs; the highest is in the REF scenario ($2438/tonne-$CO_2e$) with 13 Mt CO_2e mitigated over the study period.

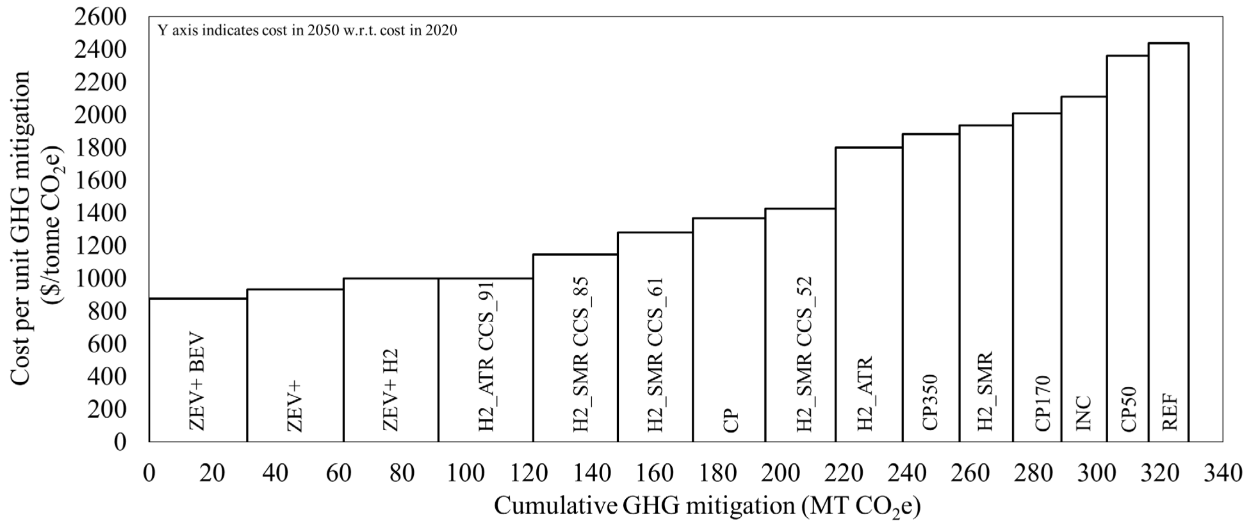

Figure 4.5: Cost curve for different scenarios.

4.3. Recommendations for future work

Based on the results of the present study, and considering the present study as a baseline work for the transportation sector in Canada, the following avenues for future study are recommended:

- The present study investigated the impact of hydrogen and electric vehicles in the road transportation sector. This investigation needs to be extended to other modes of transportation to include the rail, air, and marine sectors. Further study may enhance our understanding of the GHG emissions and the GHG mitigation potential of the entire transportation sector.
- Along with the total cost of operation, the intangible factors that impact the adoption of zero-emission vehicles can be assessed. It would be interesting to see the impact of these factors on the market share of zero-emission vehicles.

- Further investigation is needed to determine the strategies needed for net-zero emissions from the transportation system. This involves transitioning the sectors to zero-emission vehicles and decarbonization of the upstream processes.

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