WELL-TO-WHEEL GREENHOUSE GAS EMISSIONS AND ENERGY USE ANALYSIS OF HYPOTHETICAL FLEET OF ELECTRIFIED VEHICLES IN CANADA AND THE U.S.

by

Miguelangel Maduro

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Dr. Peter Berg
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____

Dr. Greg Rohrauer

Research Supervisor

____

Dr. Mikael Eklund

Supervisory Committee Member

As research supervisor for the above student, I certify that I have read and approved changes required by the final examiners and recommend the thesis for acceptance:

____

Dr. Greg Rohrauer
Research Supervisor

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Abstract

The shift to strong hybrid and electrified vehicle architectures engenders controversy and brings about many unanswered questions. It is unclear whether developed markets will have the infrastructure in place to support and successfully implement them.

To date, limited effort has been made to comprehend if the energy and transportation solutions that work well for one city or geographic region may extend broadly. A region's capacity to supply a fleet of EVs, or plug-in hybrid vehicles with the required charging infrastructure, does not necessarily make such vehicle architectures an optimal solution. In this study, a mix of technologies ranging from HEV to PHEV and EREV through to Battery Electric Vehicles were analyzed and set in three Canadian Provinces and 3 U.S. Regions for the year 2020.

Government agency developed environmental software tools were used to estimate greenhouse gas emissions and energy use. Projected vehicle technology shares were employed to estimate regional environmental implications. Alternative vehicle technologies and fuels are recommended for each region based on local power generation schemes.

Keywords: Well to wheel, greenhouse gas, electric vehicle, hybrid, PHEV, fuel cell, energy use.

Dedication

This thesis is dedicated to my parents and my wife. Without their unconditional love and support I would not have been able to fulfill this dream. Everything in my wonderful life I owe to you.

I also want to dedicate this thesis to my dear brother, whom I love and miss every day of my life. Your kind-hearted soul will forever be remembered.

Acknowledgements

First and foremost, my utmost gratitude to my advisor Dr. Greg Rohrauer for giving me the opportunity to work on his research team and on the EcoCAR project. His encouragement, guidance, and support from the very beginning of my masters enabled me to develop a deep understanding and passion for hybrid and electric vehicles.

Financial support of this research through the EcoCAR engineering GRA is gratefully acknowledged.

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List of Abbreviations

A	Ampere
AC	Alternating Current
AER	All-electric Range
Ah	Amp-hour
Al	Aluminum
ANL	Argonne National Laboratory
API	American Petroleum Institute
BEV	Battery Electric Vehicle
CAC	Criteria Air Contaminants
CARB	California Air Resources Board
CD	Charge depleting
CNG	Compressed Natural Gas
Co	Cobalt
CS	Charge sustaining
DC	Direct Current
DOD	Depth-of-Discharge
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
EREV	Extended Range Electric Vehicle
ESS	Energy Storage System
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
FFEV	Full Function Electric Vehicle
GEMIS	Global Emissions Model for Integrated Systems
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
HEV	Hybrid Electric Vehicles
HHV	High Heating Value
HIL	Hardware-in-the-loop
HSD	Hybrid Synergy Drive
HWFET	Highway Fuel Economy Test
ICE	Internal Combustion Engine
IEC	International Electrochemical Commission
IMA	Integrated Motor Assist
IPCC	International Panel on Climate Change
LCA	Life Cycle Assessment

LEM	Life Cycle Emissions Model
LHV	Low Heating Value
Li-ion	Lithium-ion battery
LPG	Liquefied Petroleum Gas
Mn	Manganese
MPGge	Miles-per-gallon Gasoline Equivalent
NEB	National Energy Board
NEV	Neighborhood Electric Vehicles
NHTS	National Household Travel Survey
Ni	Nickel
NiCd	Nickel Cadmium battery
NiMH	Nickel Metal Hydride battery
NRCAN	Natural Resources Canada
PbA	Lead Acid battery
PHEV	Plug-in Hybrid Electric Vehicle
PSAT	Powertran System Analysis Toolkit
PTW	Pump-to-Wheel
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SMR	Steam Methane Reforming
SOC	State-of-Charge
SUV	Sport-utility Vehicle
UDDS	Urban Dynamometer Driving Schedule
UF	Utility Factor
US DOE	United States Department of Energy
V	Volt
VKT	Vehicle Kilometres Traveled
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compounds
W	Watt
Wh	Watt-hour
WTP	Well-to-Pump
WTW	Well-to-Wheel

Chapter 1

Introduction

The automotive industry has never before been exposed to a market as restrictive and demanding as the one encountered in the first decade of the 21st century. Political measures driven by theories of climate change have forced industry scientists and engineers to come up with an array of sustainable and economically sound options that will meet the challenge of driving sales and profit growth while lowering greenhouse gas emissions.

Energy security is equally of concern for developed countries, given there is no readily available substitute for an oil based transportation industry. Terminal decline of global oil production is expected to occur over the next years as described by the Hubbert Peak Theory. At the same time China and India's vehicle fleet may triple by 2050 if it continues to grow at the current rate. [1] This growth will bring with it a drastic increase in oil demand creating a much more aggressive and sensitive global energy market. In order to mitigate the risk of a world energy crisis, it is vital that first world nations invest heavily in the development and introduction of alternative vehicle technologies that will lessen their dependence on petroleum based fuels. Diversifying the types of fuels used for transportation, beginning with public transit, household vehicles, and commercial trucks should be a top priority in every politician's agenda.

The past decade saw the hybridization of the traditional internal combustion engine vehicle. According to the Green Car Congress website, hybrid sales account for little more than 2.8% of total passenger vehicle sales (Year 2009) [2]. Growing this segment under the current financial scenario presents a challenge and will likely not be met until the price of hybrid vehicles drop. The average consumer will hesitate to enter an unfamiliar segment unless it makes financial sense.

Industry researchers are striving to develop state-of-the-art hybrid technologies and onboard energy storage systems that are capable of propelling electric vehicles with a similar range as a conventional car, while improving efficiency and minimizing greenhouse gas emissions. Industry and the general public continue to wait and see which automotive company will offer a truly revolutionary technology for the 21st century.

Goal of Thesis

In this thesis, the environmental implication of operating ten different electrified vehicle powertrain architectures is evaluated in three Canadian Provinces, and three U.S. regions. Furthermore, a recommended mix of vehicle technologies is provided based on the lowest energy use and greenhouse gas emissions for each individual geographical region.

Previous Research

Past studies such as Jenkins (2006), Elgowainy (2010), and Holdway (2010) have explored alternative transportation fuels and vehicle systems, as well as their energy use and greenhouse gas emissions implications in the U.S., France and United Kingdom. These studies found that there are distinct implications in operating certain types of vehicle technologies depending on the region where they are used and the time of the day while they are charged.

The July 2010 issue of Scientific American featured an article titled “The Dirty Truth about Plug-in Hybrids” [Moyer, Michael] in which the authors attempted to demonstrate the difference in carbon emissions when charging a plug-in hybrid vehicle in one of 13 regions of the U.S. However, this study failed to take into account all forms of electricity generation; and of special importance hydroelectric plants which account for 10% of the national electricity generation according to the U.S. Department of Energy. Although it served to establish the basic premise that vehicles that depend heavily on grid-electricity are better suited to operate in regions with lower carbon-intensive forms of electric generation, further research is necessary to obtain more accurate results.

None of the studies previously mentioned included an analysis for Canada, nor did the authors recommend a mix of technologies that results in lower emissions and energy use for the geographical regions studied.

Approach

In this study, a mix of technologies ranging from HEV to PHEV and EREV through to Full Function Electric Vehicles were analyzed and set in three Canadian Provinces and three U.S. Regions in the year 2020. Software tools GHGenius and GREET were used to estimate corresponding greenhouse gas emissions and energy use. The Powertrain System Analysis Toolkit (PSAT) from Argonne National Laboratory was employed to estimate the electric energy use of each architecture. A well-to-wheel (WTW) analysis was done to understand the implications of introducing each alternative vehicle propulsion technology to each individual region. The projected vehicle technology market shares were considered in order to understand the potential environmental repercussions.

Recommendations for each region are then given based on local electricity generation schemes and which technologies generate the least amount of WTW greenhouse gas emissions.

Summary of Thesis Sections

In Chapter 2, the most common hybrid and electric vehicle technologies are explained along with their power flow control. Chapter 3 presents the onboard energy storage systems most frequently employed in current hybrid and electric vehicle design. Chapter 4 introduces the life cycle assessment (LCA) methodology and describes two broadly used models: GHGenius and GREET. Both of these were used to calculate well-to-pump emissions and energy use. The basis of PSAT's functionality is also presented in this chapter, as well as its application to estimate vehicle energy use and fuel economy. In Chapter 5 the ten vehicle architectures selected for simulation are described. Results for each vehicle architecture are later analyzed on a regional basis. Chapter 6 presents market share projections of vehicle technologies in Canada and the U.S. over the decade of 2010 to 2020. A mix of vehicle technologies is recommended for each region based on the criteria of lowering energy use and greenhouse gas emissions in each jurisdiction. The final conclusions of this work can be found in Chapter 7.

Chapter 2

Hybrid and Electric Vehicles

Contrary to what many people think, hybrid vehicles have existed for over 100 years. The Technical Committee 69 (Electric Road Vehicles) of the International Electrochemical Commission (IEC) suggests that a hybrid electric vehicle (HEV) is a vehicle in which propulsion energy is available from two or more types of energy stores, sources or converters and at least one of them can deliver electrical energy. [3] There are many possible variations, the most common being the combination of internal combustion engines with electric motors and batteries.

Strong hybrids may have small battery packs that can produce enough power to drive the vehicle short distances in full electric mode. These battery packs are much smaller than those needed for full function electric vehicles since they are recharged by the IC engine while the vehicle is being driven. They can also retain charge gained through regenerative braking, which for a short period of time transforms mechanical energy at the wheels into electrical energy through the generator [4].

Given their distinct nature, hybrid vehicles incorporate technologies that differ significantly from traditional IC driven vehicles. Some of the advanced technologies typically used in hybrids include [5]:

1) Regenerative Braking - The electric machine can be used as a generator in situations where the vehicle is coasting or braking. This mechanical energy is transformed into electrical and harnessed through the battery until needed by the electric motor.

2) Electric motor drive/assist - In the case of parallel or series-parallel hybrids, the IC engines can be under-dimensioned for the vehicle weight and therefore would perform poorly by itself in situations where fast acceleration is required. However, in such cases, the electric motor provides additional power to assist the engine in accelerating, passing or hill climbing to maintain performance.

3) Automatic start/stop - In hybrid vehicles, it is not necessary for the IC engine to function at all times like in a conventional one. When a vehicle is stopped in traffic, for example, the IC engine is off. If the driver needs to accelerate fast, power from both the IC and electric motor will be required. At this point the automatic start system engages to turn on the engine. Conversely, if the control system of the vehicle senses that the vehicle is braking and that power from the IC engine is not needed, automatic shut off of the engine occurs.

Full function electric vehicles (FFEV), also known as battery electric vehicles (BEV), are a completely separate segment, and are not considered hybrids due to their single source of energy. Although BEVs are the most efficient, simplest, and have a low maintenance drivetrain, they are unlikely to become mainstream to the market before there is a further breakthrough in battery or high voltage super capacitor technology [6]. In anticipation of such breakthrough, extensive research and development is being carried out across the world in order to advance electric motor, transmission and power electronics technology.

2.1 Hybrid Drivelines and Power Flow Control

Analyzing the different hybrid and electric vehicle architectures and their fuel efficiency gains over IC engine vehicles is a complex process. The different control strategies employed, combined with power flow, are key given their direct impact on fuel economy [7].

Minimizing emissions and maximizing fuel economy is partly about maximizing the IC engine's efficiency, but also maintaining a standard of vehicle performance. Keeping the engine at optimum efficiency involves a series of considerations, the main ones being [8]:

- Running the ICE at the optimal brake specific fuel consumption point, minimizing emissions or reaching a compromise between these two targets.
- Given the ICE is required to deliver variable power, the previously mentioned points compose an optimal engine operating line such as the one illustrated in Figure 2-1.
- Minimize engine dynamics by regulating its operation and avoid any rapid fluctuations.
- Minimize ICE on-time to reduce fuel consumption and emissions.

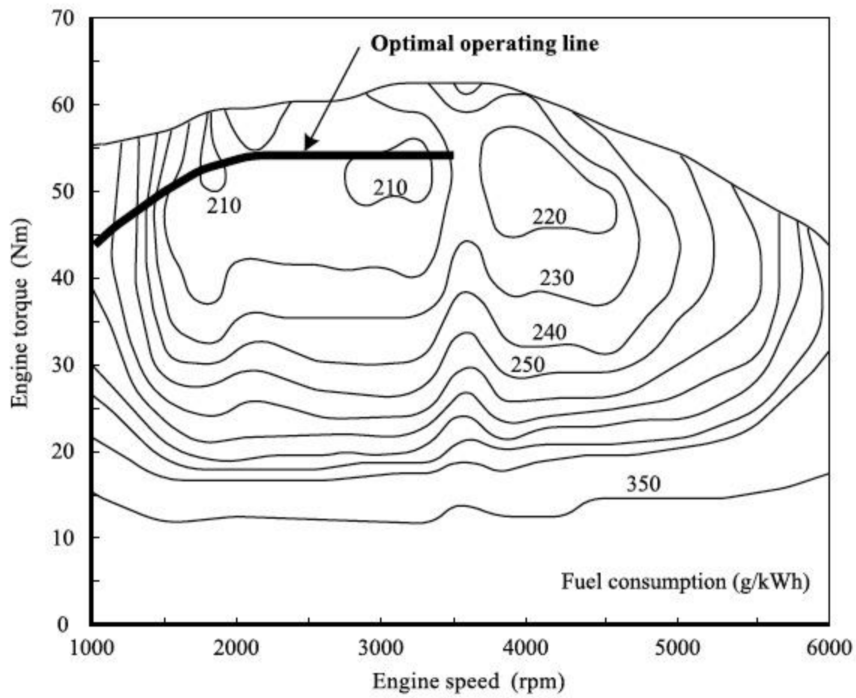


Figure 2-1. Optimal operating line on an engine fuel consumption map [8].

- Maintain proper battery state of charge so that the pack is capable of providing enough power for acceleration and accepting regenerative power during braking or downhill driving.
- Maintain safe battery voltage as it will fluctuate during discharging and charging periods. Keeping the state of charge within an acceptable range is vital to ensure long battery life.
- Proper balance of power between ICE and electric machine during the drive cycle.

2.1.1 Series Hybrid and Extended Range Electric Vehicle

There is some confusion surrounding the series hybrid and extended range electric vehicle given their similarities. Neither has a mechanical connection between the IC engine and the wheels, unlike a conventional car. This is depicted in Figure 2-2.

Therefore, their only source of motive power comes from the onboard electric motor. The purpose of incorporating an internal combustion engine is to keep the battery pack small, given it is used in combination with a generator as a charge sustaining device to maintain the battery pack's energy supply [9,10]. Both vehicle architectures are able to recover energy through regenerative braking.

The main difference lies in the size of their battery pack and the possibility of plugging in the vehicle to charge it. Usually battery packs on series hybrid vehicles are very small, and some don't even have one. They act as an energy buffer to isolate the IC engine from rapid transients. A plug-in series hybrid is one that can be grid connected to recharge the battery pack and hence doesn't depend solely on the ICE for recharging; in that sense it can be considered a range extended electric vehicle via the onboard generator set.

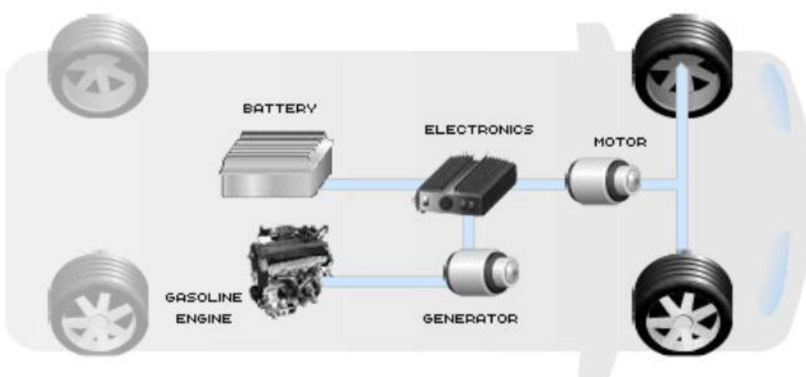


Figure 2-2. Series hybrid drive layout (Courtesy of www.hybridcenter.org). [11]

Extended range electric vehicles (EREVs), such as the announced GM Volt and the Fisker Karma, are typically able to travel between 40 and 50 miles (65 to 80 Km) in full electric mode. The onboard IC engine can maintain the battery state of charge, thus further extending the vehicle's range quite significantly, hence the "extended range". EREVs offer the high efficiency of an electric powertrain along with the possibility to cover long distances using an IC engine. This translates into alleviating drivers who suffer from "range anxiety", a term used to refer to a drivers' concern of being left stranded before reaching their destination. The term EREV has been used to market the Chevy Volt, presently being launched. However, this architecture is still a long way from becoming mainstream and well understood by the average consumer. Figure 2-3 illustrates the basic layout of the Chevy Volt architecture.

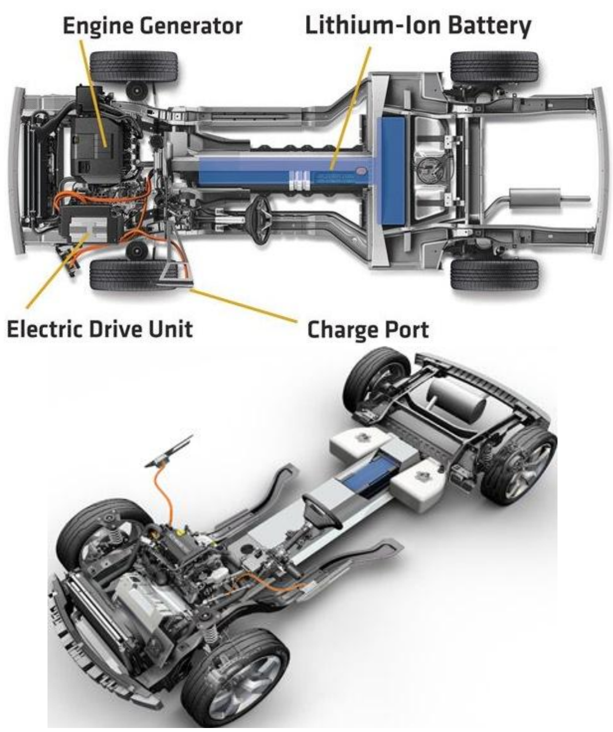


Figure 2-3. 2011 Chevy Volt drive train layout (top and bottom).

2.1.1.1 Series Hybrid Power Flow Control

The power flow in a series hybrid system can be illustrated in four basic operating modes: slow speed operation, acceleration, cruising speed, and regenerative mode [11]. When the vehicle is cruising at low speed, the battery and electronics supply the electric motor with power which in turn drives the wheels. In this case, the IC engine is off and the vehicle operates as a full function electric vehicle (FFEV). Figure 2-4 depicts the power flow in this state [10,11].

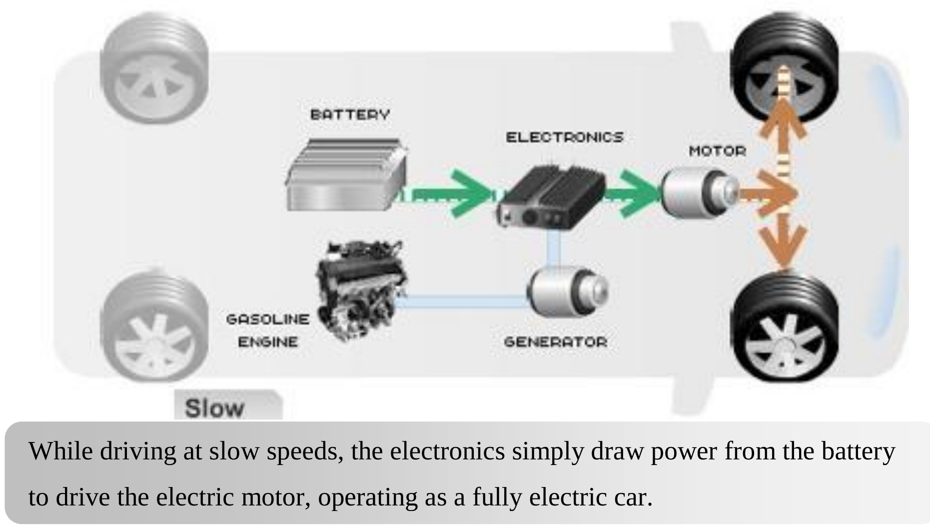
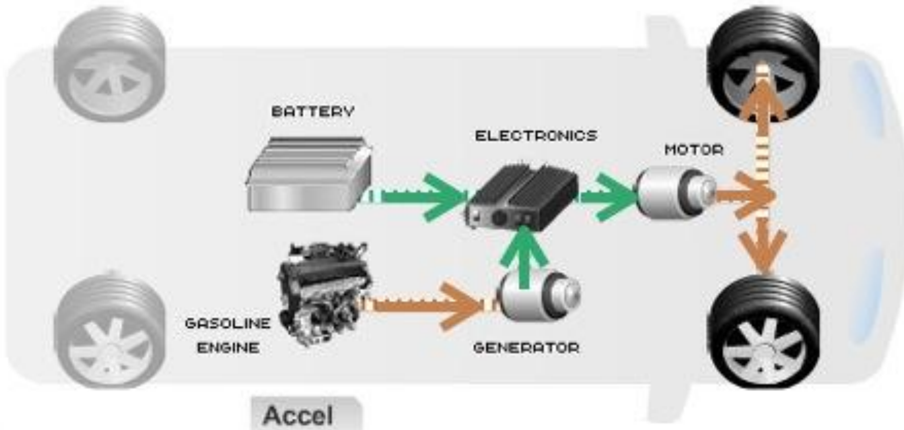


Figure 2-4. Series Hybrid slow operation power flow [11].

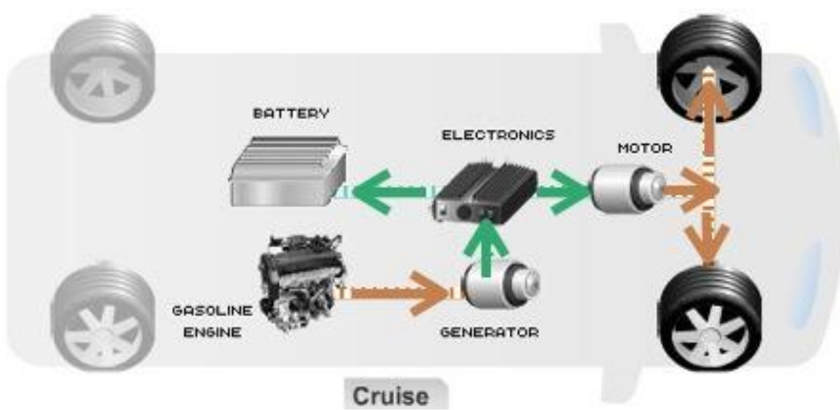
When under heavy or prolonged acceleration or heavy loads such as mountain driving, the electric machine will drain a great amount of power from the battery pack. The ICE engages and runs the generator which temporarily supplements the battery. Figure 2-5 illustrates this scenario.



During acceleration, the gasoline engine runs the generator to supplement the power being drawn from the batter.

Figure 2-5. Series Hybrid acceleration power flow [11].

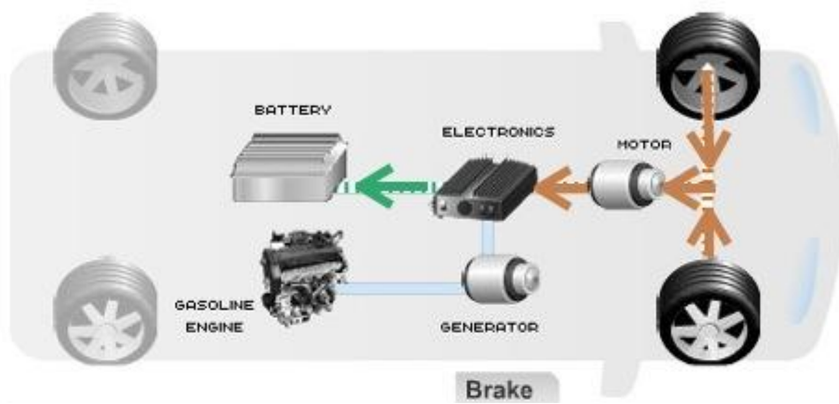
The cruising mode engages all systems; however power flow changes direction from the electronics to the battery. During this control scheme the ICE engine powers the generator which can either supply power to recharge the batteries and/or simultaneously provide additional power to the electric machine [8].



While cruising at a steady speed, the gasoline engine runs the generator which provides power to drive the electric motor. If necessary, additional power may be drawn from the generator and sent to recharge the battery.

Figure 2-6. Series Hybrid cruising speed power flow [11].

During braking, the mechanical energy from the wheels is transmitted mechanically through the drive axels which spin the motor (and in this state acts as a generator) thus creates power to recharge the battery pack. This operational mode is known as regenerative braking and occurs equally if driving downhill, assuming that the vehicle doesn't require additional power [8,9].



While braking, the energy of the braking wheels is sent back through the motor, creating power to recharge the battery pack.

Figure 2-7. Series Hybrid braking power flow [11].

2.1.2 Parallel Hybrid

As the name implies, in a parallel hybrid the IC engine and motor are placed in parallel and each is capable at any given moment to propel the vehicle. Both of the mechanical power outputs from the electric motor and the ICE drive the transmission and are shown in Figure 2-8. In situations of high power demand, the electric motor supplements the ICE to provide the driver with the required performance. When the vehicle power demand is much lower than what the ICE is capable of supplying efficiently, it will shut down and engage the motor to propel the vehicle under battery power. Not all parallel hybrids support this capability as it requires de-clutching the engine. To a certain extent, a parallel hybrid can be seen as an electric-assisted ICE vehicle, where the electric motor acts as a buffer to aid the ICE in situations where it is loaded beyond capacity. To keep the battery charged, maintaining the ICE at a nearly constant but higher output power level when it does run increases the net efficiency and therefore the vehicle's fuel economy. As in the case of series hybrids, parallel hybrids are also capable of making use of regenerative braking in stopping or down-slope driving to extend the battery pack's state of charge [11].

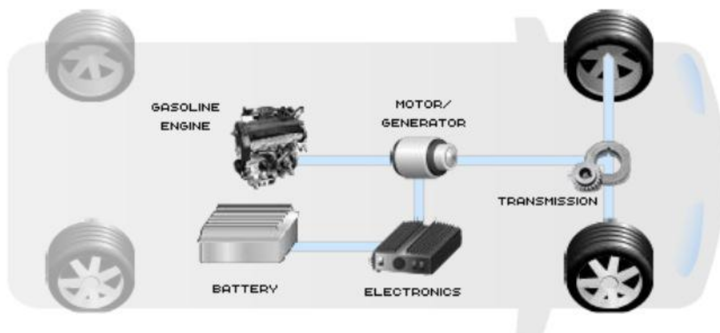


Figure 2-8. Parallel hybrid drive layout (Courtesy of www.hybridcenter.org) [11]

Some advantages of the parallel system are that the peak performance is met using both systems and therefore the electric machine (electric motor) can be kept smaller, and that only a single electric machine is required. Additionally, electrical losses are minimized because most of the power is delivered directly rather than converted to electricity and then back to mechanical as in a series path [7]. Unfortunately, the engine cannot always be run at its optimum operating point and this is a drawback of parallel architecture. Also, a mechanical transmission is required making this configuration more complex than a series hybrid.

A few modern examples of this type of vehicle architecture are the Honda Insight shown in Figure 2-9 which uses an Integrated Motor Assist (IMA) system consisting of an ultra thin DC brushless motor sandwiched between the ICE and the transmission [10]. Here the electric machine is directly coupled to the ICE, typical of a “mild hybrid” design.

Figure 2-9. Honda's Insight, a Parallel HEV

2.1.2.1 Parallel Hybrid Power Flow Control

Contrary to a conventional ICE vehicle, a parallel hybrid doesn't have a starter motor. Instead, it uses the motor/generator unit for initial startup or for improved acceleration performance when proceeding from a complete stop [9].

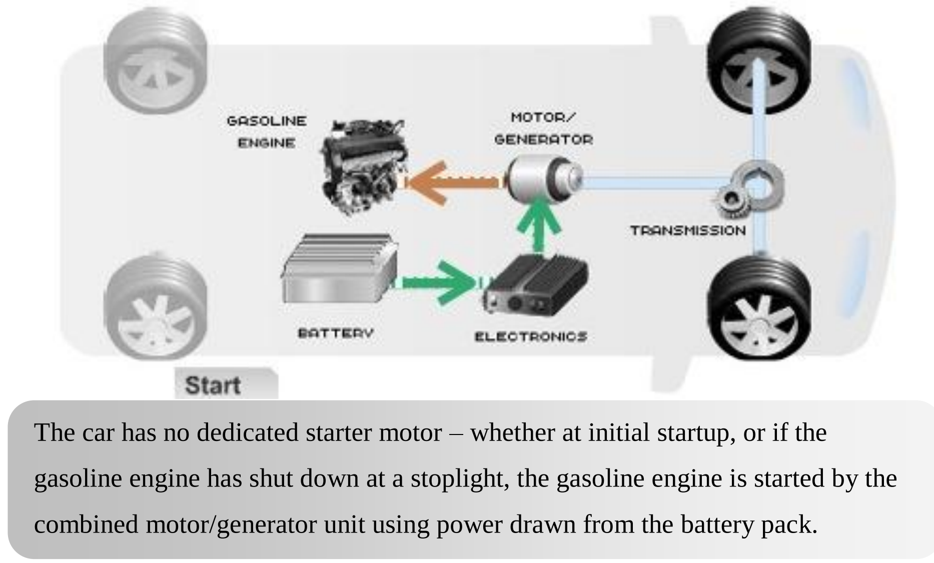


Figure 2-10. Parallel Hybrid vehicle start power flow [11].

Higher acceleration in a parallel hybrid is mainly derived from the combustion engine, although if necessary the motor/generator provides assist. In that case, the battery pack supplies the motor with the required power [11]. This scenario is depicted in Figure 2-11.

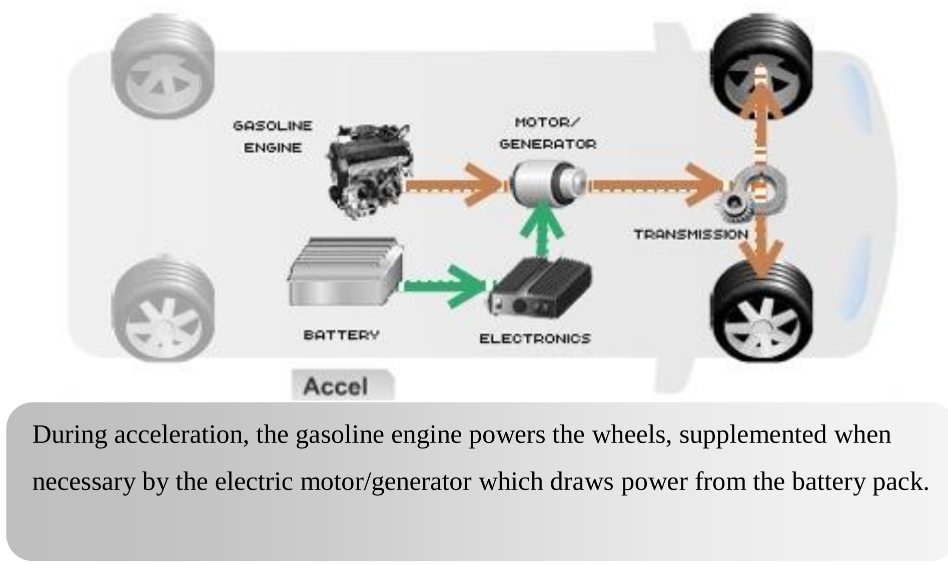


Figure 2-11. Parallel Hybrid acceleration power flow [11].

During cruising at steady speed, the combustion engine is operating near maximum efficiency. When the propulsion power available exceeds what is needed by the vehicle; the surplus can be used to charge batteries as required.

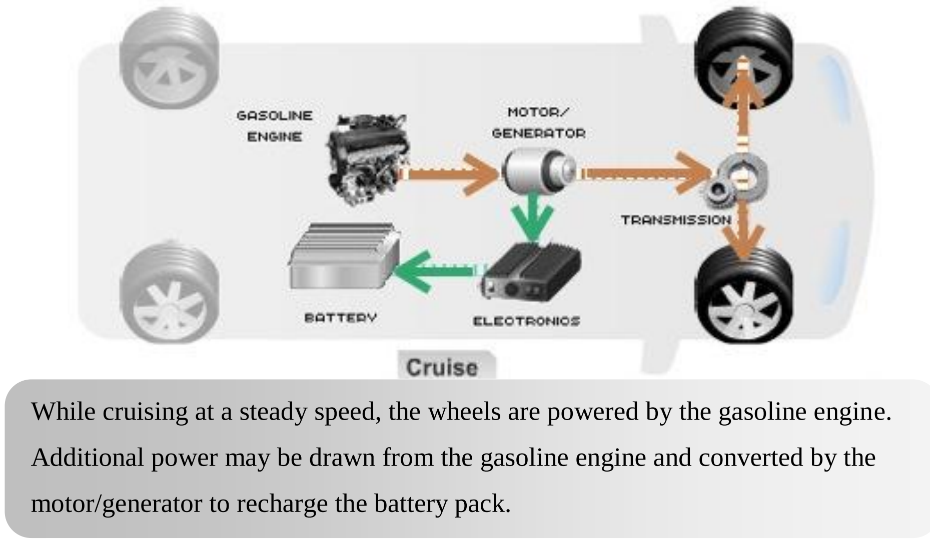


Figure 2-12. Parallel Hybrid cruising power flow [11].

The braking scheme for the parallel hybrid follows the same power flow as in the series hybrid. Energy from the wheels is recuperated through the motor/generator assembly and converted into electrical energy stored in the batteries [8].

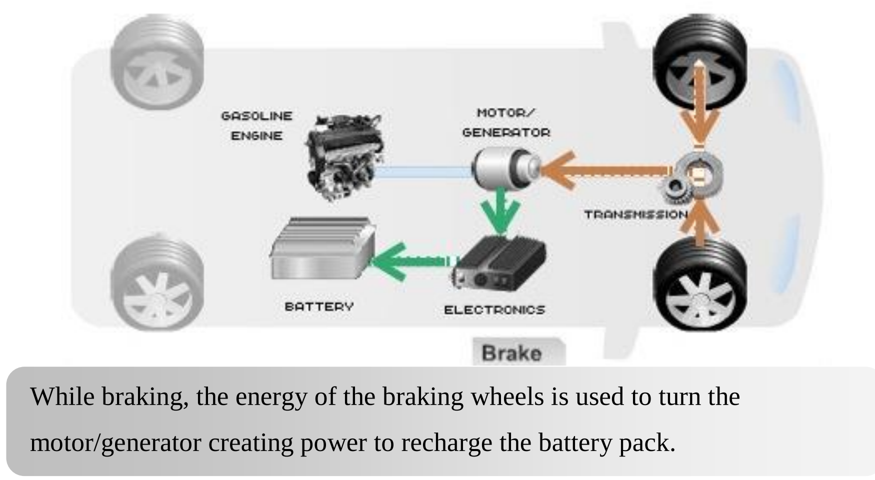


Figure 2-13. Parallel Hybrid braking power flow [11].

2.1.3 Series-Parallel (Dual Hybrid System)

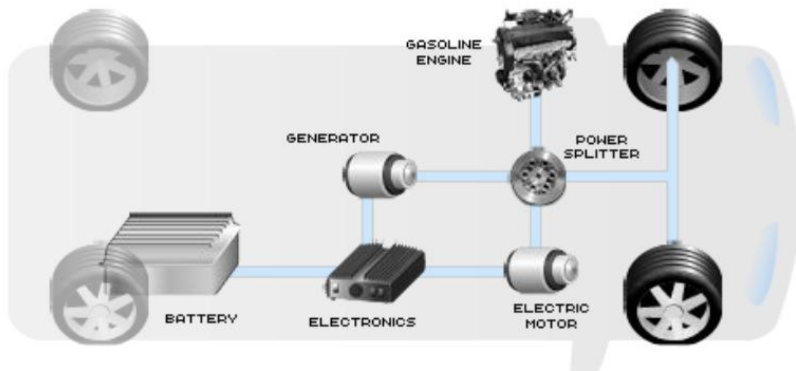


Figure 2-14. Series-Parallel hybrid drive layout (Courtesy of www.hybridcenter.org). [11]

The combination of the aforementioned drive type gives rise to the series-parallel hybrid. Series-parallel hybrids can be driven by the electric motor alone (as in series hybrids), or by the IC engine, or both through a power-split device. As a result of both power devices working in harmony, the engine will operate near optimum efficiency more of the time.

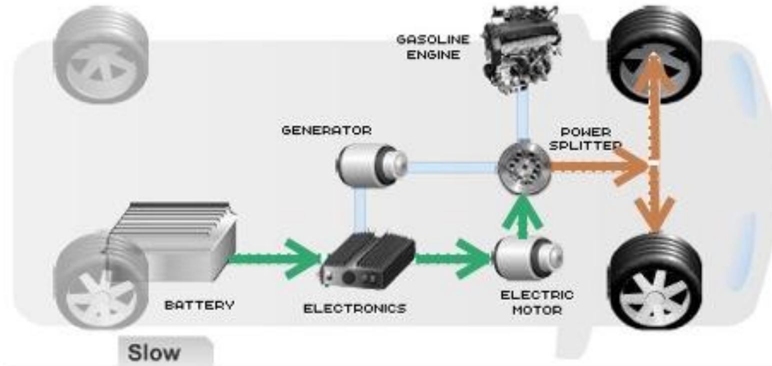
Series-parallel hybrid systems such as the one illustrated in Figure 2-14 have been made popular by Toyota and a similar implementation is alsofound in the Ford Escape Hybrid and the Lexus Hybrid SUV. By adding another electric machine and a power splitting device (functionally a torque divider), the vehicle is able to manage additional operating modes. This power splitting device divides the torque from the engine and mechanically transmits part of it to drive the wheels while sending the remainder to spin the generator and recharge the battery pack. Simultaneously an electric traction motor can engage at any moment to provide additional torque to the driven wheels. One of the most advanced designs is Toyota's Hybrid Synergy Drive (HSD) employed in the 2009-2010

Prius [10]. The engine drive shaft is connected to the planetary gear carrier, allowing power to be simultaneously supplied through the outer ring gear to the wheels and via the sun gear to the generator [10]. As a result of this dual drivetrain and the associated control software, the IC engine operates near its optimum efficiency most of the time. At lower speeds the vehicle behaves more like a series hybrid vehicle, while at highways speeds the IC engine takes over minimizing energy loss conversions.

However, incorporating the additional components creates a much more costly system. It needs a second electric machine, a torque splitting device, a larger and more powerful battery pack and complex controller to bear the highly sophisticated control scheme [10].

2.1.3.1 Series-Parallel Power Flow Control

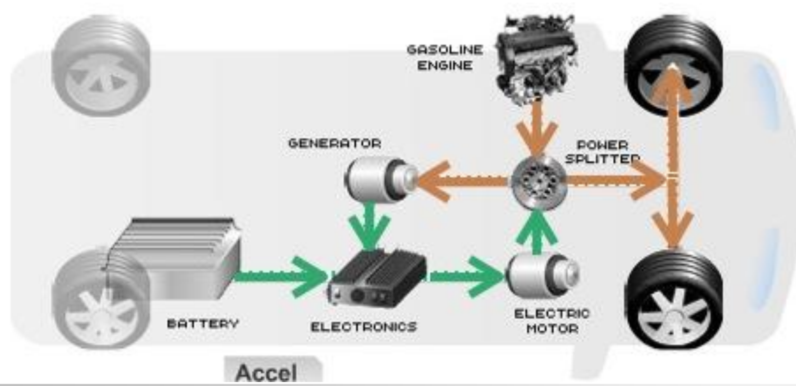
Series-Parallel control modes are more complex due to the simultaneous and combined power transfer via two paths. During slow operation the power flow is much like a parallel hybrid, in the sense that the IC engine may be off and only the electric machine provides propulsion. It can act like a full function electric vehicle during low speed city driving if there is a large enough battery pack, significantly reducing emissions in urban settings [8].



While driving at slow speeds, the hybrid synergy drive (HSD) simply draws power from the battery to drive the electric motor, and operates as a fully electric car.

Figure 2-15. Series-Parallel Hybrid slow operation power flow [11].

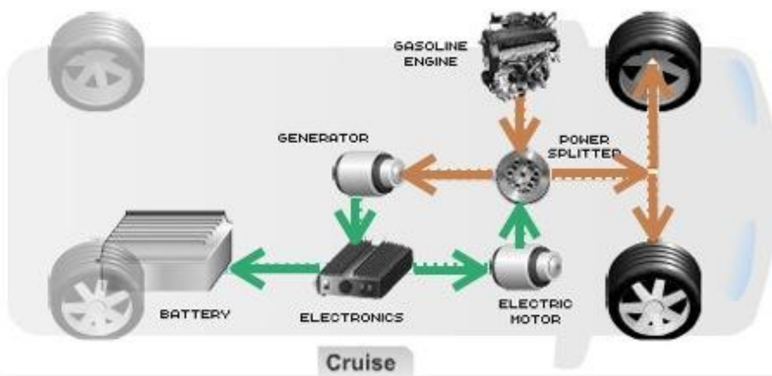
During acceleration the combustion engine is started by coupling it to the electric traction motor and its output is routed via the torque/power splitter device. Its power may be used to supplement the electric motor and/or provide additional electric power to boost the electric machine's performance via the generator (Figure 2-16). This power distribution is achieved through a planetary gear system. Sometimes more than one planetary gear set ratio can be selected as in the GM 2-Mode Hybrid.



During acceleration, power from the gasoline engine is routed by the power splitter through the generator to supplement the power being drawn from the battery.

Figure 2-16. Series-Parallel Hybrid acceleration power flow [11].

Cruising mode has a similar power flow to acceleration; however a portion of the electrical power generated in the electric machine flows into the battery pack and out the traction motor in parallel with the mechanical path of the IC engine. In sophisticated versions as the GM 2-Mode, a 100% direct mechanical path is available from the ICE to the wheels for maximum efficiency.



While cruising at a steady speed, the gasoline engine runs the generator, which provides power to drive the electric motor. If necessary, additional power may be drawn from the generator and sent to recharge the battery.

Figure 2-17. Series-Parallel Hybrid cruising speed power flow [11].

Lastly, the braking power flow is akin to previous architectures described in which the ICE is shut off and mechanical energy from the wheels is transformed into electrical energy via the electric motor. The electrical energy reverts through the power electronics and is used to recharge the battery pack [8].

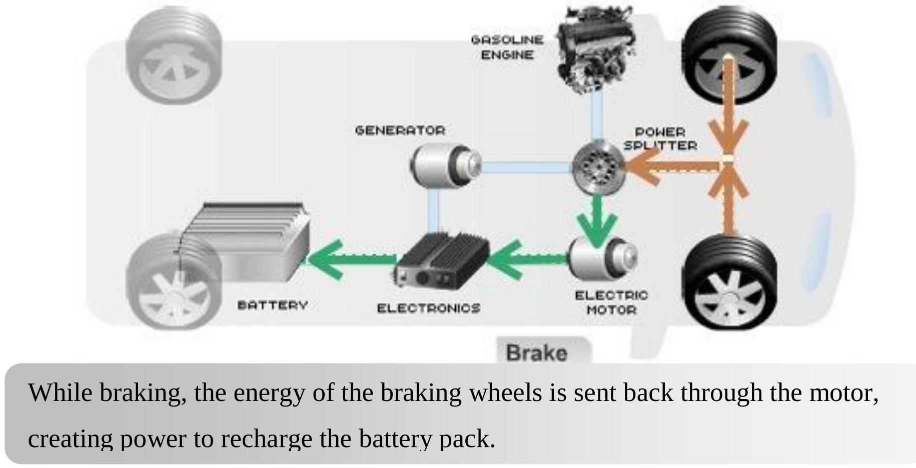


Figure 2-18. Series-Parallel Hybrid braking mode power flow [11].

Modeling tools have been developed to simulate the previously highlighted power flows and control schemes. One of the most advanced is the "Powertrain System Analysis Toolkit" (PSAT) developed by Argonne National Laboratory (ANL). This flexible tool written in MATLAB, Simulink and State Flow, simulates fuel economy and performance parameters in a realistic manner, taking into account transient behavior and control system characteristics [12]. Such tools are used to evaluate the many design alternatives available, and for initial architecture optimizations. An introduction to some of these tools can be found in Chapter 4.

2.2 Fuel Cell Vehicles

A fuel cell vehicle (FCV) is essentially an electric vehicle that uses tanks filled with hydrogen gas as its energy storage or fuel system instead of a battery. Unlike a heat engine, its operation relies on the chemical recombinant reaction that occurs between a fuel (hydrogen) and an oxidant (oxygen) in the presence of a catalyst (typically platinum) to produce an electric current and the reactant product water. The principle behind the operation of a polymer electrolyte membrane (PEM) can be seen in Figure 2-19.

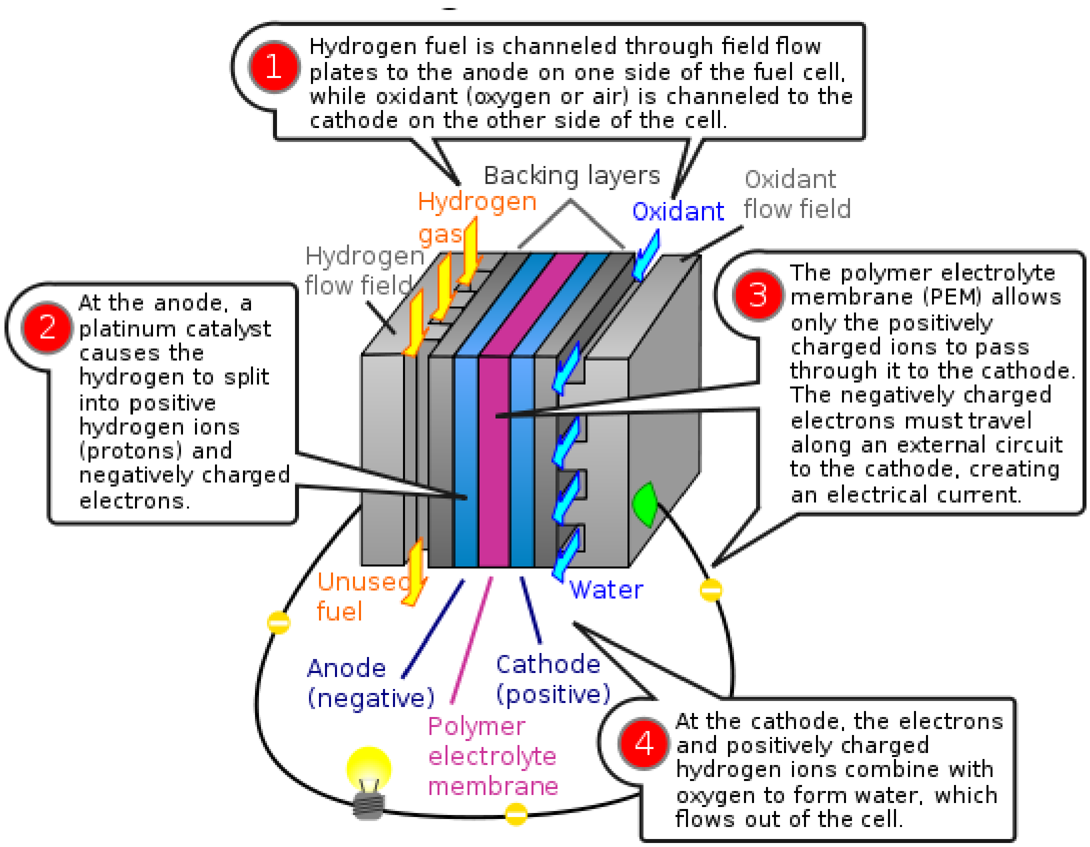


Figure 2-19. Operation of PEM fuel cell. [13]

A fuel cell is considered a thermodynamically open system given that the hydrogen fuel must be replenished in order for it to function and generate electricity. In contrast, secondary chemical batteries store electrical energy when they are recharged and therefore represent a thermodynamically closed system.

The average operating efficiency of a fuel cell system lies around 50%, meaning that half of the energy stored in the hydrogen is dissipated as heat. These losses added to the large amounts of energy lost in the production, distribution, and storage process of the hydrogen gas lower its efficiency on a well to wheels basis. However, FCV are an arguable alternative to BEV when considering that their electric powertrains are nearly identical.

The Honda Clarity is one of a few commercial FCV available in test fleets, released in areas where hydrogen fast-fill stations are available in the U.S., Japan, and Europe. The 2011 model is based on the original 2006 Honda FCX platform and can be seen in Figure 2-20.

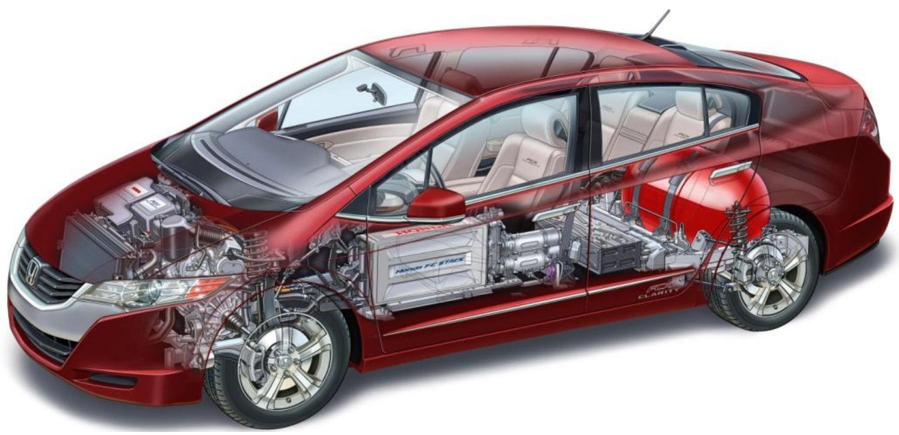


Figure 2-20. 2011 Honda Clarity Fuel Cell Vehicle. Courtesy of Honda.

The Clarity uses the V Flow fuel cell stack (Figure 2-21) developed by Honda which delivers 100 kW of power. It uses a vertical flow of hydrogen and oxygen derived from air through what Honda claims is a more efficient package. The unit is located under the center console and converts the hydrogen stored in the rear tank (visible in red in Figure 2-20) into electricity to operate the 100 kW electric machine under the hood. It is common for FCVs to include a small battery pack as a supplemental power source which provides power when starting at cold temperatures or during aggressive acceleration. The Honda Clarity contains a 288 V lithium-ion battery pack located under the rear passenger seats.

Figure 2-21. Fuel Cell stack used in the 2011 Honda Clarity. Courtesy of Honda.

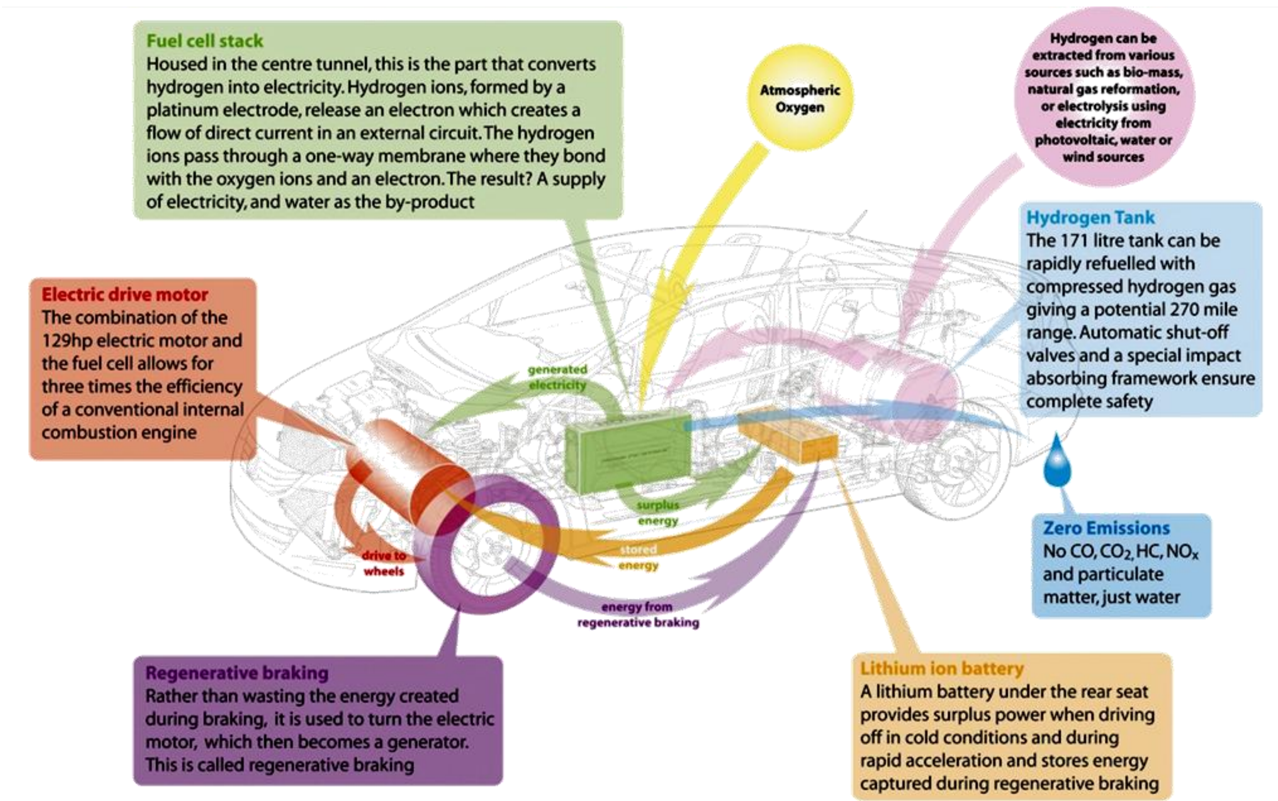


Figure 2-22. 2011 Honda Clarity Diagram. Courtesy of Honda.

Table 2-1. 2010 Honda Clarity Specifications.

Fuel Cell Stack Power Output	100 kW
Li-ion Battery Pack Output	288 V
Electric Motor Power	129 hp
Curb Weight	1625 kg
Range	240 mi
Fuel Capacity / Tank Pressure	3.94 kg @5,000 psi

Chapter 3

Onboard Energy Storage

In plug-in hybrid vehicles, the efficiency and performance of the battery system in conjunction with the powertrain determines the range the vehicle may drive in full electric mode. In full function electric vehicles the battery pack is the only source of energy, therefore higher energy content will translate into greater range. [6] It is not difficult to understand the important role a battery plays in modern vehicle technology. However, present battery technology remains expensive and does not offer the range nor the recharge times consumers expect. Fuel cell technology has also seen experimentation; however hydrogen storage, high component costs, and a lack of distribution infrastructure have slowed down its commercial development. These are only a few of the ongoing challenges that researchers and engineers around the world are trying to address. Their success determines if and when the transition to electric vehicles will occur.

3.1 Battery Technology

There are many different types of commercial battery technologies available today. Lead acid batteries for electric vehicles (long the staple design point) have been superseded. However, newer battery technologies are all still based on the same principle: two electrodes of different material are mated with an electrolyte conductor which allows an ion exchange between them. This reaction potential forces an electron flow through an external circuit, hence discharging the cell. In the case of rechargeable cells, such as the ones applied in modern vehicles, the chemical reaction can be reversed by switching the current polarity and thus returning the cell to its initial state. [9] A collection of cells in series forms a battery of higher voltage, whereas increased cell area allows for more current flow. The “external circuit” constitutes the drive motor and controller.

Each chemistry varies in cost, operating temperature, energy and power density, and many other parameters that will be described briefly. Engineers must consider the characteristics of the battery chemistry when designing a vehicle in order to meet the costs, performance and range requirements established in any product. In hybrid vehicles, the battery will continually cycle electrical energy as it operates in a charge sustaining mode, and in some cases for short periods in charge depleting mode. In BEVs, the battery pack is the only source of energy, thus it operates in charge depleting mode all the time except during braking and downhill driving where one can assume that for short instances recharging is taking place. Battery hardware-in-the-loop (HIL) simulation permits researchers to model and test energy consumption along with fluctuation of the state of charge (SOC) under different drive cycles [14].

3.2 Battery Parameters

Cell and Battery Voltages: Cells have open circuit voltages. From basic circuit theory, the loaded voltage is:

$$V = E - IR, \qquad \text{(Equation 3.1)}$$

Where "V" represents terminal voltage, "E" open circuit voltage, "I" current flowing out of the battery, and "R" the cell's internal resistance. If the battery is being charged, then the voltage will increase by "IR". This equation provides a fairly good prediction of the "in use" battery voltage; however other factors such as temperature, state of charge, and dynamic polarization effects influence this voltage further [4].

Charge (Amp-hour, Ah) Capacity: Battery capacity can be measured in different units, the basic physical charge quantity being the Coulomb (6.24 x 10^{18} electrons = 1 Coulomb). However, for vehicle applications this unit is inconveniently small. Therefore, the Ah (3,600 Coulombs) is used which represents 1 Ampere flowing for one hour. It is worth noting that an Ampere is equal to 1 Coulomb per second. Each cell chemistry exhibits a rate dependence. For example a 40 Ah battery may be able to provide 1 Ampere for 40 hours, but not 40 Amps for 1 hour, rather a lesser value. Traction batteries for automotive use are often quoted for a 3 hour discharge (C/3, where C denotes the nominal Ah rating). Figure 3-1 depicts how battery capacity is affected by rate of discharge [9].

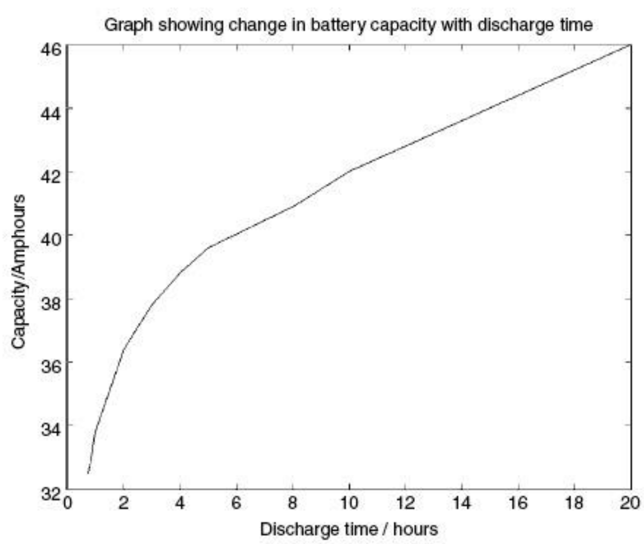


Figure 3-1. Change in Ah charge capacity of a nominally 46 Ah battery. Graph is based on measurements from a Hawker Energy Products Inc. lead acid traction battery [9]. C/20 is standard automotive rate on lead acid battery.

Therefore the speed at which a battery is discharged affects its capacity. This is known as the Peukert Effect. The Peukert value or exponent is proportional to the internal resistance of the battery and polarization effect; therefore the higher the internal resistance and slower the ion diffusion, the higher the losses during charge and discharge, especially at higher currents. Consequently at faster discharge rates the Ampere-hour (Ah) capacity of a battery decreases.

Energy Stored: The fundamental unit of energy that can be stored is measured in Joules, the product of cell voltage and charge. As in the case of the Coulomb, the Joule is too small a unit for practicality. Therefore, the Watt-hour (Wh) is used, and related to the Ah and voltage through the following expression [9]:

$$Energy\ (Wh) = \int_{t_0}^{t_1} V(t)A(t)\,dt \qquad \text{(Equation 3.2)}$$

Quick energy release invokes dynamic losses as indicated above, and goes beyond internal resistance, as exemplified by Figure 3-1. Thus each cell type is ideally operated within its recommended rate characteristics for efficient discharge or recharge.

Specific Energy: Specific energy, also known as gravimetric energy density, can be defined as the amount of electrical energy stored for every kilogram of battery mass and is usually denoted in Wh/Kg. This parameter is helpful in estimating the approximate mass of the required battery box. [8] For example if an 80 KWh battery pack is needed in an electric vehicle, and the designer is considering lithium polymer batteries with a specific energy of approximately 190 Wh/Kg, then one can easily estimate that the total cell weight will be 80,000(W)/190(Wh/Kg) = 420 Kg. The battery system weight accounting for the containment structure, controls, and cooling system, are in addition typically at least another 25%, given the system is well designed.

Energy Density: This parameter is also known as volumetric energy density and is similar to specific energy. As its name implies, it indicates energy on a volumetric basis instead of mass. Frequently it is expressed in Wh/liter and it serves as a guide for battery volume requirements [9]. This factor often constitutes the practical limiting case in terms of packaging for modern electric vehicle designs.

Specific Power: The specific power value indicates the amount of power obtained per kilogram of battery. It is a value which fluctuates given peak power draw and time. It depends much upon the dynamic load connected to the battery. The typical unit for specific power is W/Kg and must not be confused with the Wh/Kg (specific energy). A battery may have a low specific energy but a high specific power, meaning it can store a limited amount of energy, but is capable of giving it out in high bursts [9]. An ultra capacitor represents a class of energy storage device with extremely high specific power.

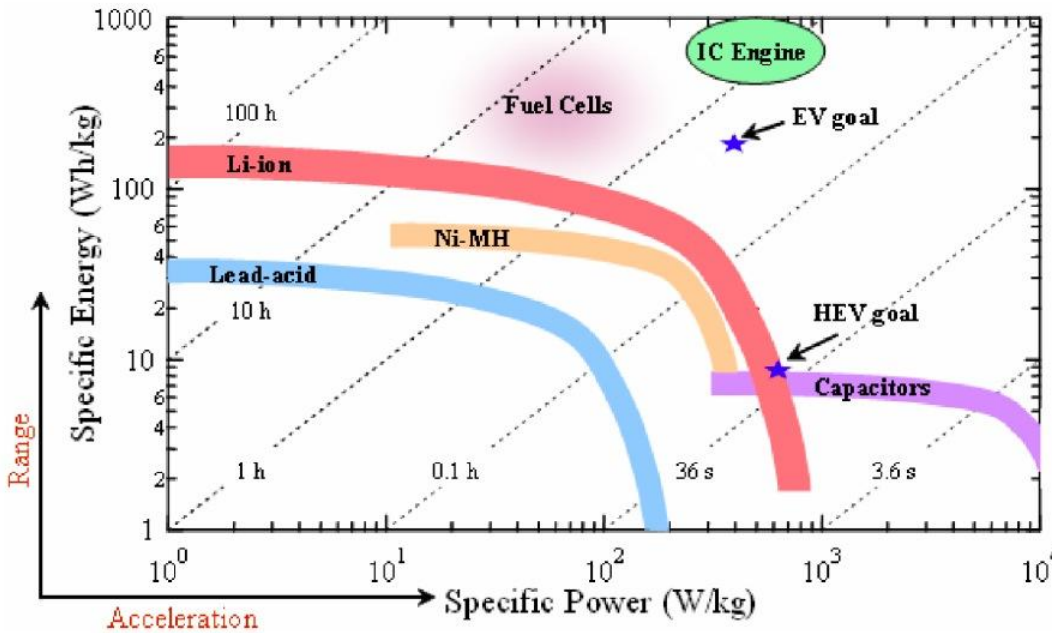


Figure 3-2. Battery energy and power vs. engine and capacitor [Srinivasan 2004].

The relation between specific power and specific energy is very important and is often illustrated in a graph known as a Ragone plot. Ragone plots are useful for comparing various energy storage devices. Both axes are logarithmic allowing for comparison of very different devices such as those that are extremely high or low power. Two examples for this type of representation can be seen in Figures 3-2 and 3-3. The objective is to realize the best combination of specific energy and specific power suitable for a vehicle architecture (HEV, EREV, BEV) that any particular battery chemistry can deliver.

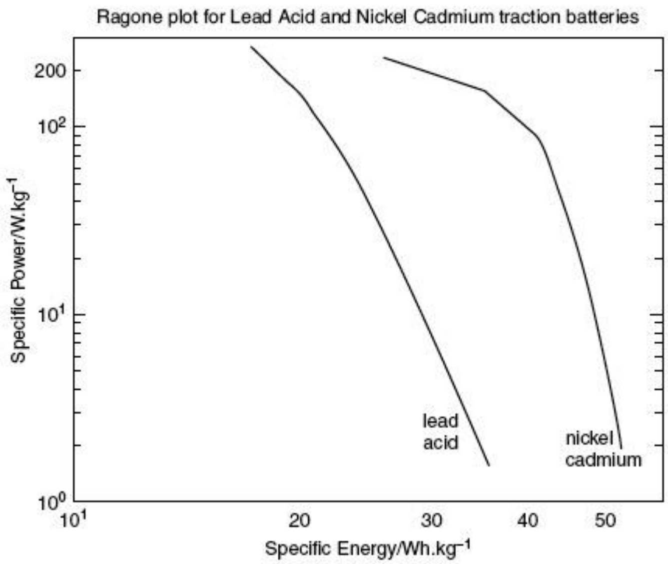


Figure 3-3. Ragone Plot showing typical lead acid and nickel cadmium traction battery specific power and energy. [9]

3.2.1 Lead Acid Batteries

If one considers the fact that one ton of lead acid batteries will store the same energy as 3 liters of gasoline [6], it is no wonder why IC engine vehicles won over the market at the beginning of the 20th century. However, when analyzed from an efficiency standpoint, a different picture emerges.

Lead acid is the best known and most widely used battery in automotive applications for engine starting [4]. The type used for hybrid and electric vehicles, however, are more robust and employ a gel type electrolyte or electrolyte absorbed into a glass mat. Liquid sulphuric acid is used in the more common starter battery which is optimized for highest power. The overall reaction that occurs in these cells is [9]:

$$Pb + PbO_2 + 2H_2SO_4 \leftrightarrow 2PbSO_4 + 2H_2O \qquad \text{(Reaction 3.1)}$$

One of the better features found in this battery chemistry is its low internal resistance, meaning the fall in voltage as current is drawn remains small. Unfortunately, given the nature of the reactions that occur within, lead acid batteries are prone to self discharge. This complicates charging of battery packs and also their equalization which consists of leveling the charge in all the cells within a pack [9]. As a consequence, some cells will need to tolerate overcharging in order to assure the complete pack is fully charged. Overcharging, however, involves additional reactions in which water is lost and turned into hydrogen and oxygen. Older lead acid battery designs simply vent and dispose of these gases. However, modern batteries are sealed in order to force the gases to recombine and reform as water [6]. This process is not perfect and the cells will dry out if abused.

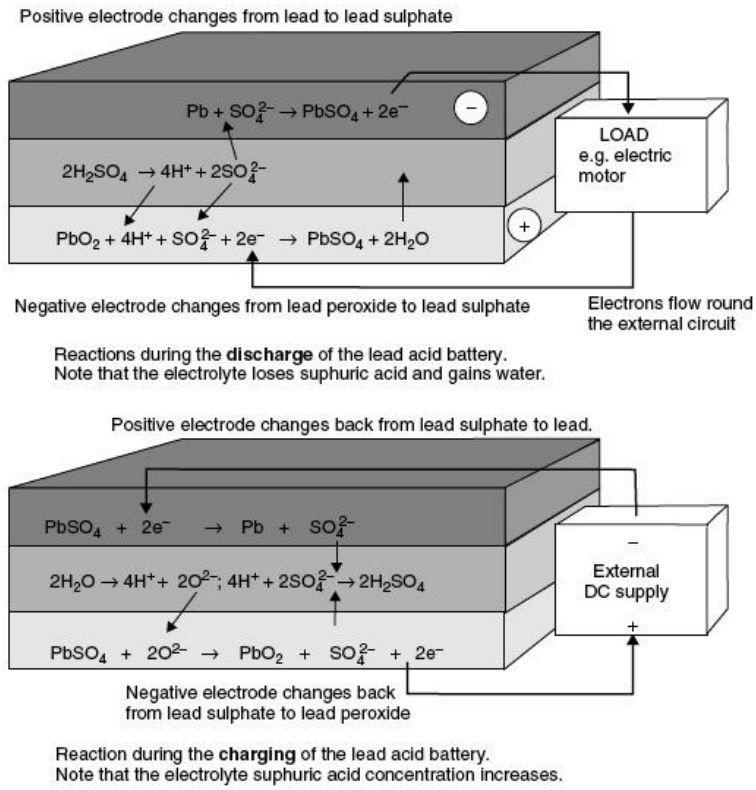


Figure 3-4. Reactions in lead acid batteries during charge and discharge [9].

Charging lead acid batteries is complex and as in the case of other battery chemistries, if carried out incorrectly, will ruin the battery or decrease its life dramatically. The most common technique used to charge lead acid batteries is known as "step charging" [9]. Cells are charged at constant current until their voltage reaches a predetermined level, then the voltage is held constant to “float charge” at a very low amperage. The required voltage level varies, depending on the exact battery chemistry and ambient temperature. The battery management system (BMS) and charger must manage this correctly to assure long battery life.

Lead acid batteries will probably remain the cheapest rechargeable battery per kWh of energy, but given their low specific energy and relatively short life span under deep discharge, they are unlikely to be used in electrified architectures. However, for price sensitive markets they may continue to be popular especially in short-range vehicles such as NEVs (neighborhood electric vehicles), golf carts and forklifts [4].

3.2.2 Nickel Cadmium

Nickel Cadmium (NiCad) is only one of an array of nickel based batteries: nickel iron, nickel zinc, and nickel metal hydride also exist. NiCad batteries use nickel oxyhydroxide for the positive electrode and metallic cadmium for the negative terminal. Electric energy is produced through the chemical reaction shown below [9]:

$$Cd + 2NiOOH + 2H_2O \leftrightarrow Cd(OH)_2 + 2Ni(OH)_2 \qquad \text{(Reaction 3.2)}$$

Due to its higher specific energy and specific power compared to lead acid battery chemistry, NiCad cells were first considered an ideal replacement for lead-acid. Their particular characteristic is a long cycle life (up to 2,500 cycles), they can operate at temperatures ranging from -40°C to +80°C and can be made to have reasonably low self-discharge. They have found particular favor in remote telecom applications for repeater stations due to their ruggedness and longevity. However, the operating cell voltage is very low, sitting at around 1.2 V, so that 10 cells are needed for a 12 V battery versus only 6 for lead acid. Additionally, cadmium is much more expensive than lead, environmentally harmful and carcinogenic, which in turn makes this battery technology less appealing [4,9]. Consequently, it has virtually disappeared from the market.

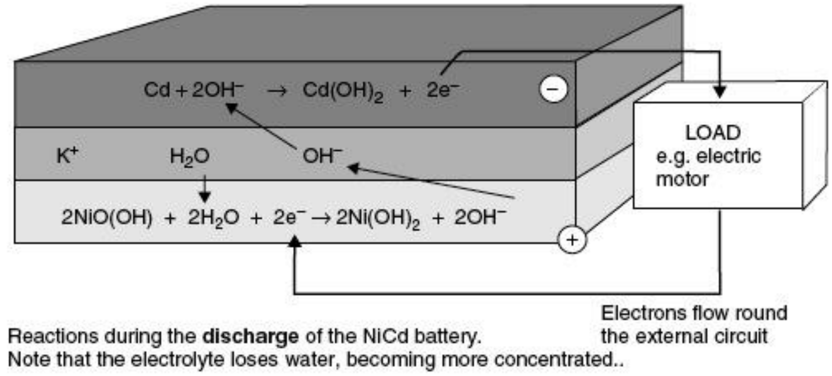


Figure 3-5. Discharge reactions in a NiCad cell. Recharge reactions occur in reverse [9].

Charging of NiCad batteries is similar to that of lead acid batteries and is usually done through the step charging method. Another option is to simply charge at a lower current without the need to stop at predetermined levels of voltage, wait for voltage decay and so forth. Self discharge levels are low and in the range of 0.5 % per day, but still high by modern standards relative to lithium-based battery technologies.

A unique feature of the NiCad battery is how it copes with overcharging. Although it represents a waste of energy, the possibility to overcharge a battery is important since battery pack cells must be equalized to extract maximum energy from the assembly. In the case of NiCad batteries, overcharging results in a series of reactions in which oxygen is produced which diffuses to the negative electrode (anode) where it reacts with cadmium and water, producing cadmium hydroxide. In parallel, the charging reaction generates cadmium and hydroxide ions in the same proportion as at the positive electrode (cathode), therefore, creating a perfectly sustainable system [4,9].

However, the wet cell NiCad chemistry requires high maintenance in the form of cell watering, especially for equalization cycles; thus it is not a “sealed system”. Out-gassing of hydrogen during this process requires ventilation similar to wet-cell lead-acid batteries. Such service intense limitations have spawned development of maintenance free battery systems.

Figure 3-6. NiCad Battery packs from an electric bus owned by the University of Ontario Institute of Technology, Ontario, Canada.

3.2.3 Nickel Metal Hydride

Nickel metal hydride batteries (NiMH), were developed in the 1990's as an evolution of the NiCad chemistry. NiMH use stored hydrogen in the negative electrode (anode) as its name implies, and they are cadmium free which gained them significant interest from industry. The cathode is composed of Nickel-hydroxide and the anode of hydrogen absorbing alloys with a Potassium-hydroxide (KOH) electrolyte. The reaction that occurs in the positive electrode is exactly like the one in NiCad batteries (the only difference is that it uses hydrogen instead of cadmium to react with the 2OH). The hydrogen is held in a hydrogen absorbing metal alloy, namely $MnNi_5$ (AB_5 type) or Zr-Ti-Ni hydride (AB_2 type). The overall reaction that takes place in NiMH batteries is [9]:

$$MH + NiOOH \leftrightarrow M + Ni(OH)_2 \qquad \text{(Reaction 3.3)}$$

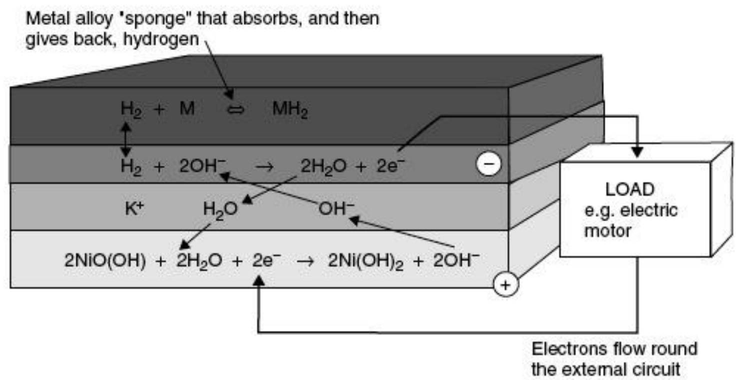


Figure 3-7. Discharge reactions of NiMH cell. Charging reactions occur in reverse [9].

In general, it can be said that NiMH batteries offer improvements in terms of performance versus NiCad. NiMH batteries have somewhat better energy and power density and can be charged faster. However, a vital feature for NiMH battery packs is a cooling system. They heat up during use due to the greater internal resistance of the battery at high states of charge and via the reaction in which hydrogen bonds with the negative electrode's metal [9].

Although NiMH battery systems have a higher energy storage capacity than NiCad, they have one big drawback: self-discharge. Compared to NiCad batteries which self-discharge at approximately 0.5 % per day, NiMH can self-discharge at up to 5 % per day [4,9]. Recent advances in consumer cells' chemistry have overcome this problem, but the same advances have not yet been applied to large format EV batteries.

Figure 3-8. VARTA 4-cell, plastic case, 40 Ah NiMH module (below) and Modular Pack System (above) [15].

In terms of life cycles, manufacturer's literature states that NiMH can withstand around 1,000-2,000 cycles to 80 % discharge. However, some evidence has been found in papers and studies, such as one conducted by the Electric Power Research Institute (EPRI), that this can be extended further, and NiMH battery packs have been deep cycled up to 5,000 times [15]. Their longevity track record and price point accounts for why many automotive companies have selected this battery chemistry for the current hybrid models. In hybrid vehicle applications 300,000 shallow discharges (2 % SOC swing) is a typical requirement.

3.2.4 Lithium Ion / Lithium Polymer

The leading prospects today in battery technology are those based on lithium chemistries [1]. Lithium is the lightest and the most reactive of metals and has an ionic structure that gives up one of its three electrons freely. Two of the most promising lithium-based cell construction variants are lithium-ion (Li-ion) and lithium polymer [9].

Their construction is similar to other batteries, except they lack the heavy metals. This is appealing given today's 'green' trend, and minimizes environmental impact when the complete life cycle of the battery pack is considered.

The current flow in lithium ion batteries occurs via the passage of electrons through an exterior working circuit from the lithium metal oxide cathode (+) to the lithiated carbon anode (-). The overall chemical reaction for the battery is [9]:

$$C_6Li_x + M_yO_z \leftrightarrow 6C + Li_xM_yO_z \qquad \text{(Reaction 3.4)}$$

The cell voltage of Li-ion and Li-Poly chemistry is around 3.7 V, (depends on metal oxide) which compared to other chemistries is high and beneficial for reducing the number of cell interconnects. This high voltage is also a fundamental reason why Li-ion's specific energy and power is substantially better than lead acid and nickel-based batteries, and the fact that it avoids the use of dense metal reactants.

Figure 3-9. Li-ion cell used in Chevy Volt.

Figure 3-10. Chevy Volt battery pack with 288 Li-ion cells.

Charging procedures for Li-ion batteries need to be precise due to their sensitivity. A slight over-voltage can cause damage to the cell. Li-ion packs must be paired with battery management systems designed to individually balance and monitor cells and maximize the pack's operational life, and to ensure safety.

A transition metal oxide in the positive electrode stores lithium ions via intercalation (between layers). The lithium polymer battery has essentially the same construction as lithium ion, except for the separator. Instead of using a more conventional porous separator and liquid electrolyte, it relies on a very thin polymer membrane. During discharge the lithium ions, also held by intercalation between the carbon/graphite anode material, combine with the metal oxide at the cathode to form a lithium metal oxide. This process releases energy and is reversed during charging. The lithium ion is mobile and moves through the electrolyte where the polymer membrane acts as the separator between anode and cathode. In practice the cell is lightly soaked with a non-reacting conductive salt ($LiPF_6$) and organic solvent (for example: ethylene carbonate family) to increase conductivity and diffusion rates for higher power capability. This organic solvent turns the plastic membrane into a gel-like consistency.

A cause for concern with lithium battery chemistry is the passivation of the anode reducing the rate of the reaction; which represents a permanent loss. It is aggravated by exposure to a hot environment and over discharge. Charging schemes are similar to those used for NiMH except the cells have virtually zero tolerance for overcharge and accurate "coulomb counting" is requisite. This presents safety concerns, mainly thermal run-away as a result of overcharge that can ignite the organic solvent and cause rapid venting (with flame); possibly an explosion if no pressure relief device is present.

3.3 Summary Graph

Figure 3.11 presents a Ragone plot of the battery chemistries reviewed and their spectrum of power and energy densities. Lithium based batteries offer a set of design advantages, pending their cost. Early adopters of the technology tend to pay for these premiums whilst production ramps up and it becomes a mainstream commodity.

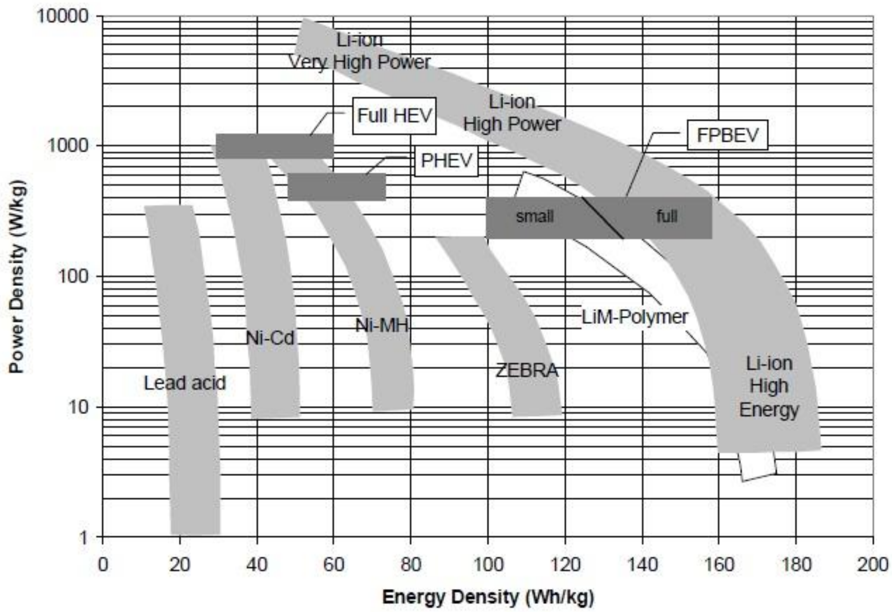


Figure 3-11. Potential of Battery Technologies for HEV, PHEV and EV Applications. [16]

3.4 Ultra capacitors and super capacitors

Ultra capacitors are similar to batteries in the sense that they separate positive and negative charges, but instead of chemically they do it physically. The prefix 'ultra' or 'super' is used for capacitors that are capable of retaining large amounts of energy. This is possible due to the surface area of the electrodes which have recently been increased further by employing nano-technology. A positive aspect is that capacitor life spans are very long and can withstand over 500,000 charge/discharge cycles since they do not rely on a reversible chemical reaction.

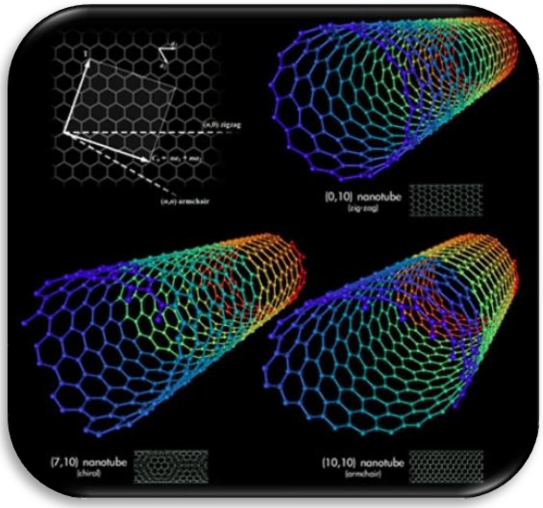


Figure 3-12. Computer generated image of a nano-tube super capacitor [17].

One type of ultra capacitor, known as a double-layer capacitor, uses an electrolytic solution and polarizes it in order to store energy electro statically. It is not really an electrochemical device as the process involves no reactions, thus highly reversible, offering a cyclic life in the hundreds of thousands [17].

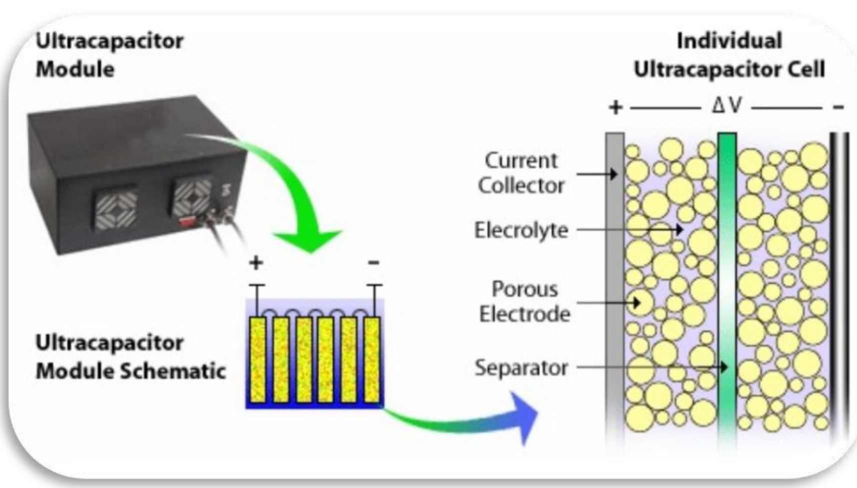


Figure 3-13. Schematic of an ultra capacitor module and individual cell configuration [17].

It is possible to string many super capacitors in a module, hence capable of delivering a vast amount of power. Companies like Honda are investing resources into the development of such units, one of which can be seen in Figure 3-14. Capacitors are an alternate source of energy storage, particularly suited for small hybrids where power requirements are very high, and energy storage needs are quite low.

Figure 3-14. Honda FCV ultra capacitor storage unit [18].

3.5 Fuel Cell and Battery Electric Vehicle Comparison

Much debate surrounds FCV and BEV technology, and which is superior. Under the Bush administration, significant investments were made towards hydrogen fuel cell research. This investment was geared towards the development of hydrogen as a primary source of fuel for cars and trucks. However, since President Obama’s inauguration, interest has shifted back from FCV to BEV as existed under Clinton. The hydrogen fuel cell research budget was reduced from $168 million in 2009 to $68.2 million in 2010 as stated by the U.S. Department of Energy [19]. In Europe, however, car manufacturer and energy companies alike continue to push for FCV to be considered in short term plans for passenger transportation. A recent publication titled "A Portfolio of Power-Trains for Europe: A Fact-Based Analysis" positions FCV as one of three vehicle architectures with the potential to significantly reduce CO_2 emissions over the next decades. According to this report, FCV "*..are the lowest carbon solution for medium/larger cars and longer trips*" while "*..BEVs are ideally suited to smaller cars and shorter trips"*. Though this may be the case on paper, it is far too soon to make such assumptions. The apparent range advantages purported for FCV are meaningless without significant infrastructure investment.

In an attempt to compare current FCV and BEV technology, key specifications of the Tesla Model S EV and the Honda Clarity FCV are shown in Table 3-1.

Table 3-1. Comparison of Tesla Model S BEV, Honda Clarity FCV and Toyota FCV.

	Vehicle Architecture	Power Source	Motor Power (kW)	Estimated Cost	Weight (Kg)	Passenger Volume (cu. ft)	Range**** (miles)
Tesla Model S	BEV	Li-ion cells	185	$49,000*	1,735	<115	160*
Honda Clarity	FCV	V Flow Fuel Cell	100	$600**	1,625	100.8	240
Toyota Highlander	FCHV	Toyota FC Stack	90	$425 ***	1,880	145.7	< 430

* Base price for 160 mile range model. Price for 230 and 300 mile range models not yet published. Price after $7,500 Federal tax credit.

** 3 Year Lease term with Honda with no option to buy. Cost of lease for 3 years is $21,800.

*** 30 month lease with Toyota with no option to buy. Cost of lease for 30 months is approximately $12,750.

**** Advertized maximum range.

The Tesla Model S will be Tesla Motor's second vehicle and is scheduled for release in 2012. The entry level Model S is expected to offer mainstream affordability at half the price of the Tesla Roadster. It is aimed at competing with vehicles in the E-class (full size vehicle) of the BMW 5 Series, the Audi A6, Mercedes-Benz CLS, and Cadillac CTS Sedan.

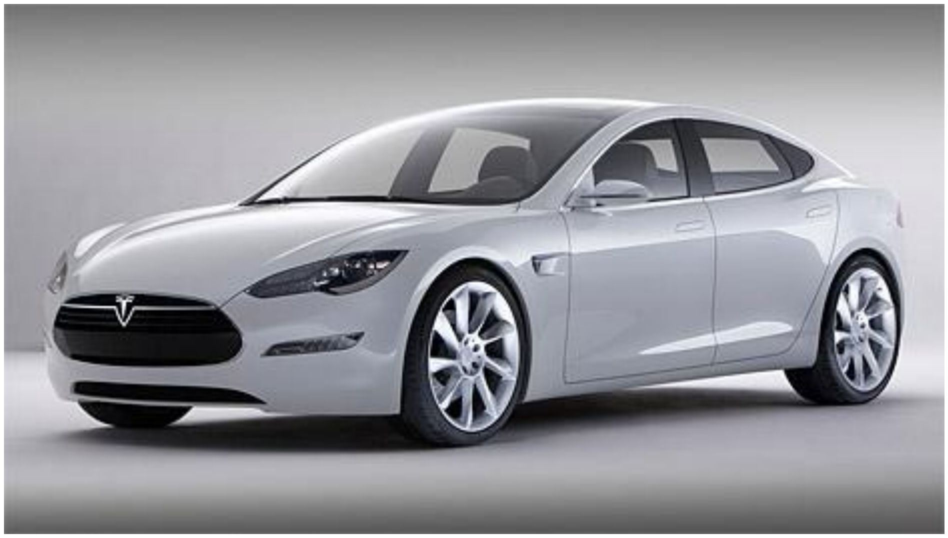


Figure 3-15. Tesla Model S.

The Model S will break the paradigm that BEVs have little or no storage space and offers seats for 5 adults and 2 children plus additional storage space under the hood. The standard battery pack, consisting of 8,000 cells, is expected to have a capacity of approximately 42 kWh and is removable, thus enabling battery swaps. Future packs are slated to have fewer cells as Tesla transitions from widely available small format consumer cells to larger EV cells as they become more affordable. Tesla claims the sedan will accelerate from 0-60 mph in 5.5 seconds and attains a maximum speed of 120 mph. Charge time will ultimately depend on the pack version, initial state of charge and charging level used. For a Level II charging system (220 V at 80 A), it would take approximately 2 hours to charge from 15 % SOC to 90 %.

The Honda Clarity is not available for purchase anywhere in the world. Engineers from Honda in 2005 estimated that their previous FCVs cost over $ 1 million each to build. K.G. Duleep, Managing Director for Transportation, Energy and Environmental

Analysis Inc., conducted a study in 2008 for the U.S. Department of Energy in which the author determined that Honda had cut the Clarity's production cost to between $ 120,000 and $ 140,000 per vehicle (McClatchy, 2007). Honda claims that the Clarity is production-ready, however it will not be sold until an adequate hydrogen infrastructure is in place.

It is difficult to predict whether either of these vehicle architectures will be successfully deployed over the next decade. Nevertheless, all major vehicle manufacturers have unveiled shorter range BEV prototypes in auto shows around the world and many have announced the introduction of commercial models now being sold, or ready for release in the next 2 to 5 years. The fact that only a handful of OEMs have invested enough resources in FCV technology to put working prototypes into circulation gives reason to believe that BEVs will dominate the alternative vehicle technology stage for the next decade.

Chapter 4

Hybrid and Electric Vehicle Greenhouse Gas Emissions and Energy Use Simulation

Government environmental agencies around the world have spent countless resources over the past decades on the development of software tools that aid in lifecycle assessments, as well as greenhouse gas emissions and energy use in transportation. It is of crucial importance to understand the environmental impact of each type of technology, improve the efficiency of energy generation and usage, and lower the dependence on fossil fuels. The results obtained through these tools allow government, industry experts, and researchers to forecast the effects of future hypothetical fleets of different vehicle technology mixes.

4.1 Life Cycle Assessments

According to the U.S. Environmental Protection Agency (EPA), "life cycle assessment (LCA) is a technique for evaluating the potential environmental aspects associated with a product or service by compiling an inventory of relevant inputs and outputs, evaluating the potential environmental impacts associated with those inputs and outputs, and interpreting the results of the inventory and impact phases in relation to the objectives of the study."

LCA begins with the gathering of feedstock materials from the earth and ends when materials are returned to the earth. It evaluates every individual stage throughout a product's life in order to provide an accurate assessment of the environmental trade-offs involved.

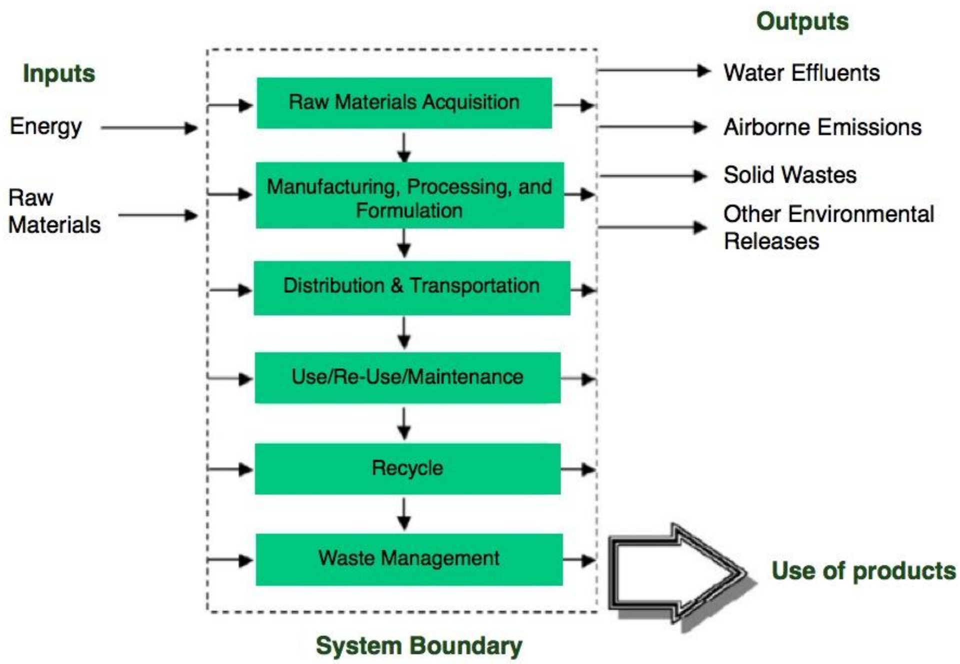


Figure 4-1. Life Cycle Stages [20].

LCAs allow decision makers to investigate a wider range of scenarios to help them select the option that generates the lowest environmental impact. Specifically, in the transportation industry, this tool can be used to understand the impact of different types of vehicle technologies, whether they use petroleum based fuels, biomass, hydrogen, or stored energy in batteries.

Ultimately the accuracy of the results is subject to the availability and accuracy of the input data. It is important that LCAs be utilized as one element in the decision making process, while assessing the trade-offs with performance and cost.

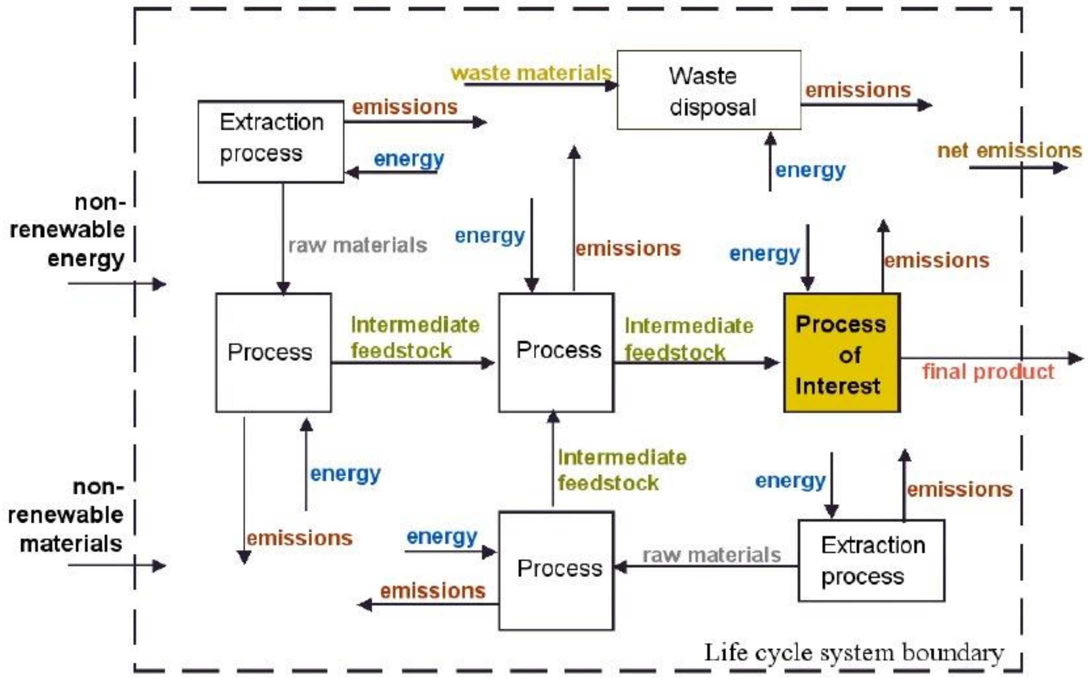


Figure 4-2. Product Life Cycle. [21]

Life cycle assessments consist of 4 distinct phases: [21]

- Goal definition and Scoping - In this phase the product, process or activity being studied must be defined and described. The context in which the assessment is to be made and the boundaries and environmental effects to be reviewed for the assessment should be established.
- Inventory Analysis - All energy, water, materials usage, and environmental release (e.g. air emissions, solid waste disposal, waste-water discharge) must be identified and quantified.
- Impact Assessment - Evaluate the human and ecological impact of energy, water, and material usage and the environmental releases identified in the inventory analysis.

- Interpretation - Study the results of the inventory analysis and impact assessment to select the preferred process, product, or service. It is important to have a clear understanding of the uncertainty and the assumptions used to generate the results.

Due to the volume of data required to perform LCAs and its systematic approach, software tools are typically employed. The US Environmental Protection Agency (EPA) lists 29 tools on their website [21].

This list contains 5 American, 23 European, and one Canadian model. Most of these are open sourced models and available for download. They have been developed and improved over the past 10-20 years and contain predetermined data from their respective region's national energy and statistics agencies. However, some models are flexible and allow users to modify input data to fit their specific needs, execute sensitivity analyses, or even run stochastic models such as Monte Carlo.

The number of transportation LCA tools is more limited. The more prevalent are:

- GHGenius - (Natural Resources Canada);
- GREET - (Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation Model - Argonne National Laboratory);
- LEM - (Lifecycle Emissions Model - Mark Delucchi, UC Davis);
- GEMIS - (Global Emissions Model for Integrated Systems (GEMIS) - Öko Institut (European);
- GaBi - PE International (European);
- SimaPro - PRé Consultants (European).

When performing a lifecycle analysis in transportation, it is often referred to as a well-to-wheel analysis. This type of study is usually split into two phases. The first phase is commonly referred to as well-to-pump and considers all of the processes in the fuel production cycle. Emissions from feedstock recovery and transmission, fuel production, land-use changes from cultivation, fertilizer manufacture, fuel distribution and storage, fuel dispensing, and gas leaks and flares are amongst the most important processes considered in this phase. Typically these emissions are reported in grams of CO_2 equivalent per unit of energy delivered to end users. Unfortunately, likely due to the level of complexity, the emissions and energy use from the construction of hydrogen-based infrastructure to support a large fleet of FCV is not accounted for in the software tools employed in this study. Typically the assumption used is that the infrastructure or factories already exist.

The second phase is known as pump-to-wheel and accounts for the emissions and energy use of the vehicle while operating. Tailpipe emissions in grams of CO_2 equivalent per kilometer driven or per unit of energy of fuel burned, as well as fuel economy, are considered during this stage of the analysis. The following subsections will introduce the three simulation tools that were selected to perform the well-to-wheel analysis of the ten electrified vehicle architectures studied, which will be presented in Chapter 5.

4.1.1 GHGenius

GHGenius is a lifecycle analysis tool developed by Dr. Mark Delucchi. It was originally based on a Lotus 123 spreadsheet model at the University of California in the late 1980's. Later, in 1998, Delucchi incorporated Canadian data. In 1999 Natural Resources Canada requested Levelton Engineering to use the model for the Transportation Table of the National Climate Change Process, and this was when the name GHGenius was first adopted. Since then, over 200 transportation fuel pathways have been added and much more Canadian specific data is now available [21].

GHGenius follows an accepted LCA process and, although it is transportation specific, covers most energy sources and many materials manufacturing processes and land use changes. It contains formidable databases for the U.S. and Canada and allows comparison between both countries for the same processes. [21] For the effect of this study however, GHGenius was used solely for the simulation of the Canadian Provinces of Alberta, Ontario, and Quebec.

4.1.1.1 Model Scope

The model scope covers all processes from the extraction of raw materials, their production, and end use. The lifecycle stages can be divided in:

- Raw Materials Acquisition;
- Feedstock production and recovery;
- Feedstock transmission;
- Fertilizer manufacture;
- Land use changes;
- Leaks and flaring associated with fossil fuels;
- Manufacturing;
- Fuel production;

- Fuel storage and distribution;
- Fuel dispensing;
- Emissions displaced by co-products;
- Vehicle Operation.
- Vehicle materials, assembly and transport

4.1.1.2 Inventory Data

When possible, the model relies on public data. U.S. data stems from the U.S. Census and Department of Energy (DOE), Energy Information Administration (EIA). The data sources for existing processes in Canada are extracted from Statistics Canada, Industry Reports, and GHG Registries (formerly VCR). For processes that are new to Canada, information may come from foreign operating data, engineering studies, and/or basic scientific assessments. By and large, industry averages are used rather than plan specific data [21].

4.1.1.3 Impact Assessment

With GHGenius it is possible to estimate life cycle emissions for primary greenhouse gases, the criteria air contaminants (CAC), and the energy balance. Intergovernmental Panel on Climate Change (IPCC) weighting factors are used as default values for primary GHG: carbon dioxide, methane, nitrous oxide, chlorofluorocarbons, and hydrofluorocarbons. The CACs considered are: carbon monoxide, nitrogen oxides, non-methane organic compounds, sulphur dioxide, and total particulate matter. Energy required per unit of energy produced as well as cost effectiveness in $ per ton of CO_2 displaced for gasoline and diesel engines are possible [21].

4.1.1.4 Interpretation Capabilities*:*

Emissions may be calculated for any years between 1996 and 2050 and are based on historical trends or in some cases electric power and oil forecasts made by institutions such as the National Energy Board (NEB). Results are calculated on a per lifecycle stage and per contaminant basis. The model is currently able to estimate emissions for Canada, U.S., Mexico and India; also regionally for east, central, or western North America. It is possible to analyze some fuel pathways Provincially as well.

4.1.1.5 GHGenius Model Overview

The current version of GHGenius consists of 46 sheets and contains over 230 thousand data and result cells. Compared to GREET, LEM, and GEMIS, GHGenius has many more pathways. It is easier to make changes to those pathways and the model provides much more detailed outputs. Calculations are done on a per unit of energy basis while automatically correcting for volumetric fuel differences. Emissions associated with fuel production and fuel use are calculated and then merged into a single data set. The energy consumption by fuel type for each lifecycle step, as well as the emissions associated with each step, is specified. A more comprehensive explanation of the model's capabilities and programming can be found in Appendix A.

ISO 14000 guidelines for environmental management systems are commonly followed. The model calculates emissions associated with vehicle use and manufacture, and energy use and emissions involved in the manufacture and maintenance of the trucks, tractors, trains, ships, and pipelines employed to make and transport the fuels that feed those vehicles. The energy and emissions involved in the construction of the production plant are not considered in the model as it assumes that the plant is operational.

Figure 4-3 provides a graphic representation of the lifecycle stages that are considered for the estimation of well-to-pump and pump-to-wheels energy use and GHG emissions. The top image represents petroleum based fuels and the bottom image is for ethanol based fuels.

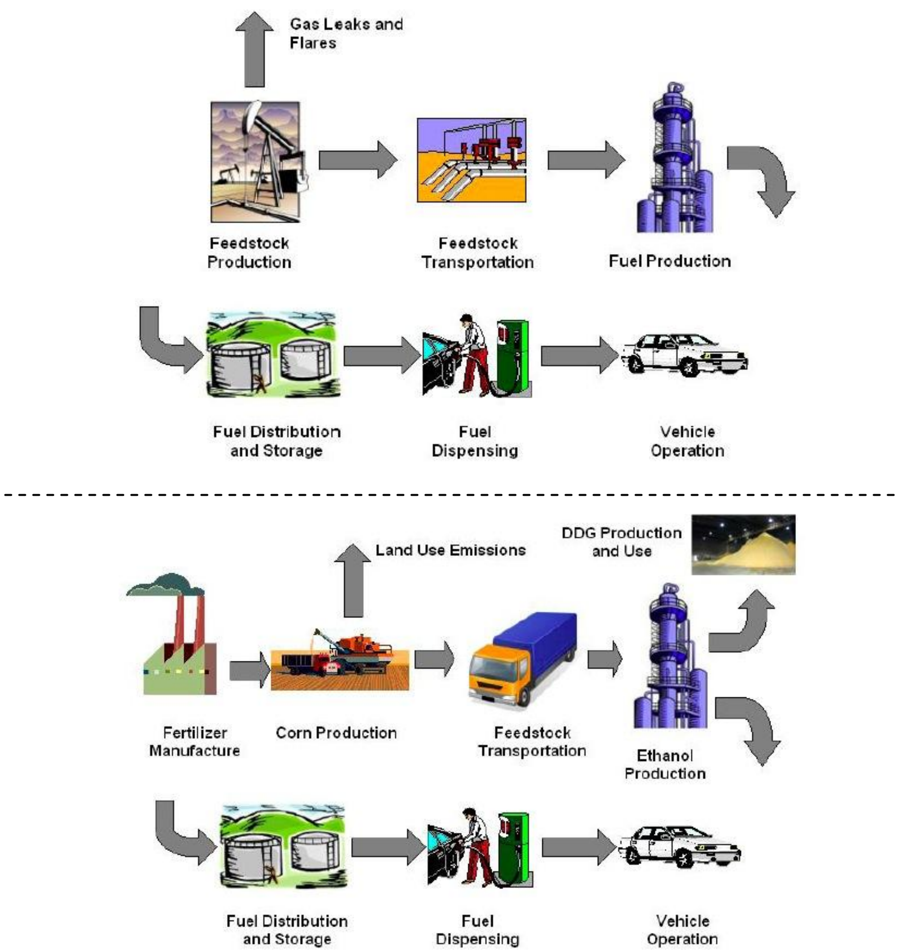


Figure 4-3. Graphic representation of fuel cycles in GHGenius. [21]

Well-to-Pump emissions are expressed in terms of the emissions per Giga Joules of fuel delivered to the nozzle and can be calculated on a basis of the fuel's higher heating value (HHV) or lower heating value (LHV). The American Petroleum Institute (API) defines the lower heating value of a fuel as the amount of heat released by combusting a specified quantity, initially at 25 °C, and returning the temperature of the combustion products to 150 °C. This means that the LHV assumes the water content in the product of the combustion is in vapor state thus the latent heat of vaporization of water in the fuel and the reaction products are not recovered. This value's practicality comes forth when comparing fuels where it is impractical for the condensation of the combustion products to occur, or it is not possible to put to use heat at a temperature under 100 °C. In contrast, the HHV includes the heat of condensation of water in the combustion product. [20] This is important given that comparison between different chemical energy carriers can be based on the true energy content, or the HHV of all the fuels considered.

The criteria emissions for gasoline and diesel powered vehicles uses an algorithm that mimics the results obtained from EPA's Mobile 6.2C model. Mobile 6.2C is the latest release of a vehicle emissions modeling software that is capable of predicting grams per mile emissions of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx), carbon dioxide (CO_2), particulate matter (PM), and other toxics from cars, trucks, and motorcycles under various conditions. [23] GHGenius calculates the emissions over vehicle life based on the average per year emissions provided under Mobile 6.2C. Emissions for alternative fuels are estimated on a relative basis to gasoline and diesel fuel.

GHGenius is capable of modeling both light and heavy duty vehicle architectures including conventional ICE, fuel cell, and battery powered types. Fuel pathways in the model can be indirect, such as natural gas to methanol and then methanol to hydrogen, or direct. Fuel blends, diesel and biodiesels are also available. The model additionally includes fuel pathways for power generation and space heating. [21]

	Coal	Gasoline	Gasoline Lo S	Diesel	Fuel Oil	Still Gas	LPG	Coke	FT Distillate	HRD	NG	Hydrogen	Methanol	Ethanol	Butanol	Biodiesel	DME	Mixed Alcohols	Electricity
Coal	X								X		X	X	X						X
Crude Oil		X	X	X	X	X	X	X				X							X
Natural Gas							X		X		X	X	X				X	X	X
Uranium												X							X
Electricity												X							
Wood									X		X	X	X	X				X	X
Corn Stover											X	X	X	X					
Wheat Straw														X					
Switchgrass														X					
Hay														X					
Manure											X								
Corn												X		X	X				
Wheat												X		X					
Barley														X					
Peas														X					
Sugarcane														X					
Sugar beets														X					
Canola										X						X			
Soybeans										X						X			
Palm										X						X			
Tallow										X						X			
Yellow Grease										X						X			
Fish Oil										X						X			
Algae										X						X			
Jatropha										X						X			
RDF									X									X	
LFG												X	X						
Used Oil					X														

Figure 4-4. Fuel pathways in GHGenius. Vertical list represents feedstock. Top horizontal row lists fuel produced using each feedstock. [21]

By default, gasoline and diesel are the baseline fuels for which four types of crude oil are considered in their production: Onshore and offshore conventional oil, conventional heavy oil, bitumen, and synthetic. Due to the fact that more than half of the crude oil that is refined in Canada is imported (from Algeria and Norway), some data is taken from international sources. The sulphur content of each fuel can be set by the model, or by the user.

For ICE light duty vehicles the user can select from the following list of fuels:

- Gasoline (conventional and low sulphur);
- Diesel (low sulphur and ultra low sulphur);
- Liquefied Petroleum Gas (LPG - refinery or field source);
- Natural Gas (CNG - Compressed Natural Gas and LNG Liquefied Natural Gas from fossil or biomass);
- Hydrogen (SMR - Steam Methane Reforming or electrolysis).

Gasoline and diesel powered hybrid vehicles and plug in hybrids are also considered in the model. Power from the grid used for battery powered vehicles is modeled Provincially; national and regional power mixes are also available. For fuel cell powered vehicles, 13 hydrogen pathways are available: 3 methanol, 7 ethanol, liquefied petroleum gas (LPG), gasoline or Fisher Tropsch (FT) distillate reformed onboard. For this study, however, hydrogen is assumed to be produced mainly through steam methane and natural gas reforming.

Light duty vehicle fuels include the following blends:

Gasoline:

- Ethanol Gasoline (Low level such as E15 and high level such as E85). Eight feedstock families are available;
- Butanol gasoline (Low and high level);
- Methanol gasoline (Low and high level). Four feedstocks;
- Mixed alcohols (Low and high level). Three feedstocks.

Biodiesel:

- Eight feedstocks.

Hythane (Hydrogen and Natural Gas):

- Two hydrogen sources.

In the case of heavy duty ICE vehicles they can be analyzed combined or separate and the following fuels are available:

Pure Diesel and Diesel blends (0 to 100 % blends)

- FT Distillate. Four feedstocks;
- Biodiesel. Eight feedstocks;
- E-Diesel (Oxygenated diesel, 15 % ethanol). Eight feedstocks;
- Mixed alcohols. Three feedstocks;
- Hydrogenated Renewable Diesel. Eight feedstocks;
- FT Distillate. Three feedstocks.

LPG. Two feedstocks.

Natural Gas (methane) (CNG, LNG, fossil and biomass).

- Dimethyl Ether (DME).
- Hydrogen. Two feedstocks.
- Ethanol. Eight feedstock families.
- Butanol.

- Methanol. Four feedstocks.
- Mixed alcohol. Two feedstocks.
- Hydrogenated Renewable Diesel (HRD). Eight feedstocks.

Heavy Duty (HD) fuel cell vehicles with the following fuel pathways:

- Methanol reformed on board. Three feedstocks;
- All 10 of the hydrogen pathways.

The GHGenius Input Page contains data for vehicle energy use. Three default fuel economy values are available for Canada, U.S., Mexico, and India. Fuel consumption for light duty gasoline vehicles (LDGV), light duty diesel vehicles (LDDV), heavy duty gasoline vehicles (HDGV), and heavy duty diesel vehicles (HDDV) is also included. The user can set different city and highway fuel economies by entering new assumptions. This, however, limits the user to a specific set of vehicle technologies and does not allow simulating more precise vehicle configurations. For this reason, GHGenius was only used for its well-to-pump capabilities and a separate program was employed to simulate the vehicle powertrains selected for this study.

In Sheet D, Figure 4-5, the user can specify parameters for the regional production of electricity, efficiency and types of fuel used. For Canada only, individual Provinces or regions may be selected. Additional yellow cells for EV's in regions other than Canada are also contained in this sheet.

ELECTRICITY GENERATION: EFFICIENCY, AND TYPES OF FUEL USED											
NET EFFICIENCY OF ELECTRICITY GENERATION, YEAR 2009											
	Coal	Oil	Gas Boiler	Gas Turbine	Nuclear	Wind	Other Carbon	Biomass	Hydro	Other	
Looked-up net efficiency-->	0.33	0.34	0.36	0.45	0.35	1.00	0.39	0.27	1.00	1.00	
SOURCE OF ELECTRICITY, BY TYPE OF GENERATING PLANT, FOR VARIOUS PROCESSES, YEAR 2009											
	Coal	Oil	Gas Boiler	Gas Turbine	Nuclear	Wind	Other Carbon	Biomass	Hydro	Other	Fossil
Recharging EVs	0.11	0.01	0.09	0.00	0.14	0.02	0.00	0.02	0.61	0.00	
Oil refining and NGL plants	0.20	0.02	0.13	0.00	0.16	0.02	0.00	0.02	0.45	0.00	0.34
Oil production and NGL plants	0.57	0.01	0.29	0.00	0.00	0.03	0.00	0.02	0.08	0.00	0.87
LDV manufacture	0.18	0.04	0.11	0.02	0.44	0.01	0.00	0.01	0.18	0.00	
HDV manufacture	0.18	0.04	0.11	0.02	0.44	0.01	0.00	0.01	0.18	0.00	
Uranium enrichment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	
Starch/ethanol plant	0.14	0.01	0.11	0.00	0.22	0.02	0.00	0.02	0.49	0.00	0.26
Wood/ethanol plant	0.15	0.01	0.11	0.00	0.27	0.02	0.00	0.02	0.42	0.00	0.28
Wheat ethanol plant	0.19	0.01	0.12	0.00	0.14	0.02	0.00	0.01	0.50	0.00	0.32
Aluminum Production	0.03	0.01	0.02	0.01	0.04	0.00	0.00	0.00	0.89	0.00	
Compression of natural gas	0.12	0.02	0.09	0.00	0.12	0.02	0.00	0.02	0.62	0.00	
Compression or liquefaction of hydrogen	0.12	0.02	0.09	0.00	0.12	0.02	0.00	0.02	0.62	0.00	
Water electrolysis	0.12	0.02	0.09	0.00	0.12	0.02	0.00	0.02	0.62	0.00	
Rail Transit	0.12	0.02	0.09	0.00	0.12	0.02	0.00	0.02	0.62	0.00	
Looked-up average power*	0.12	0.02	0.09	0.00	0.12	0.02	0.00	0.02	0.62	0.00	0.23
Adjustments, renewable scenario	0.70	0.50	0.90	0.90	1.00	1.00	1.00	5.00	1.20		
EVs, intermediate result:	0.37	0.04	0.27	0.00	0.15	0.02	0.00	0.07	0.66	0.00	

Figure 4-5. Efficiency of Canadian electricity generation and types of fuels used. [Retrieved from GHGenius Excel spreadsheet]

Regional energy production from 1990 through 2031 for each fuel type can be found for Canada. Provincial power generation and split per fuel type, is preset to the values presented in Figure 4-6.

REGIONAL POWER FOR EVs								
Canada	Coal	Oil	Gas Boiler	Gas Turbine	Nuclear	Wind	Biomass	Hydro
Atlantic	0.15	0.05	0.05	0.00	0.05	0.02	0.02	0.67
Quebec	0.00	0.01	0.02	0.00	0.00	0.01	0.01	0.94
Ontario	0.08	0.00	0.12	0.00	0.53	0.02	0.01	0.24
Manitoba	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.97
Saskatchewan	0.50	0.00	0.25	0.00	0.00	0.03	0.00	0.22
Alberta	0.59	0.02	0.31	0.00	0.00	0.03	0.03	0.03
BC/Yukon	0.00	0.00	0.04	0.00	0.00	0.01	0.06	0.90
Canada	0.11	0.01	0.09	0.00	0.14	0.02	0.02	0.61

Figure 4-6. Canadian regional power generation split used by GHGenius to estimate EV indirect emissions. [Retrieved from GHGenius Excel spreadsheet]

4.1.2 Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) Model

The Greenhouse Gases, Regulated Emissions and Energy Use in Transportation Model, known as GREET, is a full life cycle model that was developed by Argonne National Laboratory and sponsored by the U.S. Department of Energy's Office of Energy

Efficiency and Renewable Energy (EERE). This simulation tool was used to obtain well-to-pump data for three U.S. regions: Northeastern U.S., California and the average U.S. mix.

4.1.2.1 GREET Model Overview

The latest version of GREET consists of 30 Microsoft Excel sheets, each of which are thoroughly explained in a downloadable user manual from the ANL website. GREET has been used to evaluate various engine and fuel systems for the U.S. Department of Energy, other government agencies, and industry.

The results obtained through GREET are affected by assumptions taken at different points in the data gathering process. For the well-to-pump portion, energy efficiencies of fuel production activities and the associated GHG emissions, as well as the emission factors of fuel combustion technologies, directly impact results. For the pump-to-wheel stage, assumptions of the associated fuel economy for each vehicle technology, as well as their tailpipe emissions, influence results. It is important to note that GREET's capability for performing stochastic simulations increments the uncertainties that exist in these assumptions. Further details on GREET can be found in Appendix B.

4.1.2.2 Model Scope

The model allows researchers and analysts to evaluate a variety of vehicle and fuel combinations on a full fuel and vehicle-cycle basis. Figure 4-7 illustrates the Well-to-Wheel logic flow in the fuel cycle (GREET 1 series), the vehicle manufacturing cycle (GREET 2 series), pump-to-wheels, and final recycling or scraping of a vehicle.

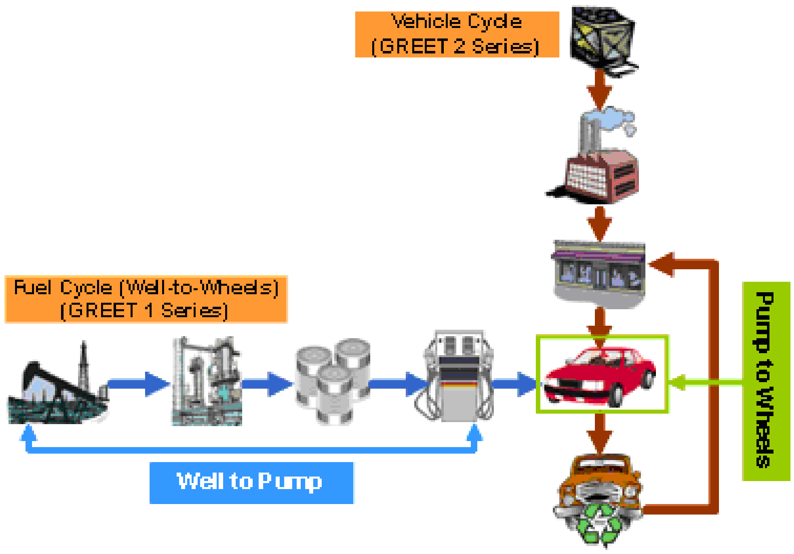


Figure 4-7. Graphic representation of logic followed by GREET for Well-to-Pump and Pump-to-Wheels cycles. [24]

GREET was developed as a multidimensional spreadsheet model in Microsoft Excel. It is open source software and available free of charge. The original version of GREET was released in 1996 and has since been updated and expanded. The most recent GREET versions publicly available are 1.8.d.0 for fuel-cycle analysis and version 2.7 version for vehicle-cycle analysis.

4.1.2.3 Inventory Data

GREET relies on a variety of data sources. For well-to-pump data, open literature engineering analysis (such as ASPEN simulations for mass and energy balance), and stakeholder inputs (e.g. collaboration with the energy industry) are used. Pump-to-wheel data sources include Argonne's own Powertrain System Analysis Toolkit (PSAT), EPA's Mobile 6 model, California Air Resources Board's (CARB) Emissions Factors model (EMFAC), as well as open literature. [25]

4.1.2.4 Impact Assessment

For a given vehicle and fuel system, GREET separately calculates the following:

- Consumption of total non-renewable and renewable energy sources, combined fossil fuels (petroleum, natural gas, and coal together), and petroleum, coal and natural gas separately;
- Emissions of CO_2-equivalent greenhouse gases - primarily, methane (CH_4), and nitrous oxide (N_2O);
- Emissions of six criteria pollutants: volatile organic compounds (VOCs), carbon monoxide (CO), nitrogen oxides (NO_x), particulate matter with size smaller than 10 micron (PM10), particulate matter with size smaller than 2.5 micron (PM2.5), and sulfur oxides (SO_x).

4.1.2.5 Interpretation Capabilities

GREET includes more than 100 fuel production pathways and more than 70 vehicle/fuel systems. Version 1.8b introduced new fuel production pathways such as Brazilian sugarcane ethanol, corn to butanol, soybeans to renewable diesel via hydrogenation, coal/biomass co-feeding for Fischer Tropsch (FT) diesel production, and various corn ethanol plant types with different process fuels. [24] Petroleum refining energy efficiencies were also revised and three methods for dealing with co-products for soybean-based biodiesel were included. General fuel production pathways are shown in Figure 4-8:

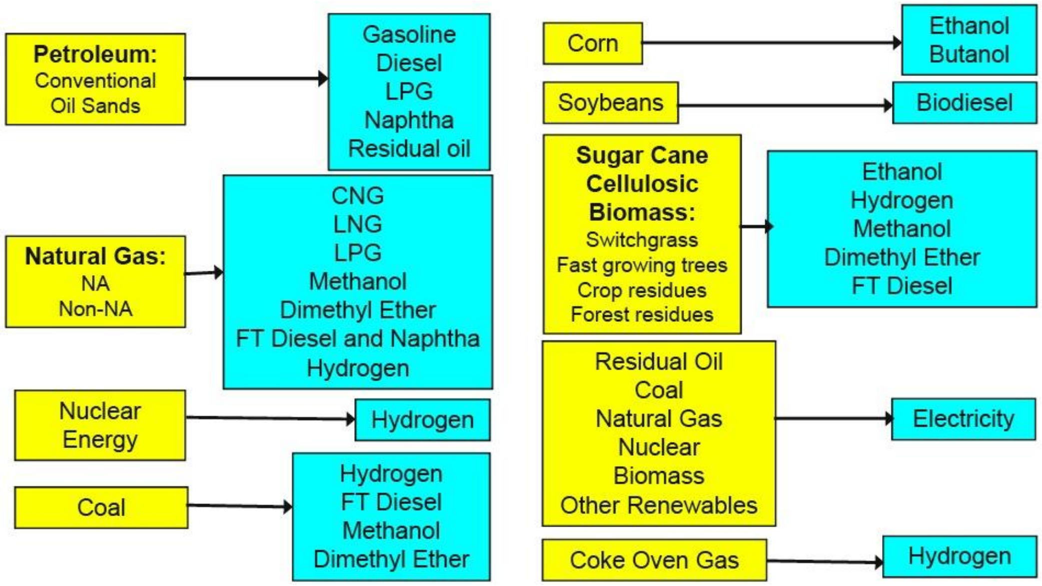


Figure 4-8. GREET Fuel production pathways and energy feedstocks. [24]

GREET includes more than 75 vehicle/fuel systems. Basic vehicle architectures covered are listed below:

- Conventional spark-ignition engines;
- Direct-injection, spark-ignition engines;
- Direct injection, compression-ignition engines;
- Grid-independent hybrid electric vehicles;
- Grid-connected (or plug-in) hybrid electric vehicles;
- Battery-powered electric vehicles;
- Fuel-cell vehicles.

To address technology improvements over time, GREET simulates fuel production pathways and vehicle systems over a period from 1990 to 2020, in five-year intervals.

4.2 Powertrain System Analysis Toolkit (PSAT)

The Powertrain System Analysis Toolkit began development in 1999 as a collaborative effort between Argonne National Laboratory, General Motors, Ford, and Daimler Chrysler. Today it is widely used in industry and academia with over 130 licenses issued to companies, universities and research labs.

PSAT enables researchers to simulate advanced technology vehicles in order to obtain emissions and energy use data. The drivetrain configurations supported by the program are:

- Conventional;
- Fuel Cell Only, Series Fuel Cell Hybrid, Fuel Cell PHEV;
- Electric;
- Parallel Hybrid;
- Series Hybrid;
- Split, Series-Parallel.

Users may select from a broad range of components which will depend on the drivetrain previously selected. Each component is emulated by a Simulink model and may be modified according to requirements. Additionally, some component models include a scaling file which allows the user to linearly scale the component size. This is particularly useful to upscale or downscale fuel cells, engines, and electric motors to meet specific design criteria. Different control strategies can also be selected which will govern various aspects of the vehicle operation including the state of charge window, when the vehicle will operate in charge depleting mode and charge sustaining mode, and regenerative braking level.

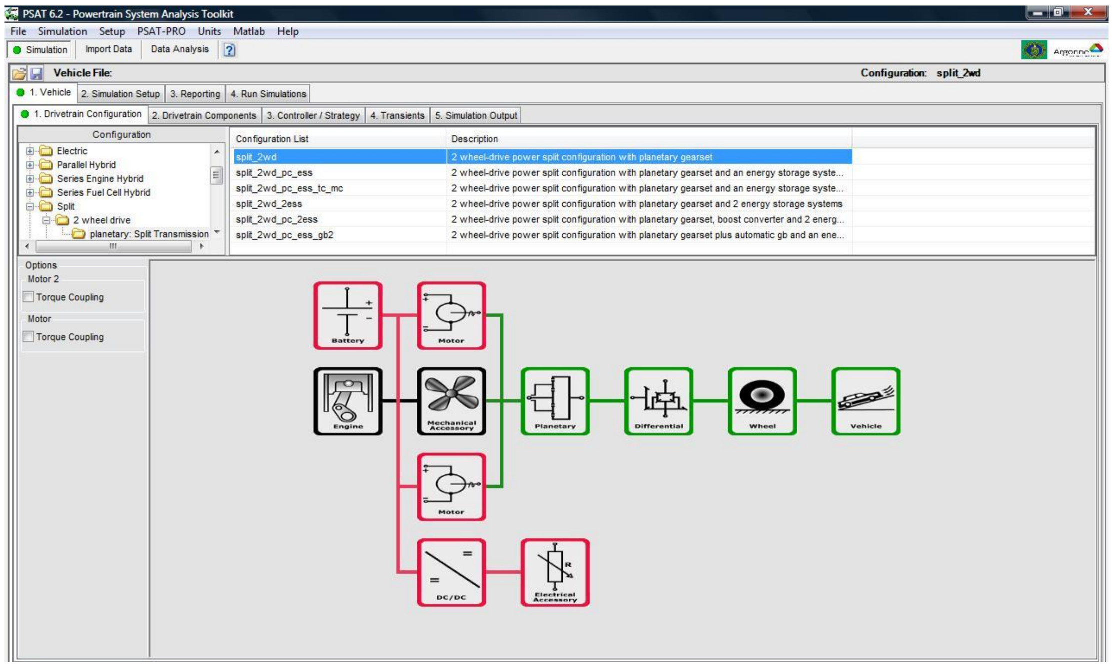


Figure 4-9. PSAT Screenshot - Split Drivetrain Diagram.

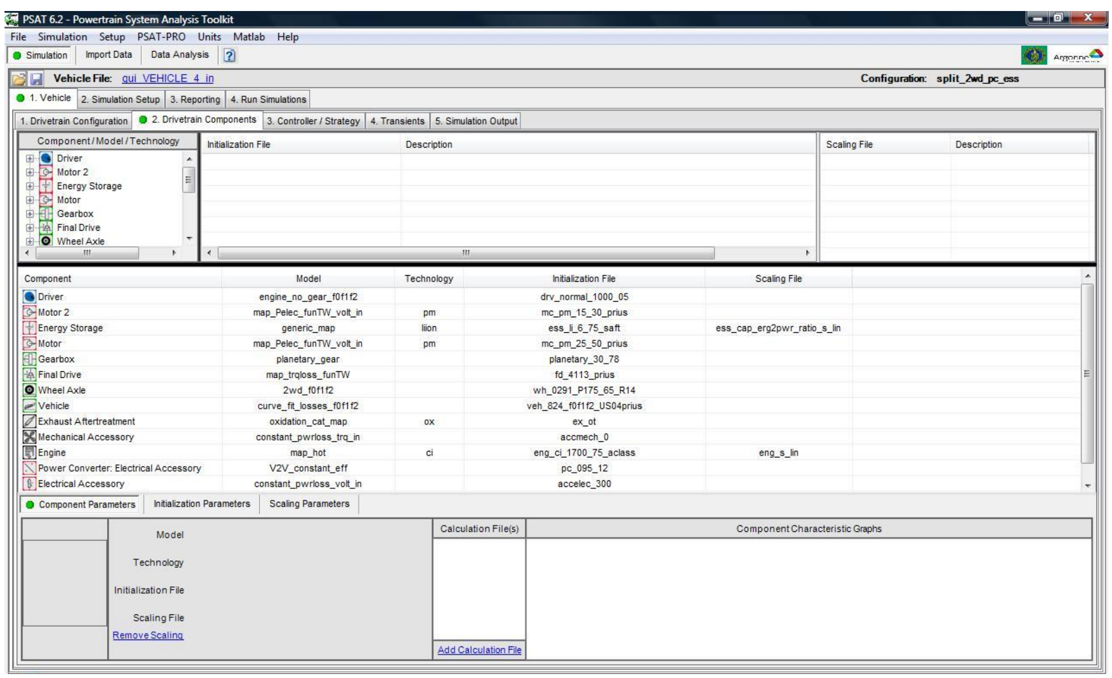


Figure 4-10. Drivetrain component selection screen.

PSAT's simulation capabilities allow users to test vehicles through standard drive schedule procedures or execute performance simulations such as acceleration, gradeability and coast down. The results allow the user to observe energy use, mile per gallon (gasoline equivalent) fuel economy, initial and final state of charge in the case of electrified vehicles, fuel mass used, and energy balance data as well as the generation of custom graphs to highlight particular aspects of the vehicle architecture being analyzed.

Chapter 5

Well-to-Wheel Simulation for Hybrid and Electric Vehicles

5.1 Introduction

As stated in previous chapters, the purpose of this work is to understand the environmental implications of introducing different electrified vehicle technologies as being developed by the automotive industry. The ten vehicle configurations and five fuels considered for this study are amongst many technologies currently being characterized by researchers, industry, and governments around the world. By no means is it implied that these architectures should be considered the best or only solutions to reduce GHG emissions and lower energy consumption levels. Nevertheless, they were selected to fulfill the purpose of this study which is to provide evidence that a particular mix of vehicle technologies may have a better optimized regional impact depending on how energy is produced. The following vehicle architectures and fuels were considered:

- 4 Powertrain Configurations: Power Split PHEV, EREV, Battery Electric Vehicle (BEV), and Fuel Cell Vehicle (FCV).
- 5 Fuels: Gasoline, E85 (85 % ethanol, 15 % gasoline mix), low-sulfur diesel, B20 (20 % Biodiesel, 80 % low sulphur diesel), and hydrogen gas.

Table 5-1. Vehicle Architectures Selected for Simulation

Vehicle #	Architecture	Fuel 1	Fuel 2
1	Power Split PHEV	Gasoline	Electricity
2		E85	Electricity
3		Diesel	Electricity
4		Biodiesel	Electricity
5	EREV	Gasoline	Electricity
6		E85	Electricity
7		Diesel	Electricity
8		Biodiesel	Electricity
9	FCV	Hydrogen gas	Electricity
10	BEV	Electricity	-

The vehicle platform selected to model the hybrid and electric vehicle architectures evaluated in this study can be classified as "compact car". The drag coefficient, frontal area, and tire characteristics of a Toyota Prius were used for each powertrain and fuel configuration. The same chassis (roller) was used for all architectures modeled.

It is important to note that the architectures considered for this study can be implemented in any vehicle class. Although larger vehicles would be capable of accommodating more batteries, thus improving their range capability, it is likely that high battery prices will make smaller vehicles more commercially viable. Recent reports project battery pack prices in 2020 to be in the range of $ 300 - $ 400 per kWh. [26, 27, 38] This would translate into an estimated cost from $ 3,500 for a small PHEV Energy Storage System (ESS) to $ 10,000 for a larger fully electric vehicle ESS. Simulating a compact sized hybrid, electric, or fuel cell vehicle seemed to be a reasonable approach given that they will most likely constitute the center of the market.

5.2 Well-to-Pump Results

Upstream emissions were obtained for the year 2020 using the five fuels chosen in this study. GHGenius was employed to calculate the grams of CO_2 equivalent emissions per kWh for each fuel in the three Canadian Provinces studied. Fuelcycle emissions were taken from the "Upstream Results HHV" tab. The results for each of the fuels are arranged in columns. Emissions from fuel dispensing, fuel distribution and storage, fuel production, feedstock transmission, feedstock recovery, land-use changes, fertilizer manufacture, and gas leaks and flares are summed. If any emissions are displaced during the production of a specific fuel, these are subtracted from the final value. The results obtained for the Provinces of Alberta, Ontario, and Quebec are summarized in Table 5-2.

Table 5-2. Well-to-Pump Emissions for Canadian Provinces (GHGenius).

WTP GHG grCO$_2$eq/kWh	Alberta	Ontario	Quebec	Canada
Gasoline	100.8	84.3	77.3	82.5
E85	160.8	129.4	117.3	127.8
Diesel	88.8	70.9	68.6	74.0
B20	76.6	60.0	57.6	62.4
Electricity	750.8	142.2	37.2	174.5
H_2 Gas	454.3	342.5	323.2	349.9

For the U.S. Regions the GREET 1.8d excel file was used. Data was taken from each fuel's energy and emissions summary table. GHG emissions values in GREET are given in grams of CO_2 equivalent per mmBtu (10^6 Btu). These values were converted to grams of CO_2 equivalent emissions per kWh of fuel available. The results for the average U.S. mix, Northeastern U.S., and California can be seen in Table 5-3.

Table 5-3. Well-to-Pump Results for U.S. Regions (GREET).

WTP GHG $grCO_2eq/kWh$	U.S. Mix	NE US	California
Gasoline	68.3	64.8	56.9
E85	185.2	174.2	170.9
Diesel	60.8	57.7	51.6
B20	46.8	39.2	33.3
Electricity	679.2	377.6	317.4
H_2 Gas	348.0	323.2	318.3

Notable differences can be seen across regions for each fuel, which suggests that the hypothesis of certain vehicle technologies holding widely varying environmental implications is correct. One of the most important energy carriers, electricity, has a very broad range of WTP GHG emissions. In the Canadian Province of Quebec, electricity generation results in 37.2 grams of CO_2, whereas the Northeastern U.S. shows a value over 10 times higher (377.6), and Alberta over 20 times higher (750.8). Other fuels, such as hydrogen gas, show more consistent values in the range of 300 to 450 grams of CO_2 emissions per kWh.

5.2.1 Net Efficiency Ratio

In order to determine the total upstream energy use it was necessary to obtain the net efficiency ratio of energy production in each region. This ratio represents the amount of energy required to be put into a production process versus the amount of energy available to end consumers. Table 5-4 shows the NER for electricity generation in the Canadian Provinces considered for this study.

Table 5-4. Net Energy Ratio for electricity generation in Canada. Source: GHGenius

	Coal	Oil	Gas boiler	Nuclear	Wind	Biomass	Hydro	
ALBERTA	**Coal**	**Oil**	**Gas boiler**	**Nuclear**	**Wind**	**Biomass**	**Hydro**	
% of Generation	0.390	0.050	0.330	0.100	0.070	0.030	0.030	
Net Efficiency	0.330	0.320	0.370	0.350	1.000	0.260	1.000	**NER**
	0.129	0.016	0.122	0.035	0.070	0.008	0.030	**0.410**
ONTARIO	**Coal**	**Oil**	**Gas boiler**	**Nuclear**	**Wind**	**Biomass**	**Hydro**	
% of Generation	0.000	0.000	0.238	0.465	0.043	0.045	0.209	
Net Efficiency	0.329	0.309	0.368	0.350	1.000	0.246	1.000	**NER**
	0.000	0.000	0.088	0.163	0.043	0.011	0.209	**0.513**
QUEBEC	**Coal**	**Oil**	**Gas boiler**	**Nuclear**	**Wind**	**Biomass**	**Hydro**	
% of Generation	0.000	0.009	0.021	0.020	0.050	0.014	0.886	
Net Efficiency	0.340	0.319	0.386	0.350	1.000	0.340	1.000	**NER**
	0.000	0.003	0.008	0.007	0.050	0.005	0.886	**0.959**
CANADA	**Coal**	**Oil**	**Gas boiler**	**Nuclear**	**Wind**	**Biomass**	**Hydro**	
% of Generation	0.068	0.011	0.117	0.145	0.046	0.033	0.580603	
Net Efficiency	0.340	0.319	0.386	0.350	1.000	0.340	1.000	**NER**
	0.023	0.003	0.045	0.051	0.046	0.011	0.581	**0.760**

The NER for electricity generation was calculated using data from GHGenius and GREET. The adjusted PTW combined cycle energy use (CC_{EU}) from Table 5-14 (to be presented subsequently), was then divided by each region's NER as well as the charging efficiency (η_C) and the electricity distribution efficiency (η_D)in order to obtain the total PTW energy use. A battery charger efficiency of 90 % and an electricity distribution efficiency of 92 % were assumed.

$$Total\ PTW_{EU} = \frac{CC_{EU}}{NER \times \eta_C \times \eta_D} \qquad (1)$$

5.3 Pump-to-Wheel Results

In order to simulate vehicle configurations, the individual components of each of these architectures must be carefully selected in PSAT. The models representing vehicle components can be modified according to the needs of the user. The following subsections describe how these components were selected and the assumptions that were made during this process.

5.3.1 Engines and Storage

Conventional gasoline and diesel engines were selected for the split parallel/series drivetrains as these were available in model form. In order to simulate the use of E85 and B20 in these engines, the MATLAB code for the corresponding engine was modified. Lower heating values (LHV), carbon ratio, and fuel density values for E85 and B20 were extracted from GHGenius and used in PSAT. For the E85 Power Split PHEV, a Honda Insight gasoline engine model was selected. The data for this 1 L, 55 kW engine was originally derived at ANL's Advanced Powertrain Research Facility (APRF) and collected by measuring wheel torque. For the diesel version of the Power Split PHEV and the EREV, a 1.7 liter, 4 cylinder engine model was selected. The model was scaled down to either a 1.0 L or 1.3 L, capable of delivering 55 kW and 57 kW respectively. Table 5-5 highlights the engine assumptions for each fuel and powertrain technology used.

Table 5-5. Main Engine Assumptions

	Split PHEV Gasoline/E85	Split PHEV Diesel/B20	EREV Gasoline/E85	EREV Diesel/B20
Cylinders	4	4	4	4
Displacement (cc)	1497	1290	1000	1000
Power (kW)	57	57	55	55
Engine Mass (Kg)	108	80	55	65
Peak Efficiency (%)	34.4	40.5	36.2	40.5

The capacity of each vehicle's energy storage systems (ESS) was determined according to expected average all-electric range (AER) for the respective vehicle technologies by 2020. The Toyota Prius PHEV, Chevy Volt, and Nissan Leaf were used as present day benchmarks for ESS sizing and energy consumption. Their energy storage system capacity, usable energy and advertised all-electric range in miles can be seen in Table 5-6.

Table 5-6. Commercial vehicles used as benchmarks.

Make	Model	Powertrain - AER in miles	ESS Capacity (kWh)	Usable Energy (kWh)	Manufacturer AER (km)	EPA AER (km)
Toyota	Prius PHEV	Power-Split PHEV-12	3.5	2.1	23.5	TBT*
Chevrolet	Volt	EREV- 40	16	10.4	64	56
Nissan	Leaf	BEV-100	24	19.2	160	117

* TBT: To be tested. Expected release MY 2012.

Lithium-ion energy storage system models were used for every vehicle simulated. The Li-ion models were based on the SAFT 6 Ah and 14 Ah cells, with 75 either or 96 cells in series respectively, and various numbers of modules in parallel depending on the architecture being evaluated. In some cases cell capacity was modified using a scaling algorithm. A mass packaging factor of 1.25 was instigated for all architectures. Table 5-7 contains more detailed information on each ESS such as state-of-charge (SOC) window, battery pack capacity and total vehicle mass.

Table 5-7. Energy Storage System Assumptions

	Power-Split PHEV		EREV		FCV	BEV
Vehicle	1 2	3 4	5 6	7 8	9	10
# of Cells	150	150	207	207	42	550
Nominal Cell Voltage (V)	3.6	3.6	3.6	3.6	3.6	3.6
Min SOC (%)	30	30	25	25	25	10
Max SOC (%)	90	90	90	90	90	95
Cells in Series	75	75	69	69	42	110
Modules in Parallel	2	2	3	3	1	5
Cell Capacity (Ah)	14	14	20	20	20	20
Total Pack Energy (kWh)	7.6	7.6	14.9	14.9	3.0	39.6
Usable Pack Energy (kWh)	4.536	4.536	9.688	9.688	1.966	33.660
Vehicle Mass						
Vehicle Body Mass	824	824	824	824	824	824
Powertrain Mass (Kg)	520	529	575	577	749	301
Pack Mass (Kg)	104	104	143	143	29	380
Curb Vehicle Weight (Kg)	1,448	1,457	1,542	1,544	1,602	1,505
LVW* (as simulated) (Kg)	1,584	1,593	1,678	1,680	1,738	1,641

* Loaded Vehicle Weight = curb weight + 136 Kg (300 lbs, as required by EPA)

Fuel characteristics data was taken from Sheet E of the Excel based GHGenius model. The "Fuel Characteristics" input/active data" table beginning on row 87 provided the data for E85 and B20 which was used to modify the MATLAB code; the LHV data employed can be seen in Table 5-8.

Table 5-8. Main fuel characteristics. Source: GHGenius

Fuel	Density (kg/L)	LHV (MJ/kg)	Carbon Ratio
E85	0.7442	42.2	0.826
B20	0.884	37.4	0.770

5.3.1.1 Fuel Cell Systems

The fuel cell system model used was developed by Dr. Romesh Kumar of Argonne National Laboratory (PSAT v6.2). The original fuel cell model is capable of delivering a continuous output of 50 kW and uses gaseous hydrogen as fuel. The associated scaling file allowed increasing the peak power output to 100 kW at a maximum efficiency of 59.5 %. Losses associated to transient operating conditions are not taken into account by PSAT. Figure 5-1 shows the steady state fuel cell system efficiency versus the total system power in hot and cold operation. An onboard tank weighing 75 Kg was assumed as the hydrogen storage system with a storage capacity of 3 kg of gaseous H_2.

Table 5-9. Main Fuel Cell Assumptions.

Rated Peak Power (kW)	100
Specific Power (W/kg)	625
Peak Efficiency (%)	59.5
Fuel Tank Mass (kg)	75
Initial Fuel Mass (kg)	3

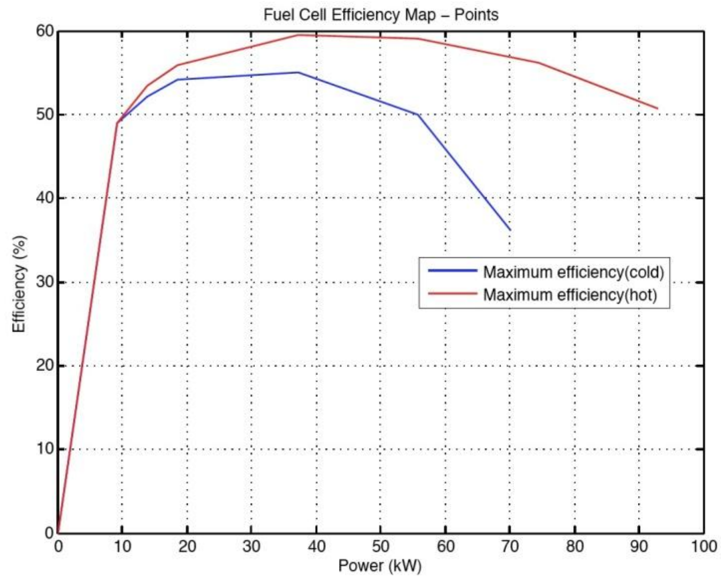


Figure 5-1. Fuel Cell System Efficiency versus Fuel Cell System Power under cold and hot operation. Source: PSAT

5.3.1.2 Electric Machines

Vehicles utilizing a power split device were simulated using two permanent magnet motors: one rated at 50 kW and the other at 30 kW. These models correspond to the motors used in the MY04 Toyota Prius. No scaling algorithm was employed and the motors' 96 % efficiency was maintained. For the EREV, FCV, and BEV a 100 kW (peak power) permanent magnet electric machine model from UQM Technologies was scaled at 94 % peak efficiency. Table 5-10 lists the main assumptions for the selected motors.

Table 5-10. Electric Machine Main Assumptions

	Power-Split PHEV				EREV				FCV	BEV
Fuel/Chemistry	Gasoline/ Li-ion	E85/ Li-ion	Diesel/ Li-ion	B20/ Li-ion	Gasoline/ Li-ion	E85/ Li-ion	Diesel/ Li-ion	B20/ Li-ion	H_2 / Li-ion	Li-ion
Motor Model Used	MY04 Prius motors M1/M2				UQM PowerPhase100					
Rated Peak Power (kW)	50/30				110				110	110
Specific Power (W/kg)	1,430/1,500				1,467				1,467	1,467
Peak Efficiency (%)	96				94				94	94
Motor Mass (Kg)	30/15				65				65	65
Controller Mass (Kg)	5/5				10				10	10

5.3.2 Transmission

To simulate the power split vehicles a planetary gearset with a ratio of 2.3:1 was selected based on the torque efficiency map. A final drive with a ratio of 3.267:1 provided an overall reduction of 7.514:1. The two electric machines are mechanically linked to the planetary gearset and are capable of driving the vehicle in all electric mode (at lower speeds and when the SOC is above 30 %). Assist from the combustion engine occurs during normal driving and acceleration, converting mechanical energy to electric and maintain the battery state-of-charge.

The EREV, FCV, and BEV all use a single gear transmission, with a second reduction ratio at the final drive. The ratio at the torque coupling to the motor is 2.5:1 for the EREV, FCV and BEV. The final drive ratio is 3.208:1 for an overall reduction of 8.02:1. Table 5-11 lists the transmission assumptions.

Table 5-11. Transmission Main Assumptions

	Power-Split PHEV	EREV	FCV	BEV
Transmission Type	Planetary	-	-	-
Torque Coupling Motor	-	2.5	2.5	2.5
Gearbox Ratio	2.3:1	-	-	-
Final Drive	3.267	3.208	3.208	3.208
Overall Ratio	7.514	8.020	8.020	8.020

5.3.3 Vehicle

According to the 2009 Canadian Vehicle Survey, over 95 % of the vehicles on Canadian roads fall under the light vehicle category (< 4.5 tonnes). The same source states that out of the approximately 300 billion vehicle-kilometers traveled in 2009, 52 % were done in passenger cars, and 96 % of these were powered by a gasoline engine [28].

For this study, the light vehicle category selected for all simulations was the compact sized vehicle, according to American and Canadian definitions. Vehicles such as the Toyota Prius PHEV and Nissan Leaf fall under this category, and will enter the market in 2011. The Chevy Volt, considered an EREV, is a mid-sized plug-in hybrid electric vehicle and will also enter the market in 2011 with a limited number currently on the road.

The following vehicle characteristics were set in PSAT to match the compact vehicle category as closely as possible:

- Vehicle Chassis Mass = 824 Kg;
- Drag coefficient = 0.26;
- Frontal Area = 2.25 m^2;
- Tire = P175/65/R14;
- Rolling Resistance Coefficient as a function of speed (s in mph) = 0.007 + 0.00012 * (s).

Additionally, all vehicles simulated were assumed to have a constant electrical accessory power load of 500 W, according to SAE J1634. This load corresponds to that of basic electronics running, but no air conditioning. An additional mass of 300 lbs (136 kg) was added to each vehicle to correspond with the EPA testing standards. Test conditions were ambient and represent “unadjusted” EPA drive cycle values.

5.3.4 PSAT Simulation Results

The ten powertrain configurations previously described were simulated through the UDDS and HWFET drive cycles. A first simulation was done beginning at 80 % SOC to force the vehicle to operate in charge depleting mode and thus obtain electric consumption data for this mode. In the case of the power-split PHEV architectures, the combustion engine turns on for brief instances during the UDDS cycle due to the need for supplemental power in order to meet the acceleration requirements of this drive profile. Due to the briefness of these occurrences (<100 seconds total over 23 minutes), the fuel economy value reported by PSAT for the combustion engine is misleadingly high given that it is averaged over the entire distance traveled. Therefore, the fuel consumption in charge depleting (CD) mode was not used to calculate a combined value and only fuel economy in charge sustaining (CS) mode is reported in the upcoming tables. In the case of the EREVs, all configurations were able to complete the UDDS and HWFET drive cycles in CD mode when starting at a high SOC.

A second simulation for the Power-Split PHEVs and EREVs was done starting off at 30 % and 25 % SOC respectively to force the vehicle into CS mode. Electric energy consumption data was collected in Wh/km and fuel economy in miles per gallon gasoline equivalent (mpgge) for each vehicle; the results are shown in Table 5-12.

Table 5-12. Energy consumption and fuel economy results for PSAT simulation.

PSAT Wh/km and mpgge				Power-Split Device PHEV		EREV Series Hybrid	
	Drive Cycle	Wh/km	mpgge	CD Electric (Wh/km)	CS Engine (mpgge)	CD Electric (Wh/km)	CS Engine (mpgge)
Gasoline	UDDS			145	71.5	124	71.2
	HWFET			173	63.5	139	76.9
E85	UDDS			145	72.8	124	73.6
	HWFET			173	64.7	139	79.3
Diesel	UDDS			145	75.8	124	76.9
	HWFET			174	74.0	139	84.0
B20	UDDS			145	86.2	124	90.0
	HWFET			174	84.1	139	94.4
FCV	UDDS	161	129.5				
	HWFET	145	143.8				
BEV	UDDS	130	161.0				
	HWFET	141	148.1				

As of MY 2008, EPA requires vehicles to be tested on 3 additional cycles in addition to the UDDS and HWFET: A high-speed aggressive cycle (US06), a hot weather cycle at 95°F (SC03), and a cold weather cycle at 20°F (cold FTP). As an alternative to running these cycles, EPA developed mpg-based formulas (Equations 2 and 3) which can be used to obtain a five-cycle equivalent fuel economy value using only UDDS and HWFET results. [27]

$$Five\ cycle\ city\ fuel\ economy = \frac{1}{(0.003259 + \frac{1.1805}{UDDS\ fuel\ economy})} \qquad (2)$$

$$Five\ cycle\ highway\ fuel\ economy = \frac{1}{(0.001376 + \frac{1.3466}{HWFET\ fuel\ economy})} \qquad (3)$$

Previous studies done by ANL have shown that the actual on-road energy usage and fuel economy may vary from what is predicted by PSAT. This is due to many unaccounted factors in the simulation software such as additional loads on the electric system, more aggressive driving, and cold or hot weather performance. In order to compensate for these circumstances, an adjustment factor was used to approximate the values obtained to real-world fuel economy and energy use for each vehicle.

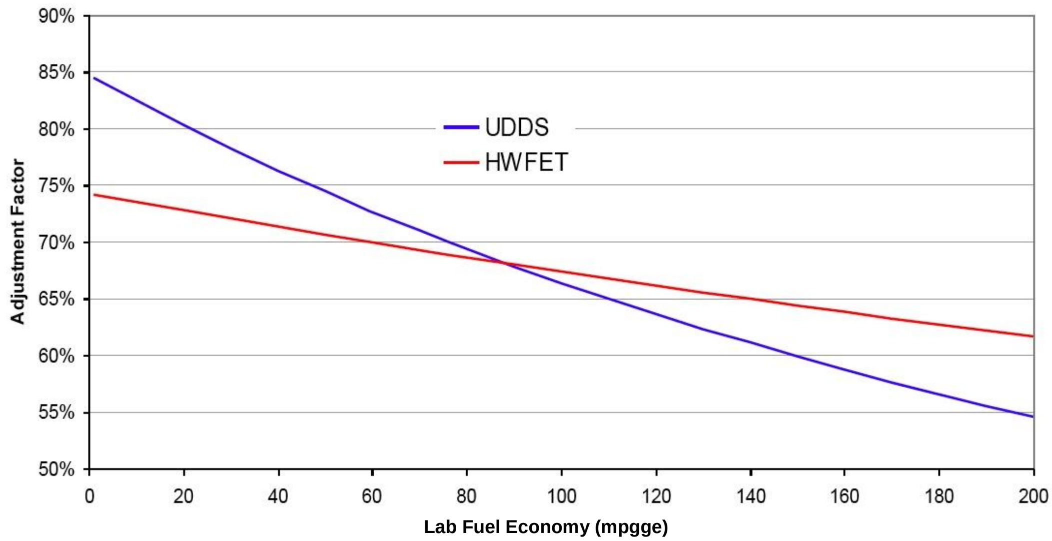


Figure 5-2. On-Road adjustment factor for PSAT fuel economy. Based on EPA's MPG-Based formulas [27]

Figure 5-2 shows how the impact of the adjustment factor on higher fuel economy vehicles (hybrid, fuel cell, and battery electric) is more substantial than on conventional vehicles. ANL researchers conclude the impact of “real world” driving in hybrids is greater than on conventional vehicles due to diminished energy recovery from regenerative braking under high deceleration rates and increased penalties on powertrain efficiency from air conditioning loads, or cold weather operation. [27] ANL also indicated in their research that the mpg-based equations are suitable for estimating on-road fuel economy for HEV, FCV, and BEV until EPA develops a more formal methodology for these advanced vehicle technologies.

The fuel economy results from Table 5-12 were adjusted using Equations (2) and (3) and a factor of 0.7 was employed to adjust the energy consumption of EREVs, FCVs, and BEVs. Figure 5-3 was taken from a PHEV well-to-wheel study done by ANL [27] and illustrates the various adjustments made to different vehicle architectures. The same methodology was followed in this study.

Due to the blended operation (engine and motor) in CD mode of the power-split PHEVs, many different adjustments could be made to fuel and electricity consumption (d-$D_{2,3}$ arrows in Figure 5-3). For power split PHEVs with larger battery packs the adjustment would likely follow the direction of d-D_3. For configurations with smaller battery packs and less powerful motors, the adjustment would more likely follow the direction of d-D_2 given that the additional load would be met by the engine. This uncertainty led to the assumption that the best adjustment path for the charge depleting blended operation of the power-split PHEV design would be in the direction of d-D_1 (vehicles 1-4).

The electric machines and ESS on the EREV designs (vehicles 5-8) were sized to meet the US06 cycle without assistance from the combustion engine; hence an adjustment factor of 0.7 was used as per vector b-B in Figure 5-3. The combustion engine on the EREVs is essentially employed to maintain the SOC around 30 % during CS mode. In the case of the BEV (vehicle 10), the same adjustment factor of 0.7 was used. According to data collected as part of the DOE hydrogen fleet and infrastructure demonstration and validation projects, the on-road fuel economy data for FCVs uses an adjustment factor ranging between 0.66 and 0.70 [27]. This range is consistent with the MPG-based equations (1) and (2), therefore the method used to adjust the on-road fuel economy for vehicle 9, the fuel cell vehicle, is also 0.70.

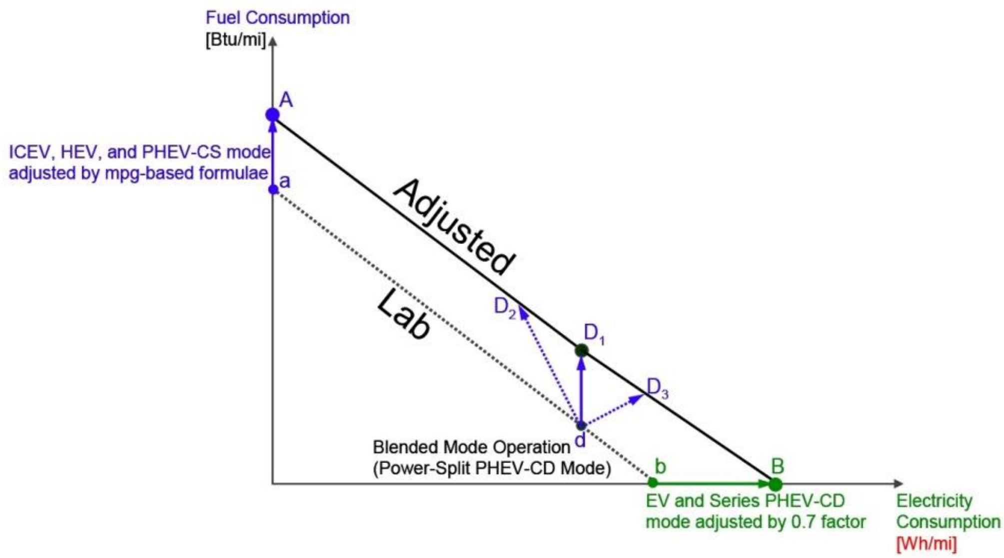


Figure 5-3.On-Road Adjustments of Laboratory Fuel and Electricity Consumption. From Argonne National Laboratory [27]

The on-road adjusted energy consumption and fuel economy values for the UDDS and HWFET cycles are listed in Table 5-13. A combined value for energy consumption and fuel economy was calculated using a weighting factor of 55% city and 45% highway as per SAE J1634. Similarities in UDDS and HWFET electric consumption amongst drivetrain groups are due to near equal vehicle weights. As seen in Table 5-7, the vehicle test weight difference amongst the Power-Split PHEVs simulated is only 9 kg, and 2 kg amongst the EREVs. Table 5-14 contains the final combined energy consumption and fuel economy values that were employed to calculate tailpipe and upstream emissions. It is worth mentioning that the small amount of fuel used in CD mode in the Power-Split PHEV is not shown in Table 5-14 , however it was accounted for in the PTW calculations.

Table 5-13. Adjusted energy consumption and fuel economy

Adjusted Wh/km and mpgge				Power-Split Device PHEV		EREV Series Hybrid	
	Drive Cycle	Wh/km	mpgge	CD Electric (Wh/km)	CS Engine (mpgge)	CD Electric (Wh/km)	CS Engine (mpgge)
Gasoline	UDDS			145	50.6	177	50.4
	HWFET			173	44.3	198	53.0
E85	UDDS			145	51.4	177	51.8
	HWFET			173	45.0	198	54.5
Diesel	UDDS			145	53.1	177	53.7
	HWFET			174	51.1	198	57.5
B20	UDDS			145	59.0	177	61.1
	HWFET			174	57.5	198	64.0
FCV	UDDS	231	90.7				
	HWFET	208	100.7				
BEV	UDDS	185	112.7				
	HWFET	202	103.7				

Table 5-14. Combined cycle energy consumption and fuel economy.

Adjusted Wh/km and mpgge (Combined Cycle)			Power-Split Device PHEV		EREV Series Hybrid	
	Wh/km	mpgge	CD Electric (Wh/km)	CS Engine (mpgge)	CD Electric (Wh/km)	CS Engine (mpgge)
Gasoline			158	47.7	187	51.5
E85			158	48.5	187	53.0
Diesel			158	52.2	187	55.4
B20			158	58.3	187	62.4
FCV	220	95.2				
BEV	193	108.6				

In order to understand the potential reduction in energy use and fuel consumption for each vehicle in CD and CS mode, it was imperative to comprehend how many "gasoline-powered" miles each vehicle was capable of replacing in all-electric mode. This was done using the Utility Factor (UF) based on the 2001 National Household Transportation Survey data [29]. Unfortunately the Canadian Vehicle Survey (CVS) provides only aggregate numbers such as total km driven in each Canadian Province. Therefore, obtaining a utility factor for Canadian populations using CVS data is not possible. It is worth noting that much work is needed in order to better understand the trip or utility factor profiles specific to regions in order for the inherent benefits of each vehicle technology to be well understood. Utility factors based on urban drive patterns tend to generate steeper curves than that of Figure 5-4. This is due to the fact that city vehicles are used to cover shorter distances, thus more daily vehicle miles can be traveled in charge depleting mode than what is predicted using the 2001 NHTS data .

The mileage weighed probability (MWP) method developed by the Electric Power Research Institute (EPRI) and the UF method by SAE J1711 were instigated in order to calculate the “average” vehicle miles traveled (VMT), displaced by a PHEV operating in CD mode. This methodology assumes that there is 100% market penetration of only the specified EV or PHEV technology, everyone drives one, and usage pattern is unaffected. The vehicle begins the day fully charged, is not recharged, and does not operate in blended mode. The average U.S. miles driven are partitioned into vehicle miles within the rated AER of the PHEV and vehicle miles that exceed it. [30] The share of national VMT by vehicles covering various distances per day, and the potential percentage of VMT that could be replaced by a PHEV in CD mode can be seen in Table 5-15. For example if a PHEV-30 travels 50 miles, only the first 30 miles are traveled using battery stored electricity. Trips between 40-60 miles account for approximately 16.8 % of the U.S. National share of VMT. Vehicles traveling over 60 miles per day constitute 51.8 % of all miles traveled. Such fluctuation is due to the variability in usage pattern. The sum of the grey cells in the PHEV-30 column represents the VMT % for PHEVs with up to 30 miles AER (3.3 + 8.1 + 10 = 24.4) %. White cells represent a sub % of VMT in electric mode out of the green column where the distance covered exceeded the all electric range. For example: 10.1 % out of the 16.8 % fraction of trips covering 40-60 miles distance could be driven all electrically by a PHEV-30. The blue cell is the column sum and represents the total % of VMT electrically over any distance for a set PHEV range.

Table 5-15. Share of Daily Vehicle Miles covered by a given PHEV range. [27]

Daily Travel Range of Vehicle	VMT Share in NHTS 2001 (%)	First VMT % in CD mode by PHEV Type				
		PHEV 10	PHEV 20	PHEV 30	PHEV 40	PHEV 60
Up to 10 Miles	3.3	3.3	3.3	3.3	3.3	3.3
10-20 Miles	8.1	5.3	8.1	8.1	8.1	8.1
20-30 Miles	10.0	3.9	7.9	10.0	10.0	10.0
30-40 Miles	10.0	2.8	5.7	8.5	10.0	10.0
40-60 Miles	16.8	3.4	6.7	10.1	13.5	16.8
Over 60 Miles	51.8	4.5	8.9	13.4	17.9	26.7
Total	100.0	23.2	40.6	53.4	62.8	74.9

Figure 5-4 plots the blue row vs. PHEV range. The resulting curve is known as the utility factor. The Utility Factor (UF) can thus be understood as the percentage of daily vehicle miles traveled in CD mode versus the AER of a particular vehicle. The UF selected for each of the vehicles simulated was based on the adjusted on-road AER which was calculated using the combined cycle energy consumption in Wh/km and the total usable onboard energy contained in each vehicle's battery. The results obtained are shown in Table 5-16, and Figure 5-4 illustrates how the UF was deduced for two specific cases. It is important to note that the ESS for vehicles 1 through 4 was sized for an AER of 20 miles and the ESS for vehicles 5-8 was sized for an AER of 30 miles.

Table 5-16. Calculated all-electric range based on electric energy consumption.

	Usable Onboard Electric Energy (kWh)	Adjusted Electric Consumption (Wh/km)	Calculated AER km (mi)
Power Split PHEV	4.5	158	28.7 (17.8)
EREV	9.7	187	51.8 (32.2)
FCV	70.4	220	320 (200)
BEV	33.7	193	174.4 (108.3)

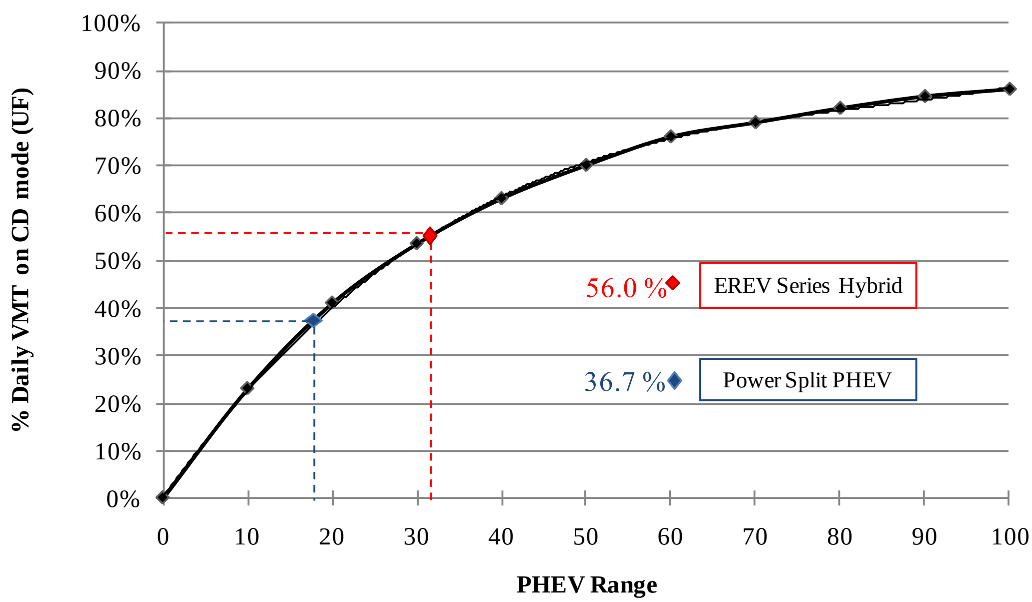


Figure 5-4. Utility Factor for selected architectures.

The results from Table 5-15 show that the Power-Split PHEVs and EREVs have an on-road AER of 98 % and 103 % respectively of what was anticipated. Due to the Power-Split PHEV's higher dependency on the combustion engine, the adjustment factor selected does not penalize the electric consumption as much. The EREV on the other hand, was assigned an adjustment factor of 0.7, further increasing the electric consumption as depicted in Figure 5-3.

5.4 Well-to-Wheel energy use and emissions calculations

In order to evaluate the overall environmental impact of the vehicles in each of the three Canadian Provinces and three U.S. Regions, the results obtained from GHGenius and GREET for the well-to-pump phase were combined with those obtained from PSAT in the pump-to-wheel phase. The hypothesis is that because fuel and electricity production have different environmental implications in each geographic region, every vehicle technology will have a different impact depending on where it is operated. The unknown element was to assess the significance of this influence and contrast it across a range of vehicle architectures. The fuel and vehicle parameters needed for the WTW calculations were tabulated in Excel. Separate results sheets for WTW total energy use, WTW fossil energy use and WTW GHG emissions were compiled. Data from GHGenius and PSAT was collected and arranged into tables in the same spreadsheet. Additional sheets containing total emissions, fuel cycle emissions and net energy ratio data were also created.

A net-energy ratio was calculated using results from the GHGenius simulations which foretell the Giga Joules (GJ) of primary energy consumed per GJ of fuel delivered from the power plant to consumer, excluding the actual end use. Additionally, the well-to-pump greenhouse gas emissions in grams of CO_2 equivalent per kWh and per unit of fuel consumed was also calculated with GHGenius and GREET. Emissions and energy use were evaluated independently for all fuels, configurations, modes of operation, and regions. The efficiency of the combustion engines in mpgge obtained from PSAT served as a starting point to determine the fuel units consumed in CD and CS modes.

The upcoming sections describe how the total energy use, fossil energy use, and emissions were calculated for each vehicle configuration.

5.4.1 Total Energy Use Results

Energy use was examined for each vehicle separately in both CD and CS operational modes. With the exception of the power-split configurations, the total energy utilized in CD mode consisted of electric energy. Hence, both the energy employed during electricity generation and the electric energy used during vehicle operation was considered. Vehicles that operate in CS mode use fossil fuel energy directly, therefore both the upstream energy for fuel production and the on-board fuel energy consumption was taken into account. The total energy use and fossil energy use are represented separately as stacked bars in the figures of Appendix C. Figures 5-5 and 5-6 summarize the energy use results for all 10 vehicle architectures in each region as colored bars. Dashed lines allow for comparison with energy use of conventional gasoline vehicles and gasoline HEV. Finally Figure 5-7 contrasts the energy use in Canada and U.S. across the architectures.

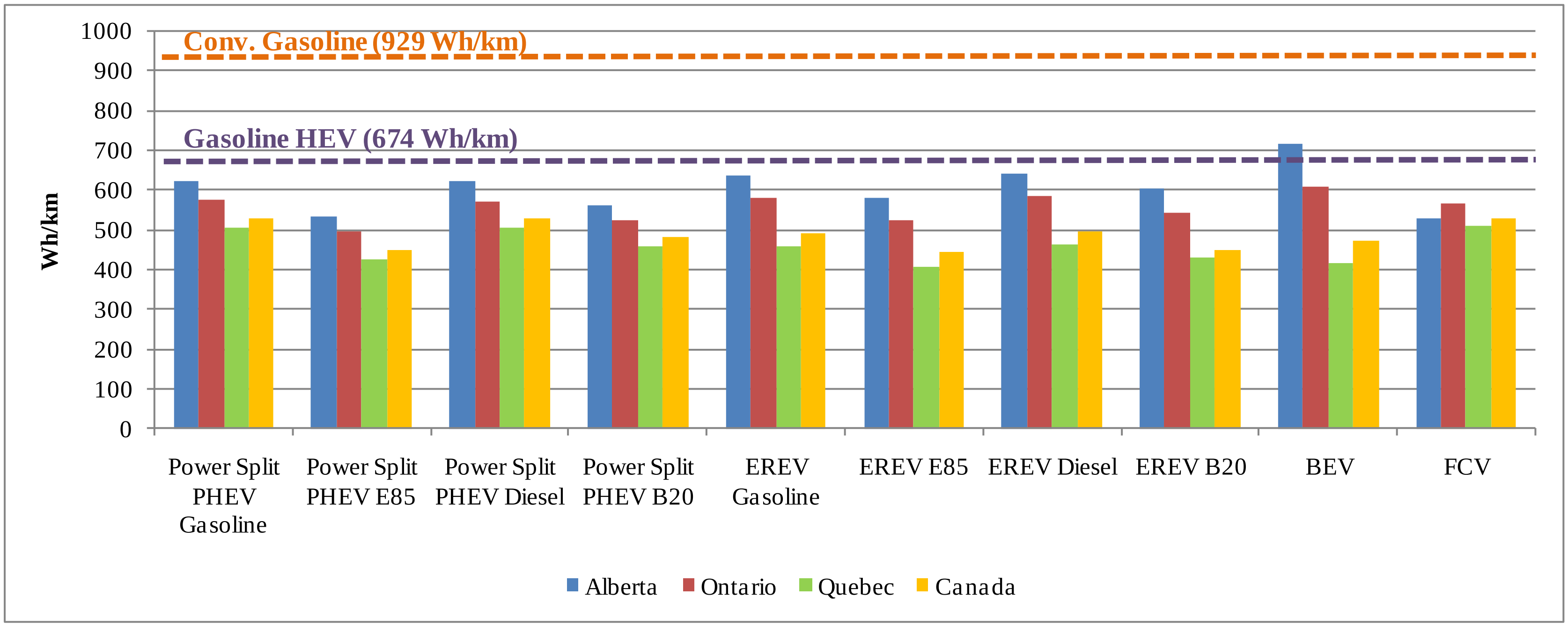


Figure 5-5. Energy Use for all vehicle configurations in Canada

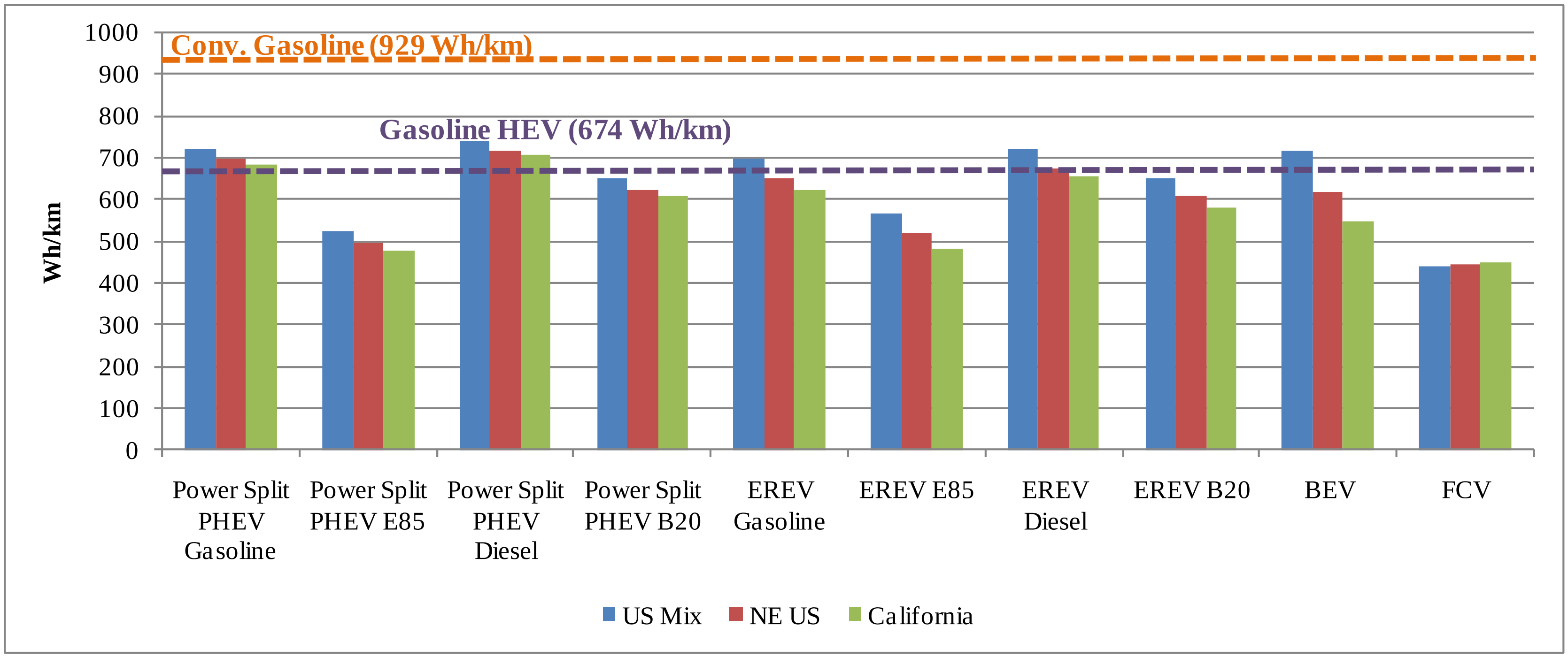


Figure 5-6. Energy Use for all vehicle configurations in the U.S.

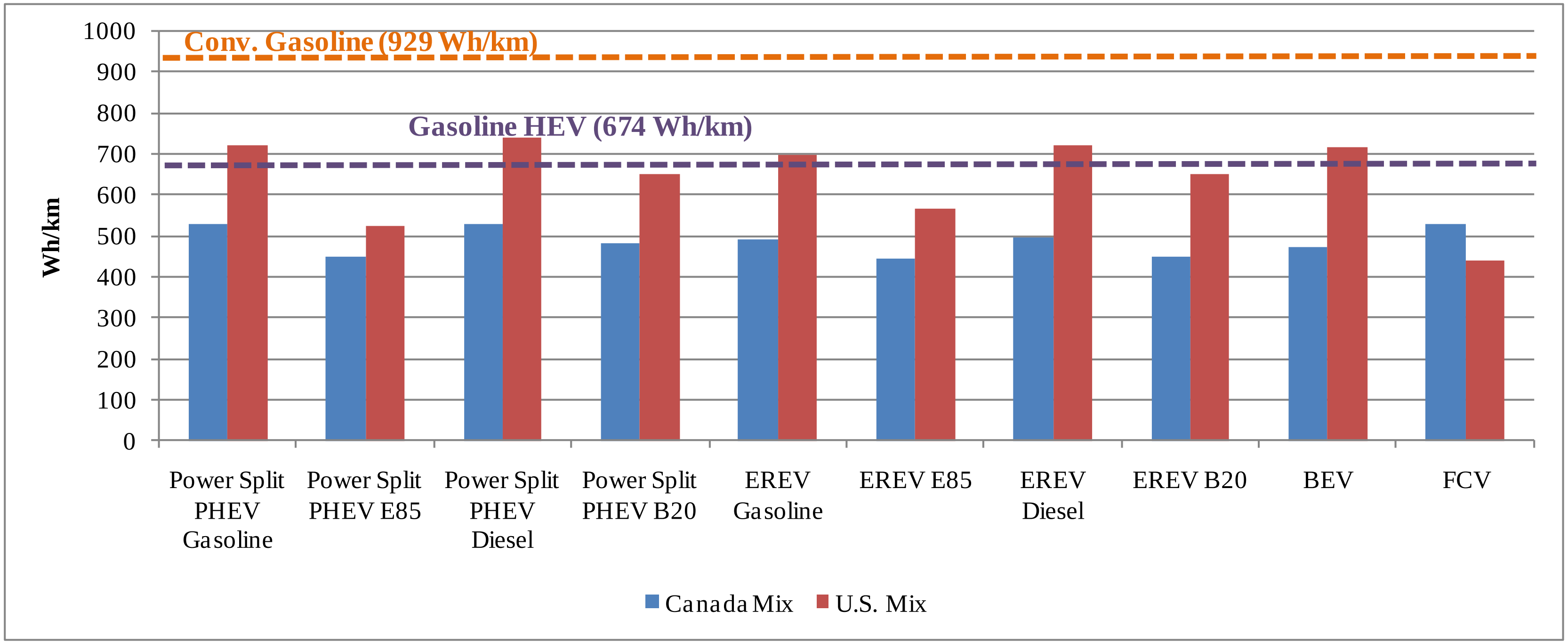


Figure 5-7. Energy Use comparison for all vehicle configurations in Canada and U.S.

5.4.2 Greenhouse Gas Emissions Results

Total WTW emissions were calculated independently for each region using fuel cycle data from GHGenius and GREET and fuel economy and energy use data from PSAT. The graphs in this section summarize the WTW emissions for each of the vehicle configurations in the 7 regions analyzed. Greenhouse gas emissions were also calculated for each vehicle in CD and CS modes. WTP and PTW emissions are reported in grams of CO_2 equivalent emissions per kilometer traveled. Upstream fuel production emissions and emissions from electricity generation are presented as stacked bars in the Appendix C Figures for both Canada and the U.S.

Figures 5-8 and 5-9 summarizes the greenhouse gas emissions results for all 10 vehicle architectures in each region. WTW CO_2 emissions for a similar sized conventional gasoline vehicle and a HEV are represented with dashed lines. Finally Figure 5-10 contrasts the WTW greenhouse gas emissions in Canada and U.S. across the architectures.

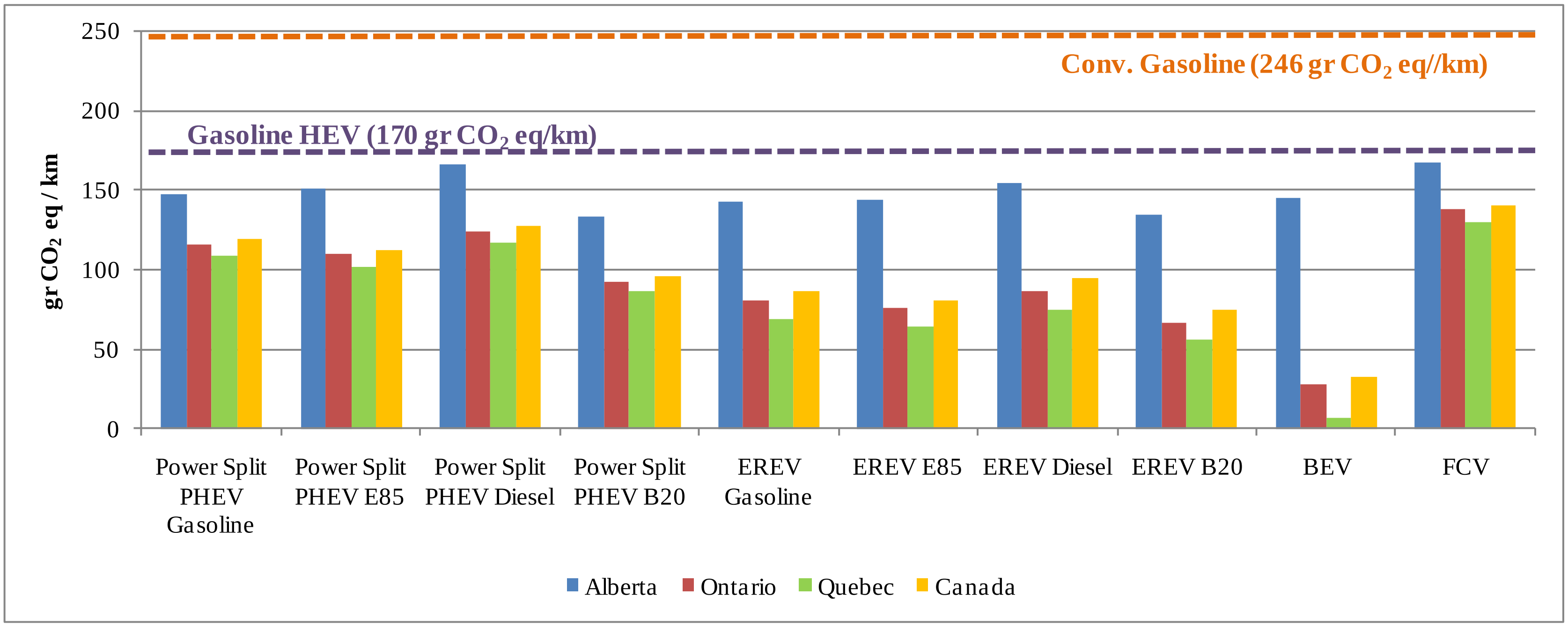


Figure 5-8. GHG Emissions for all vehicle configurations in Canada.

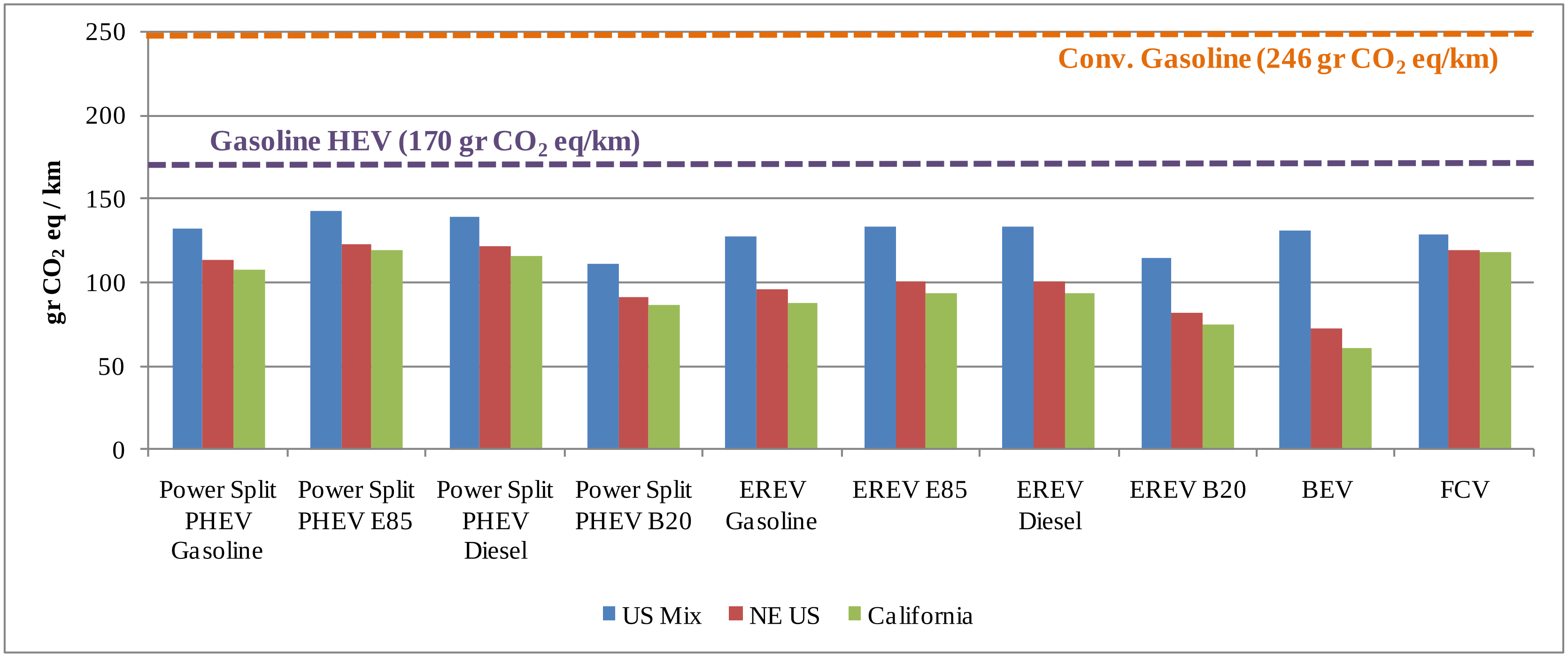


Figure 5-9. GHG Emissions for all vehicle configurations in the U.S.

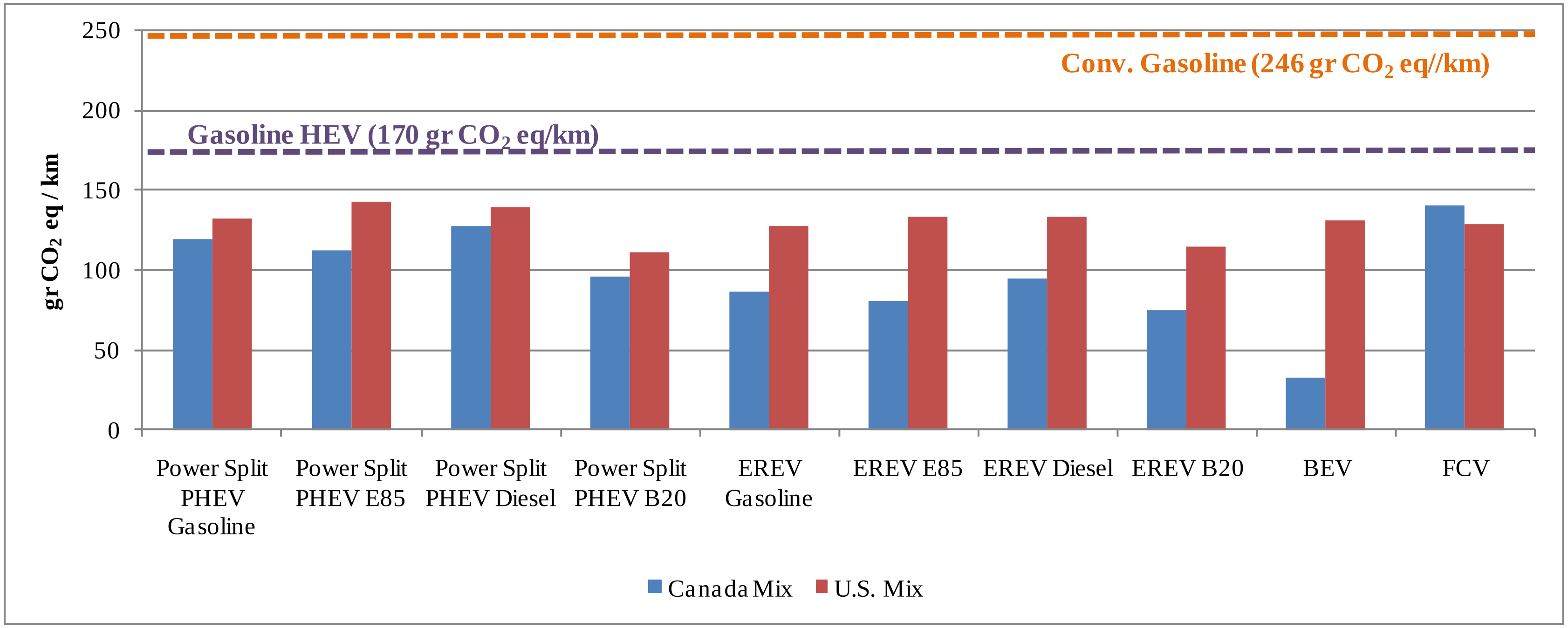


Figure 5-10.GHG Emissions comparison for all vehicle configurations in Canada and U.S.

Chapter 6

Market Share Projection of Vehicle Technologies from 2010-2020

6.1 Canadian Passenger Vehicle Market

According to Statistics Canada, in 2009 there were nearly 19.9 million passenger vehicles registered in the country. Nearly 75 % of these vehicles, 14.7 million, were registered in the Provinces of Ontario, Quebec and Alberta. Based on historical data, an estimated 17.4 million passenger vehicles could be on the road in these three Provinces by 2020 as seen in Figure 6-1. This would represent an 18.3 % increment [29].

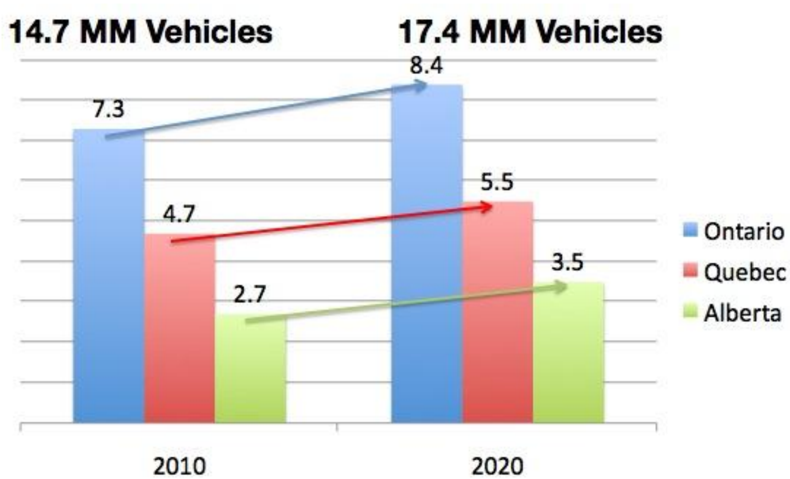


Figure 6-1. Registered passenger vehicles in Ontario, Quebec and Alberta in 2010 and 2020.

In a recent report published by the Boston Consulting Group (BCG) titled "The Comeback of the Electric Car? How real, How soon, and what must happen next", it is predicted that three possible scenarios may arise for the auto industry in the next decade, which will be determined mainly by oil prices, public and governmental concern over climate change, and technological breakthroughs [31]. According to BCG, if oil remains at $ 60 a barrel and concern over climate change diminishes, a "Market Slowdown" will occur and battery electric vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV) would see at most 2 % market penetration. A second scenario which they call "Steady Pace", assumes oil barrel prices return to the ~$ 150 per barrel levels of mid 2008 (by 2020), and alternative automotive powertrain development and concerns over climate change intensifies. Also increased tax incentives to reduce CO_2 emissions are introduced by government. In such a case, BEV and PHEV are expected to achieve each a 2.7 % market penetration in most regions. Finally, a third scenario they call "Accelerated Growth", supposes oil prices skyrocket to $ 300 per barrel and CO_2 emissions become an urgent issue. The hypothetical oil barrel prices stated are in present value, not in 2020 dollars. This case would see BEV and PHEV achieve the highest market penetration, estimated at 5 %, unless the energy cost generates an economic collapse

The conclusion reached by the BCG is that unless something radical occurs on a global scale, such as a major war or an energy crisis, the most likely scenario is the "Steady Pace". Based on this assumption, hybrids, EREV/PHEVs and BEVs would together achieve a 28 % market penetration in 2020. Conventional hybrids would reach 22.6 % market share, EREVs and PHEVs would together achieve a combined 2.7 % market share, and BEV would account for the remaining 2.7 % market share. These shares were used to calculate the approximate number of vehicles on the roads in each of the 3 Canadian Provinces being analyzed (Figure 6-2). Accordingly, the total combined number of EREVs, PHEVs, and BEVs that would be on the road in Canada by 2020 is close to 1,000,000 vehicles (470,000 EREV/PHEV and 470,000 BEVs). In a separate report developed by academia and various representatives of the Canadian auto, battery, and power generation industry titled "Electric Vehicle Technology Roadmap for Canada", it is estimated that "*by 2018, there will be at least 500,000 highway capable plug-in electric-drive vehicles on Canadian roads, as well as what may be a larger number of hybrid-electric vehicles*" [32]. These market sizes were used to gauge the potential load on each Province's grid and whether or not they would be capable of supporting a fleet of such magnitude by 2020.

According to Statistics Canada, in 2007, the country's net electricity generated was 572.8 TWh [33]. If one assumes that a medium sized full function electric vehicle consumes 225 Wh/km and travels 15,000 km a year, the total yearly energy consumption would be 3,375 kWh. Therefore a hypothetical fleet of 400,000 BEV would consume 1.35 TWh of energy, a mere 0.24 % of today's energy consumption.

Canada's power generating capacity, as indicated by Statistics Canada at the end of 2007, reached 124.24 GW [33]. In the unlikely event that all 400,000 BEV had access to typical level 2 charging (240V outlet at 30 Amps) and began charging at the same time this would represent a load of 2.9 GW, or about 2.4 % of the 2007 peak output. This shows that although grid infrastructure concerns are a valid consideration, they ought not to be limiting in the near term.

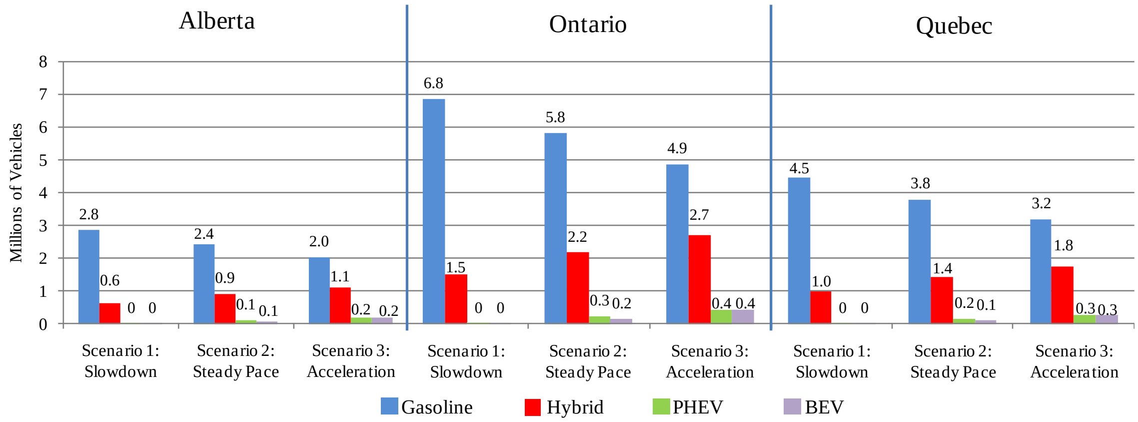


Figure 6-2. Vehicle technology mix in Canada (Year 2020) under 3 scenarios as described by the BCG.

6.2 United States Passenger Vehicle Market

According to the Research and Innovative Technology Administration (RITA) and the Bureau of Transportation Statistics, in 2008 there were close to 136 million registered passenger cars in the United States [34]. Historic data from the period of 1990 to 2008 was used to project the number of vehicles in 2020. It was estimated that this number could reach 148 million vehicles. Given the size and the diversity of the U.S. vehicle market, estimating the market mix is very challenging. The same distribution from The Boston Consulting Group study described in the previous section was used to gauge the U.S. vehicle technology shares. Again, their “Steady Pace” scenario predicts an overall market share of alternative propulsion technologies of around 28 %. BEVs however may play a more dominant role in cities and densely populated areas due to their limited autonomous range, with a predicted share of 18% among city cars.

Data from the U.S. Energy Information Administration shows that the net energy generation in the country during 2009 was almost 4,000 TWh [35]. Following the same assumptions used for the Canadian market, a fleet of 3 million BEV each consuming 225 Wh/km and traveling 15,000 km per year would require 10.13 TWh or 0.253 % of the total energy consumed.

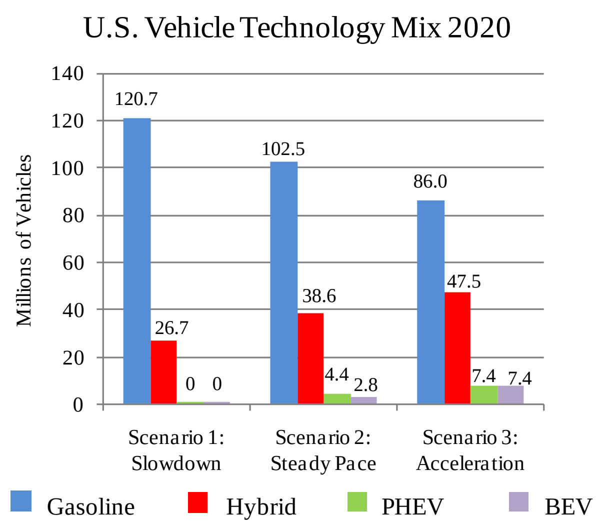


Figure 6-3. Vehicle technology mix in the U.S. (Year 2020) under 3 scenarios as described by BCG.

The U.S. Department of Energy reported for 2008 a net power generating capacity of 1010 GW. If one again assumes the unlikely event of 3 million BEVs charging simultaneously using level 2 charging, they would consume 21.6 GW or 2.14 % of the 2008 power output. One would conclude that for both countries the electricity grid will not pose any real limitations in the immediate future.

6.3 WTW GHG Emissions and Energy Use of an Electrified Vehicle Fleet in 2020

The BCG's anticipated market share was combined with the WTW results obtained in Chapter 5 in order to estimate total WTW greenhouse gas emissions and energy use for each fleet of vehicles. Additionally, the average vehicle kilometers traveled (VKT) were calculated for each region using data from the 2009 Canadian Vehicle Survey [36] and the 2009 State Transportation Statistics [34]. The average VKT for 2009 was assumed to stay the same for each region over the next decade and was used for CO_2 and energy use calculations.

Table 6-1. Vehicle kilometers traveled (VKT) for each Canadian Province (Year 2009).

	Passenger Vehicles	Total VKT (Million)	Average VKT
Alberta	2,605,010	41,672	15,997
Ontario	7,243,903	116,077	16,024
Quebec	4,613,926	68,133	14,767

Table 6-2. Vehicle kilometers traveled (VKT) for each U.S. Region (Year 2009).

	Passenger Vehicles	Total VKT (Billion)	Average VKT
Total U.S.	135,638,000	1,851	13,649
NE U.S.	25,588,292	274	10,711
California	19,706,000	201	10,204

The results presented in Table 6-3 and Table 6-4 show the total mass of CO_2 equivalent emissions released into the atmosphere by Gasoline, Hybrid, Power Split PHEV, EREV, and BEV on the road in 2020 for each Province and U.S. Region under Scenario 2. It was assumed that 50 % of what BCG denominates as PHEVs would be gasoline fueled Power-Split PHEVs and the remaining 50 % gasoline fueled EREVs. Fuel cell vehicles were not taken into account as they are unlikely to become mainstream technology over the next decade due to a lack of fueling infrastructure and the high cost of establishing such.

Table 6-3. Total Passenger Vehicle Emissions in Canadian Provinces under Scenario 2.

	Alberta		Ontario		Quebec	
Baseline (Scenario2)	**Vehicles (Millions)**	**WTW CO_2eq emissions (MT)**	**Vehicles (Millions)**	**WTW CO_2eq emissions (MT)**	**Vehicles (Millions)**	**WTW CO_2eq emissions (MT)**
Gasoline	2.42	9.52	5.80	21.09	3.80	14.96
Hybrid	0.91	2.47	2.18	5.48	1.43	3.89
Power Split PHEV	0.05	0.12	0.13	0.23	0.08	0.13
EREV	0.05	0.12	0.13	0.16	0.08	0.08
BEV	0.07	0.16	0.16	0.07	0.10	0.01
Total	**0.17**	**0.40**	**0.41**	**0.47**	**0.27**	**0.23**

Table 6-4. Total Passenger Vehicle Emissions in the U.S. under Scenario 2.

	U.S. Mix		NE U.S.		California	
Baseline (Scenario 2)	**Vehicles (Millions)**	**WTW CO_2eq emissions (MT)**	**Vehicles (Millions)**	**WTW CO_2eq emissions (MT)**	**Vehicles (Millions)**	**WTW CO_2eq emissions (MT)**
Gasoline	102.48	344.06	19.33	50.94	14.89	37.37
Hybrid	38.59	89.53	7.27	13.24	5.60	9.72
Power Split PHEV	2.22	4.01	0.42	0.51	0.32	0.36
EREV	2.22	3.89	0.42	0.43	0.32	0.29
BEV	2.82	5.04	0.53	0.42	0.41	0.25
Total	**7.27**	**15.08**	**1.37**	**1.59**	**1.06**	**0.95**

6.3.1 Recommended Regionally Tailored Powertrain Portfolios

Each of the regions analyzed in this study present particular conditions in power generation, fuel production, and the driving habits of its inhabitants. These differences have confirmed the initial hypothesis that certain vehicle powertrain configurations and fuels are better suited for a particular market.

It is also important to consider that the emissions from electricity generation used by GHGenius and GREET are an average of the daily load/supply curve. However, in order to have a thorough understanding of the difference between charging vehicle fleets at various times throughout the day, a more detailed analysis would be necessary. Figure 6-4 shows an example of the different generation resources used throughout the day to meet the daily electricity demand in Ontario.

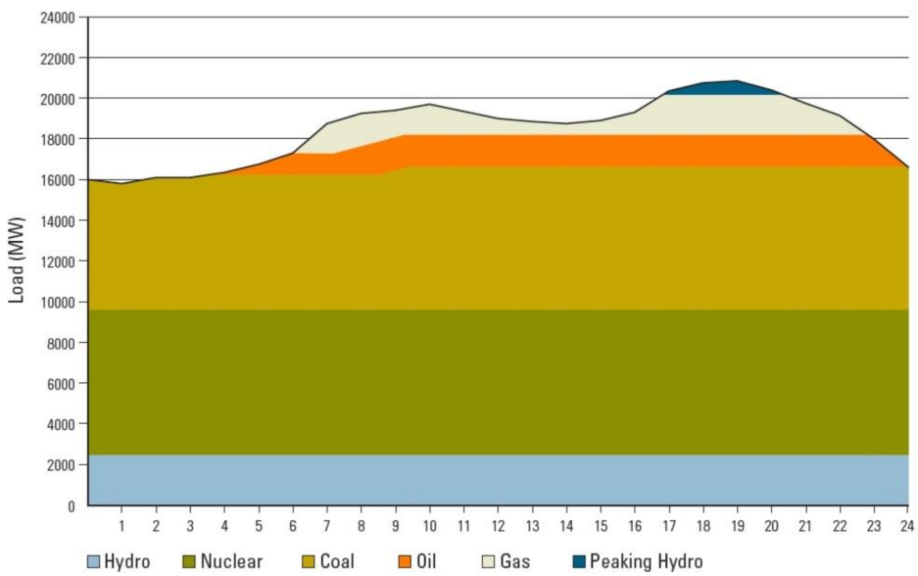


Figure 6-4. Ontario load/supply curve showing how demand fluctuates during the day and how different resources supply that load. (Source: ECSTF 2004)

Table 6-5 estimates the emissions from power generation from midnight to 1 am and from 6 pm to 7 pm. An average emissions rate for each electricity generation method was used to estimate how much more emissions are generated at peak demand versus off peak hours. The results show that charging a vehicle during peak demand could generate an additional 44 % emissions, as opposed to charging off peak. This is a significant number and leads one to believe that charge time may also play a very important role in lowering upstream emissions of electrified vehicles.

Table 6-5. Emissions from power generation in Ontario (2004) at low and high demand times. Based on Figure 6-4.

	Load (MWh)			Emissions (Kg CO_2/MWh)	
	12-1 am	6 to 7 pm	Avg. Kg CO_2/MWh *	12-1 am	6 to 7 pm
Hydro	2,500	2,500	25	62,500	62,500
Nuclear	7,250	7,250	30.5	221,125	221,125
Coal	6,250	6,500	986	6,162,500	6,409,000
Oil	-	1,750	935		1,636,250
Gas	-	2,000	450		900,000
Peaking hydro	-	1,000	25		25,000
Total	16,000	21,000		6,446,125	9,253,875

* Source: Carbon emissions calculator, www.alphaauctus.com

Given that GREET and GHGenius do not have the capability of providing the daily load/supply curves by generating source, the upstream results and the recommendations in this section are based on each region's average emissions. The following set of graphs show the potential emissions reduction, in kilotonnes (kt) of CO_2 per year, when operating a mix of electrified vehicle technologies that differs from the one predicted in the previous section (Scenario 2). A sample size of 1,000 vehicles per region was used and divided according to the market shares predicted under Scenario 2. Emissions for each vehicle technology were calculated as the number of vehicles multiplied by the corresponding CO_2 emissions per vehicle times the average yearly VKT in the region. Although sample size was kept equal for all regions in order to facilitate comparison, the

VKT varies per region (as seen in Figure 6-1 and 6-2), therefore must be considered when doing so.

In the case of Alberta, by substituting the more grid-dependant BEV with Power Split PHEVs and EREVs fueled by B20, CO_2 emissions may be reduced by 8 %. This occurs due to Alberta's fossil fuel-based power generation scheme. Essentially the B20 fueled combustion engine in the PHEV and EREV will generate fewer emissions on a kilometer basis than a coal or natural gas fired power plants delivering electricity to a BEV as evidenced in Figure 6-5.

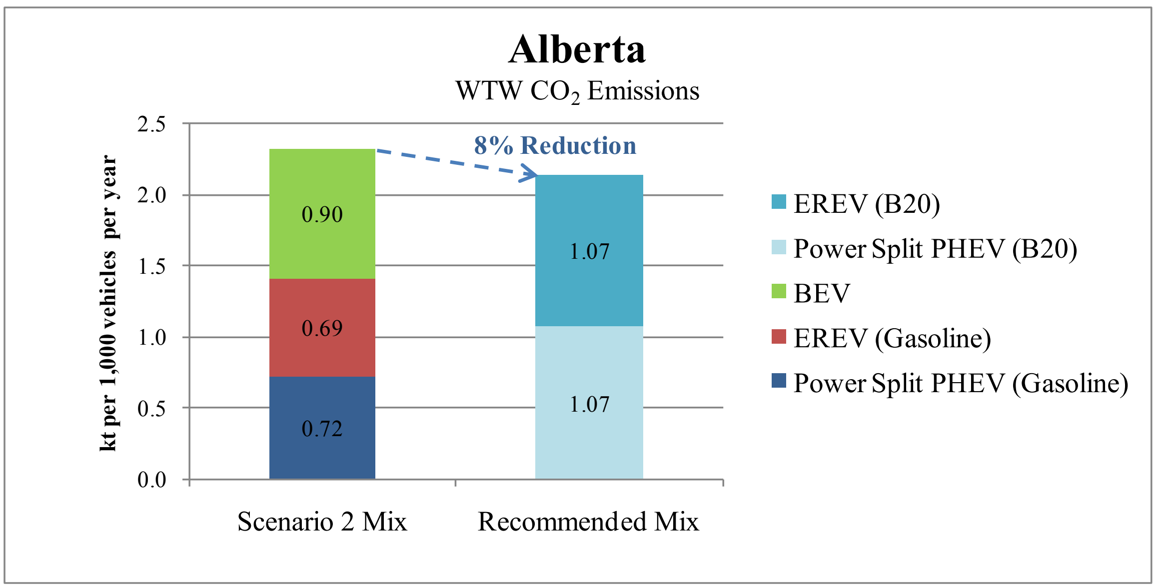


Figure 6-5. WTW CO_2 Emissions for Scenario 2 and Recommended Mix (Alberta 2020).

In the case of Ontario, where the power generation mix in 2020 is much more diverse and less carbon intensive, the more grid-dependent architectures offer the greatest benefits. By eliminating Power Split PHEV's from the Scenario 2 predicted mix, a 24 % reduction in CO_2 emissions could be achieved as seen in Figure 6-6. Growing the BEV share would require that a larger portion of the population be willing to invest in this technology, which will likely remain more expensive than a similar sized EREV or Power Split PHEV in 2020. However, adequate incentives and infrastructure investment could act as a catalyst for growth in this segment. Such investment would make the best sense when Ontario's plan to eliminate all coal fired power plants by 2014 comes to fruition.

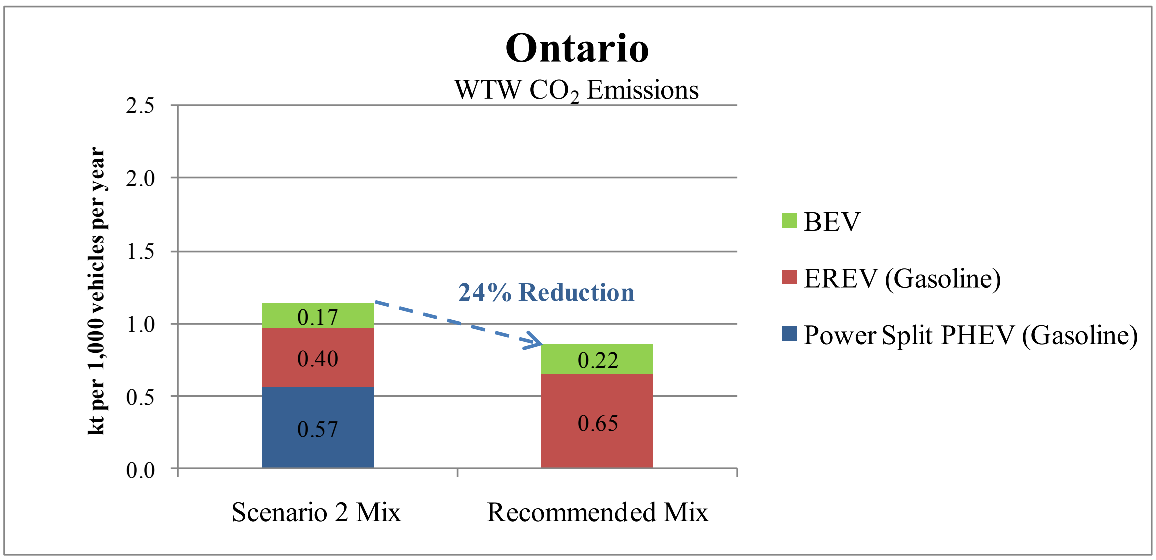


Figure 6-6. WTW CO_2 Emissions for Scenario 2 and Recommended Mix (Ontario 2020).

Quebec's predominant hydropower generation scheme offers the greatest benefits for EREVs and BEVs. The Scenario 2 mix already offers significant reductions in CO_2 emission levels compared to Ontario and Alberta. However, by eliminating Power Split PHEVs from the mix an additional reduction of 34 % could be achieved as seen in Figure 6-7. Furthermore, if the Province were able to successfully drive BEV growth to the point of completely displacing Power Split PHEVs and EREVs, a remarkable reduction of 88%

could be achieved (Figure 6-8). Despite the improbability of this occurring by 2020, it serves as an indication of the potential emissions reduction offered by BEVs in Quebec and similar regions with low-carbon power generation technologies already in place.

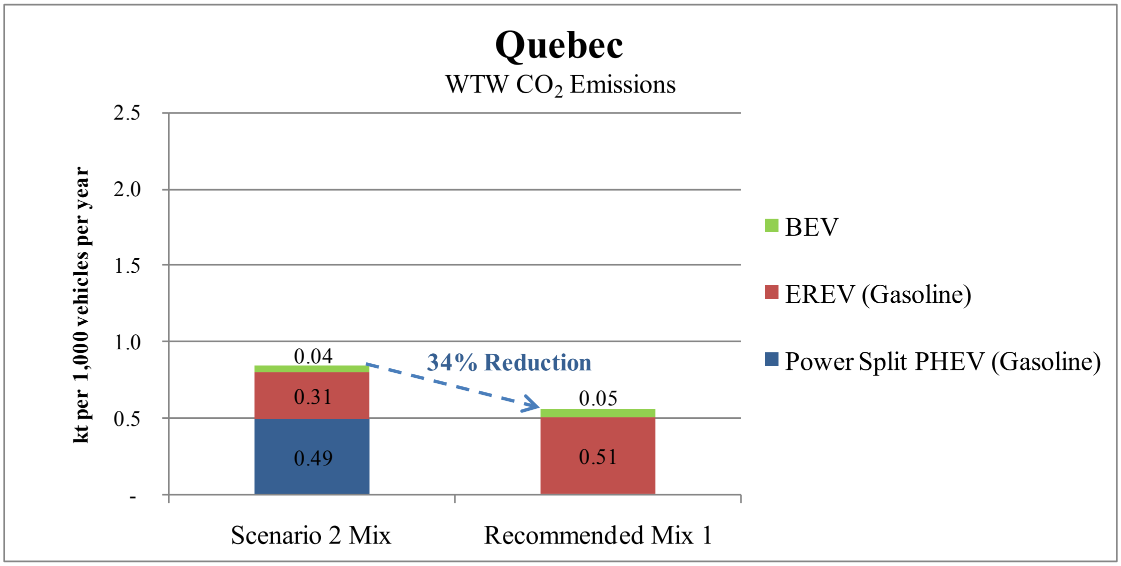


Figure 6-7. WTW CO_2 Emissions for Scenario 2 and Recommended Mix 1 (Quebec 2020).

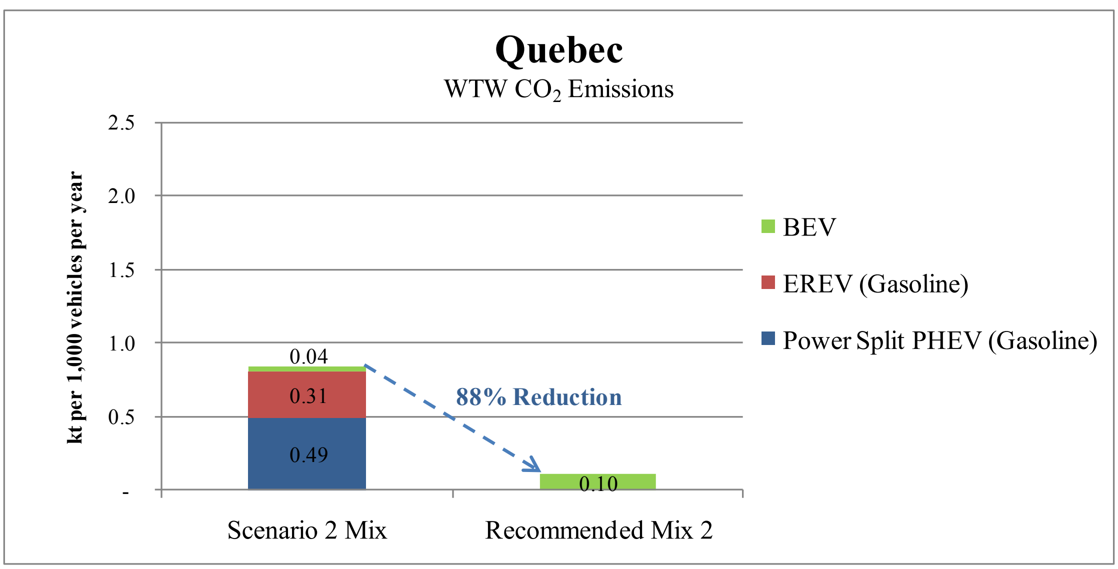


Figure 6-8. WTW CO_2 Emissions for Scenario 2 and Recommended Mix 2 (Quebec 2020).

In the case of the United States the overall picture is much too complex to generate a unique mix of vehicle technologies. Despite this, the benefits of using B20 in EREVs and E85 in Power Split PHEVs can be illustrated in Figure 6-9. A reduction of up to 8 % in CO_2 emissions could be obtained by increasing this fuel's presence and usage in strategic areas of the country.

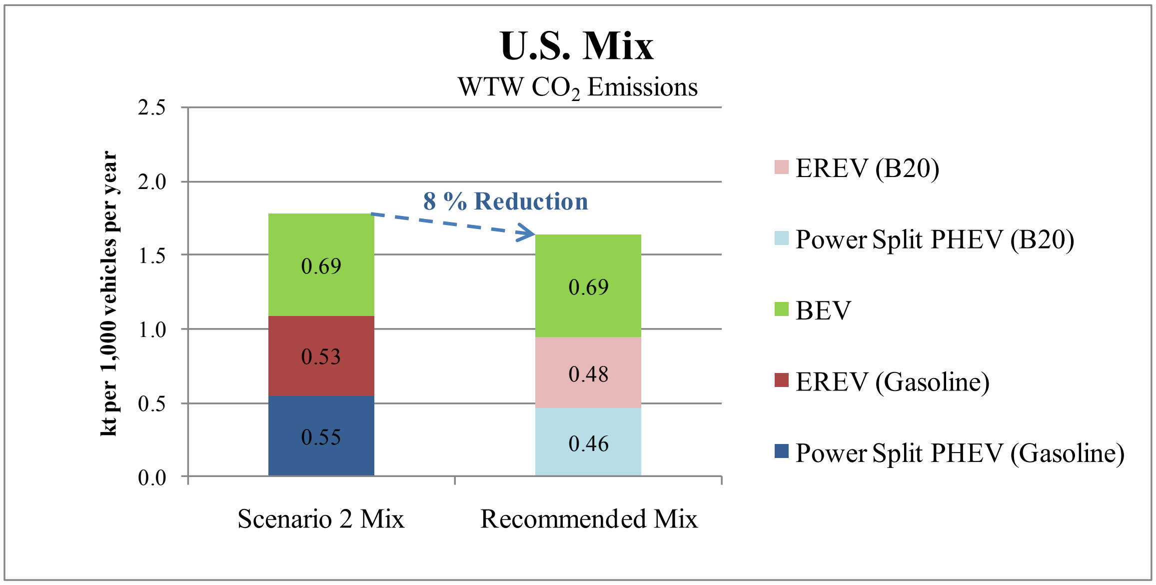


Figure 6-9. WTW CO_2 Emissions for Scenario 2 and Recommended Mix (U.S. Mix 2020).

The Northeastern states analysis shows that a 14 % reduction could be reached by implementing a similar bio-fuel targeting strategy (Figure 6-10). The similarity is mostly due to the fact that both the average U.S. and the Northeastern region in particular will most likely continue generating close to 70 % of their power using fossil fuels.

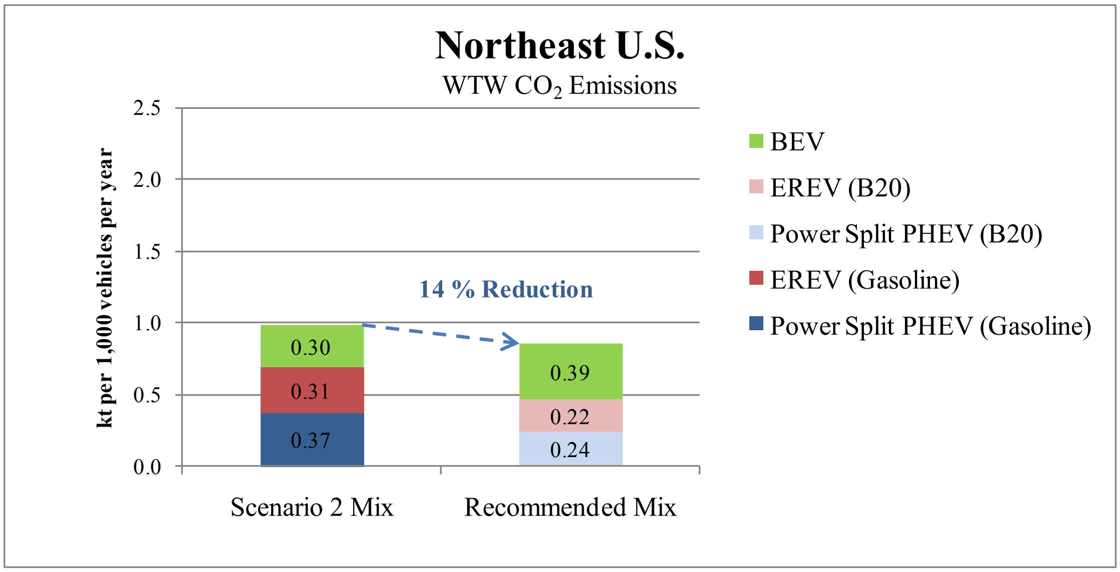


Figure 6-10. WTW CO_2 Emissions for Scenario 2 and Recommended Mix (NE U.S. 2020).

A much different picture emerges in the state of California where electrified vehicle technology presents similar benefits to those seen in Quebec. California's power generation mix is more favorable towards BEV as well as B20 in Power Split PHEVs and EREVs. A reduction of 13 % in CO2 emissions could be obtained simply by using B20 to fuel EREVs and raising the BEV share from 1.9 % to 2.5 % of passenger vehicles (Figure 6-11). As with Quebec, given legislation or tax incentives, the California Air Resources Board already embodies what other states such as Florida and Texas could accomplish if they embraced more expensive BEV technology. Furthermore, if California were to fully replace the Scenario 2 Mix with battery electric vehicles, a 27 % reduction could be achieved as shown in Figure 6-12.

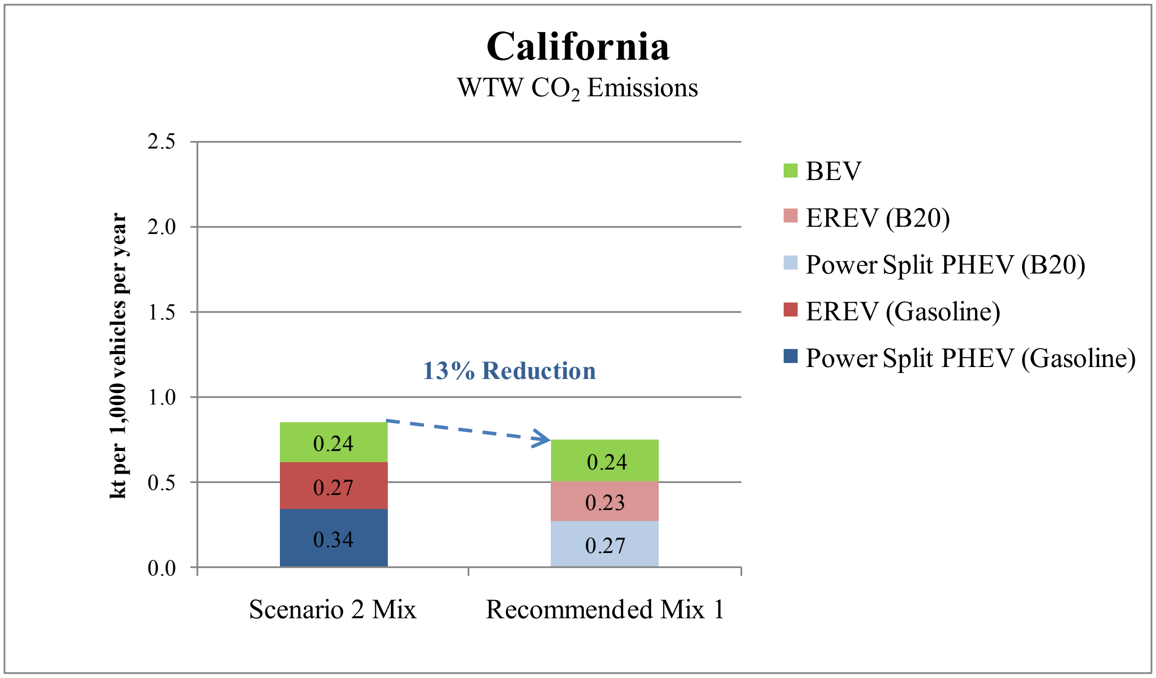


Figure 6-11. WTW CO_2 Emissions for Scenario 2 and Recommended Mix 1 (Cali. 2020)

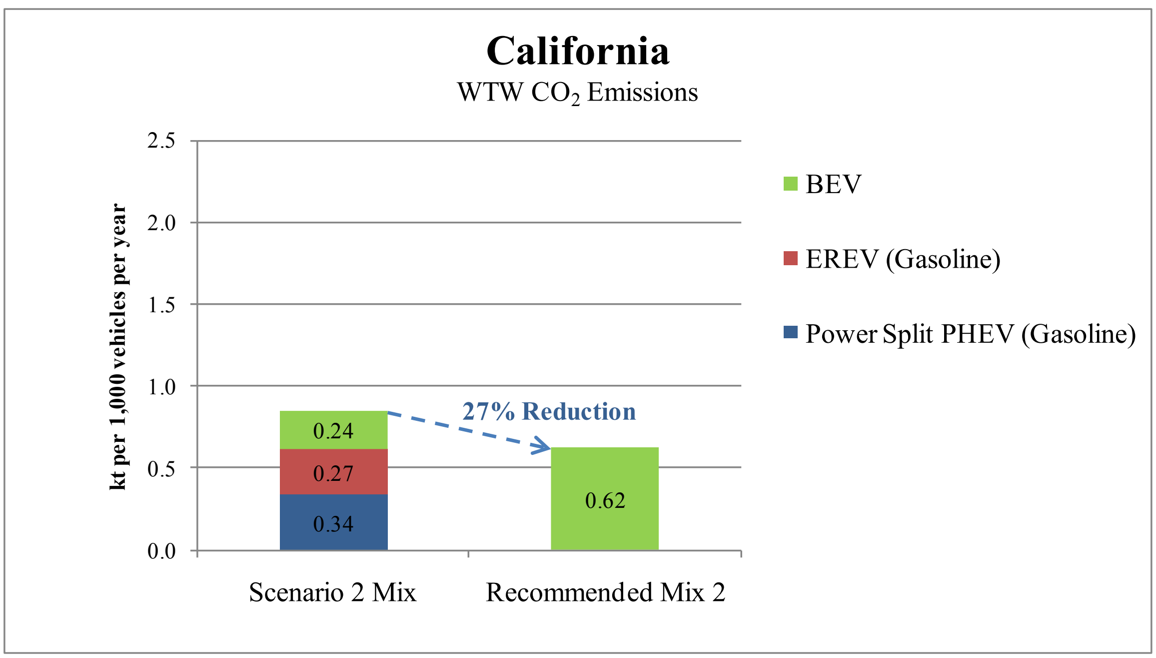


Figure 6-12. WTW CO_2 Emissions for Scenario 2 and Recommended Mix 2 (Cali. 2020)

Chapter 7

Conclusions

The transportation industry is undergoing an undeniable technology revolution which will transform everyday life and hopefully reduce the environmental reverberation caused by today's singularly fossil fueled vehicles. The objective of this revolution should not be substituting one technology for another, but more so to create a portfolio of environmentally friendly options that informed consumers may choose from depending on their needs. Governments must strive to incentivize all auto manufacturers to develop a broader range of clean technologies and work jointly with them to generate regionally based commercialization plans.

Electrified vehicle configurations such as hybrids, plug in hybrids, extended range electric vehicles, battery electric vehicles, and fuel cell vehicles are all worthy contenders and should not exclude one another. PHEVs and EREVs will possibly serve as transitional configurations that will enable consumers to capitalize on the intrinsic economic and environmental benefits of electrified powertrains pending the refinement and development of battery technology. It is expected that over the course of the next decade battery manufacturers will be able to resolve key issues such as charge time, equalization, temperature sensitivity, manufacturing reliability along with needed improvement in energy density of present cells. Battery price continues to be the main market penetration barrier. Despite some reports stating that battery prices in 2010 are in the order of \$ 1,000 per kWh and that they will drop to \$ 400 per kWh in 2020 [38], the reality is that manufacturers such as Electrovaya and A123 Systems have publicly stated that they expect to meet the 2020 price target by 2012. Based on UOIT's experience with the EcoCAR project, the current cost for automotive lithium based cells is on the order of \$ 700 per kWh in laboratory quantities; cells at half this cost are available sourced from China. Ultimately, the price of battery packs will drop as a consequence of economies of scale.

The introduction of the Chevrolet Volt and the Nissan Leaf in late 2010, along with the Ford Focus BEV in 2011, as the first mass produced EREV and BEVs to enter the North American market are driving change. These models are being followed by similar versions from many other major manufacturers as they strive to meet ever more strict emissions standards. In Europe, the latest CO_2 emissions regulation (443/2009/EC) for new passenger cars adopted in April 2009, establishes a fleet-average emissions target of 130 g CO_2/km to be reached by 2015. The same regulation establishes a long-term target of 95 g CO_2/km to be attained by 2020 [40].

Although the general public has grown accustomed to conventional ICE vehicles and their reliability and performance over the past century, a large portion of the population has shown interest in more modern and environmentally friendly alternative technologies. Early adopters of these vehicles will play a decisive role in building their reputation. How many of these vehicles will be sold is still a question to be answered over time and will greatly depend on factors such as oil prices and real-world performance. These uncertainties significantly affect the forecasts made by numerous private research firms which have attempted to quantify PHEV and BEV sales over the next decades. Each vehicle configuration may show technological strengths in specific regions under certain environmental conditions. Power generation costs in areas where fossil fuels are used may also rise, therefore diminishing the economic benefits of owning a BEV; but this must be taken in context of fossil fuel cost which will likely rise faster than electricity overall. Infrastructure investment will also play a role and it will be imperative for people to also consider the implications of owning a grid-dependent vehicle. The total cost of ownership (TCO) of each vehicle technology are a function of operating cost such as fuel price, relative maintenance cost, driving pattern, and government tax incentives. According to the Boston Consulting Group, 55 % of consumers interested in purchasing electric vehicles in the U.S. want to break even in three years or less [41]. According to this study, incentives may play a key role in significantly reducing the breakeven period; even in 2020 when they expect that battery prices will have dropped to 270-330 $/kWh. In the case of BEVs and EREVs they conclude that the breakeven period will be of 3 and 5 years respectively if the U.S. maintains the current $ 7,500 tax credit. If this tax credit were eliminated however, the breakeven period would increase to 15 (BEV) and 19 (EREV) years. The other conditions that would also meet the 3 year breakeven period according to BCG would be a 200 percent increase in gasoline prices due to higher oil cost, higher carbon taxes, or both.

Undoubtedly gasoline and conventional hybrid vehicles will continue to dominate the market in 2020 and beyond. Their impact does not depend on power generation schemes and will carry on generating over 90 % of the WTW emissions attributable to passenger transportation over the next decade. Canada and the United States governments announced in early 2010 their commitment to reduce carbon emissions by 17 % from 2005 levels as part of the Copenhagen deal on climate change. In order to deliver upon this specific goal the policies developed by local, regional, and national governments will need to converge and help sprout transportation technologies that offer the greatest benefits to each area. Complete lifecycle assessments of each vehicle technology will aid governments to understand their actual environmental impact and not limit assessments simply to tailpipe emissions. As shown in the present work, a WTW and energy use analysis can help identify reductions in transportation emissions of between 10 and 86 %. Although initially it may not seem that hybrids, PHEVs, and BEVs will play a significant role in the near term, by 2020 they are expected to represent close to 30 % of the collective passenger vehicle market. This growth will likely continue throughout the subsequent decades providing enough time to develop the incremental infrastructure and technology to support such vehicles.

Full function electric vehicles are the most promising alternative among the ones presented in this work. BEV powertrains have become reliable, are simple, low maintenance, and efficient. Their WTW emission levels and energy use were the lowest amongst the vehicle configurations analyzed with the exception of Alberta. FCVs show limited advantages when compared to PHEVs and BEVs in terms of GHG emissions. Their emissions are comparable to BEV, EREV and PHEV in the U.S., but higher in Canada relative to other options. Large amounts of energy, typically fossil fueled, are required to produce and store the hydrogen gas. FCV turn out to have about the same energy use in Canada than competing technologies. However, for the U.S., their energy consumption is marginally less than the E85 based PHEV and EREV. The biggest barrier for FCV is the high investment required to develop a refueling infrastructure to support a widespread fleet of these vehicles. They carry a driving range advantage over present ICE cost-competitive BEVs (example Nissan Leaf), however such advantage actually favors the BEV on a dollar for dollar basis, as FCV carry both a very high initial and fueling cost. The Tesla is an example of a commercial long range BEV slated for market; no equivalent FCV can yet be sold profitably. The BEV is the clear choice for Canadian urban centers primarily on the basis of outstandingly low GHG emissions. Ultimately, electric vehicles will become a technology of choice for consumers when they make better economic sense and meet normal usage requirements.

The preconception that PHEVs, BEVs, and FCV are just as clean everywhere will need to be addressed through education. However, the primary motivator for consumers will continue to be economics, rather than saving the environment. BEV market penetration will not grow significantly until battery prices drop further, government incentives are attractive, oil prices are again higher, and more public infrastructure is in place. There is an expectation that range requirements meet daily needs, charging is fast, accessible and easy, and that the vehicles are robust, safe, and functional regardless of climate. This is not yet the case, but it is definitely on the horizon for 2020.

7.1 Future Work

The following key research areas are recommended for future work:

- Replication of this study for Chinese, Indian and European markets in order to understand the broader worldwide impact of introducing electrified vehicle technology in predominantly coal-fired or oil-fueled power generation mixes, as well as populations with very different driving habits from North America.
- Utility factor calculation for Canadian and American cities in order to fully assess the potential of various electrified vehicle technologies in urban settings, as opposed to "average" requirements.
- Analyze the impact on emissions of charging vehicles during various times of the day dependant on the power generation mixes at play.

Appendix A

Using GHGenius

GHGenius has evolved from the original Lotus 123 model to an Excel spreadsheet based model. Each "run program" completes 750 cycles of the model. Processor power determines the resulting operating speed of the simulation. Cells are color coded so that users are able to easily identify what each cell represents. Cells with a yellow background have data which can be modified by the user; white cells with a red outline have input data transferred to them from another location in the model. General data inputs have been arranged on a single "Input Sheet". Additional yellow cells are found on other sheets and may also be modified by more advanced users to carry out a more detailed analysis.

The "Input Sheet", Figure A-1, is divided in several sections that make the user interface easier to understand. One can begin by specifying the year to be analyzed (Cell B3), country or region to be analyzed (Cell G3). Cells B5 to M5 select the "country or region weight" factors and can also be specified by the user; watching that they all add up to 1.

Version 3.15 of GHGenius introduced provincial default values which override other default buttons and select:

- Electric power;
- Transportation distances for petroleum based fuels;
- Types of LPG;

- Corn, wheat, and sugar cane ethanol transportation distances and producing regions;
- Canola, soybean, tallow, and yellow grease transportation distances and producing regions.

Cell B6 incorporates the Global Warming Potential values for 1995, 2001, and 2007 provided by the Intergovernmental Panel on Climate Change (IPCC) and Delucci's Carbon Emissions Factor (CEF):

- 0 = IPCC 1995
- 1 = IPCC 2001
- 2 = IPCC 2007
- 3 = Delucchi's CEF

Cell C19 extracts truck values based on class standards: 0 for no class and 3 through 8 for a specific class of truck. To activate, the user must press the button in B20. Cell C20 sets the heavy duty case(s) to be run: 0 for combined trucks and urban buses, 1 for buses only, 2 for trucks only. These settings are overridden by the "Run Program" button and will show results for all 3 options if pressed. It is important to note that for Light Duty Diesel Vehicles (LDDV), energy comes from the Input Sheet and is not calculated independently like for the other alternative fuels.

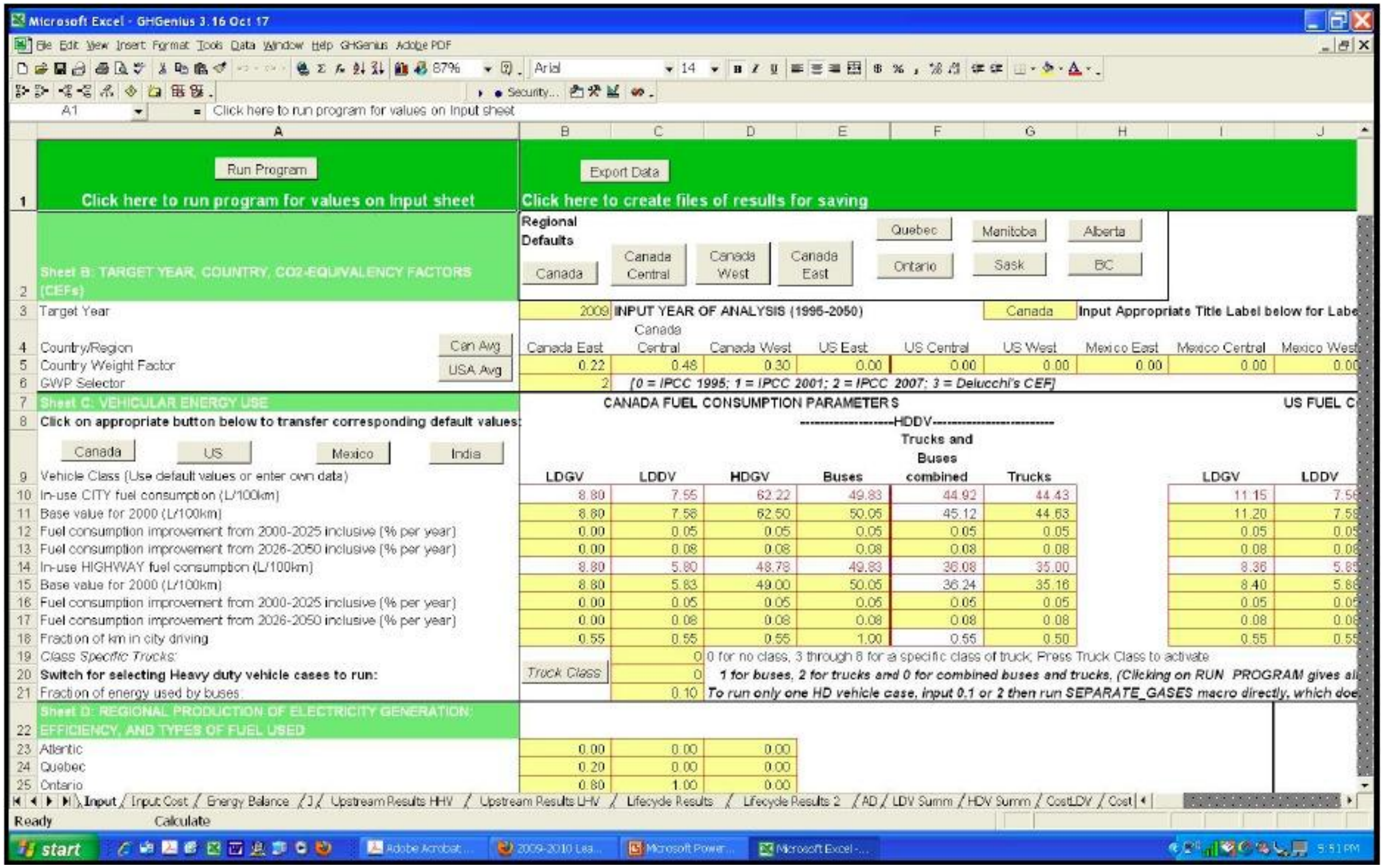


Figure A-1. Screenshot of input Sheet of GHGenius Model. [20]

Sheet E contains information on characteristics of fuels, gases, and feedstocks. Rows 32 through 54 set the various parameters for modeling. Assumed volume fractions for alternative fuels can be set in Row 35 for methanol, ethanol, butanol, diesel, and gasoline blends on a volumetric basis. The energy portions of each component of the blend will be automatically calculated. The user only needs to add one of the components as the other will be calculated by difference. Row 39 sets the assumed volume fraction of reformulated gasoline (RFG) and conventional gasoline (CG) for tractors, engines, and alcohol vehicles. Row 45 through 52 contain data for a mix of feedstocks for fuels: fossil methanol from natural gas (rest from coal), hydrogen from natural gas (rest from water electrolysis) for use in ICE vehicles, cellulose-ethanol from wood (rest from grass), diesel, hydro-treated renewable diesel (HDR) feedstock, and low and no sulphur RFG.

Once the aforementioned parameters have been set, the user may click on the "Run Program" button in cell A1 and the model will begin to run the 750 iterations. Many additional parameters are included in GHGenius that may be modified by the user to adapt the model to specific needs; however they exceed the scope of this report.

Appendix B

Using GREET

When opening the GREET Microsoft Excel file, the user will first encounter the "Overview Sheet" which presents a brief summary of each sheet and its function. The next sheet is the "Input Sheet" (IS) which is the model's main data source. Users have the option of running the model using the Excel file or by clicking on the GREET 1.8d executable file embedded in the GREET 1.8d folder. If a user selects the option of running the GUI program, the GUI input values will interact mostly with the values on the "Input Sheet" which will be referred to as IS from here onward. The IS presents the key variables and assumptions for multiple WTP and WTW scenarios. Yellow and green cells help to denote which parameters may be edited. Green cells have probability distribution functions built into them for use with the stochastic simulation feature of the model. This feature generates stochastic or randomly determined results, rather than a point estimate of energy use and emissions. Uncolored cells have formulas linked to or from them or to time-series (TS) tables in other worksheets of the model and should not be loosely edited. The sheet is divided in 14 sections:

- Selection of key options for simulation;
- Selection of vehicle types for simulation;
- Key input parameters for simulating petroleum-based fuels;
- Key input parameters for simulating natural gas-based fuels;
- Key input parameters for simulating hydrogen;

- Assumptions regarding boil-off effects of LNG and liquid hydrogen;
- Transportation distance from feedstock production sites to final destinations;
- Key input parameters for simulating fuel ethanol;
- Key input parameters for simulating soybean-based biodiesel;
- Key input parameters for simulating electricity generation;
- Key input parameters for simulating vehicle operations;
- Key GREET default assumptions for WTP activities;
- Fuel economy and emission rates of baseline vehicles;
- Fuel economy and emission changes by alternative-fueled vehicles (AFVs) and advanced vehicle technologies.

The subsequent sheet "EF_TS" presents the time-series (TS) table for emission factors (EF) considering stationary sources of fuel combustion technologies. The EF is in grams/mmBtu (grams per million Btu) of fuel burned. This allows for combustion products to change over time foreseeing technological improvements that will ultimately impact efficiency and emissions. Products considered are VOC, carbon monoxide, nitrogen oxides, particulate matter under 10 and 2.5 micrometers in aerodynamic diameter, methane, and nitrous oxide. These compounds may originate from various fuel sources such as NG, residual oil, diesel, gasoline, crude oil, LPG, coal, biomass, and hydrogen.

Emission rate calculations can be found on the emission factors or "EF" sheet. GREET uses emission factors from different combustion technologies and fuels to calculate the emissions for a specific combination at different WTP stages. GREET then uses these factors in other sheets to calculate emissions associated with various fuel combustion technologies at different WTP stages. The sheet is divided in two sections, the first lists emissions for combustion technologies applied to stationary sources; the second contains emission factors for different transportation methods of feedstock. All tables except for Table 2.1 (Emission Ratios by Fuel Type Relative to Baseline Fuel) in the EF sheet are linked through formulas and must not be changed. As the title implies, this table presents the emission ratios by fuel type relative to baseline fuel for ocean tankers, barges, locomotives, heavy-duty trucks, and pipelines. GHG in this table include VOC, CO, NOx, PM10, PM2.5, CH_4, and N_2O. Values are in percentages and are calculated as emissions from transportation over emissions of baseline fuel being transported. [23]

The “Fuel_Specs" sheet presents data for individual fuels such as LHV and HHV in Btu per gallon, fuel density in grams per gallon, global warming potentials of GHG in percentage relative to CO_2, carbon and sulphur ratios. Although GREET is predefined to utilize LHV for simulations, the user may conduct simulations based on HHV by changing the value in cell B5 on this page.

The energy and emissions of feedstock and fuels associated with their Transportation and Distribution is calculated in the "T&D" sheet. The results obtained in this sheet are expressed in Btu per mmBtu for energy use and in grams per mmBtu for emissions. Figure B-1 illustrates the logic flow for these calculations:

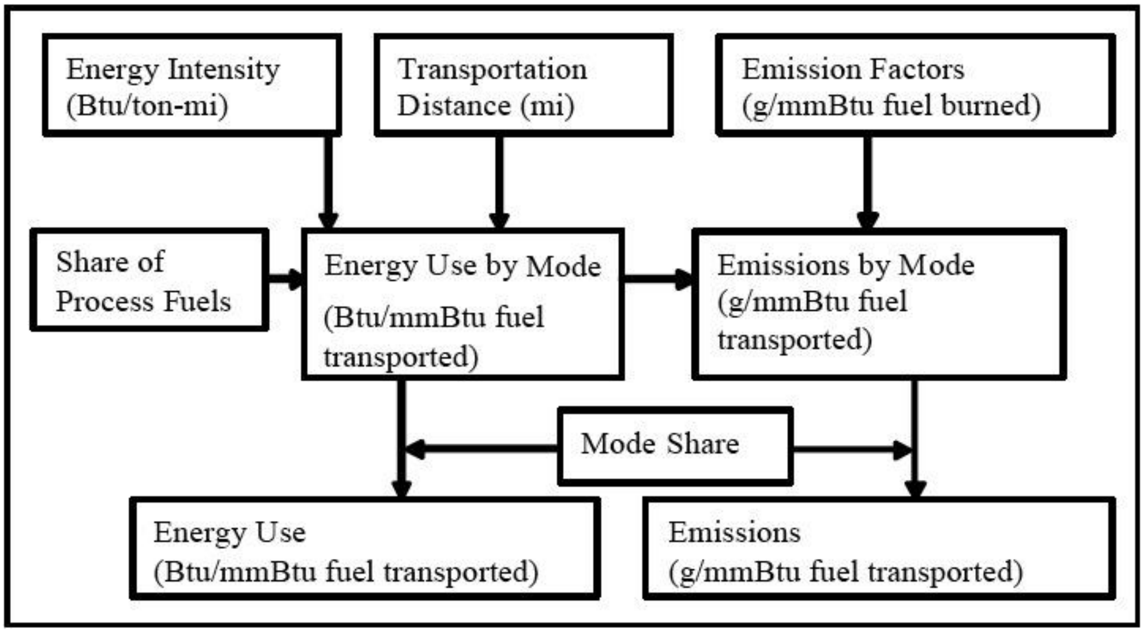


Figure B-1. Calculation logic for energy use and emissions for activities related to transportation of feedstock sources and fuels. [24]

This worksheet is divided in ten sections:

- Cargo payload by transportation mode and by product fuel type (units in tons);
- Horsepower requirements for ocean tankers and barges: Calculated with cargo capacity (units in HP);
- Shares of power generation technologies fueled with NG for pipeline operation, such as turbines and engines;
- Fuel economy and resultant energy consumption of heavy-duty trucks for transportation activities;
- Calculation of energy use for ocean tankers and barges;
- Energy intensity of rail transport in Btu/ton-mile;

- Energy intensity of pipeline distribution in Btu/ton-mile by power technology and pipelined product;
- Energy intensity ratios of different process fuels used for a given transportation mode relative to baseline fuel;
- Calculation of energy use and emissions associated with transporting feedstocks and fuels;
- Summary of energy use and emissions associated with feedstock and fuel transportation. These summarized results are employed by the model in other sections.

The "Urban _Shares" sheet contains 14 sections that split fuel production activities, fuel transportation activities, and vehicle operations in non-urban and urban areas. The user may select from three scenarios: urban vehicle miles traveled (VMT) of urban light duty vehicles (LDV), all VMT of urban LDV or all VMT of all LDV. Inputs will be used to calculate urban emissions of the six criteria air pollutants mentioned in previous sections.

The "Fuel_Prod_TS" sheet is important for electric vehicle and hybrid vehicle analysis as it presents the key assumptions for various fuel production pathways including electric generation mixes. This sheet contains Time-Series (TS) tables (1990-2020 in 5 year intervals) for each type of fuel, given the parameters associated with their production may change over time. The Time-Series tables have 3 columns including: target year, parameter value, and relative intensity of the parametric value for the given year relative to 2010. The TS tables are separated into twenty nine groups which will not all be listed. Three of these are relevant to electricity generation:

- Electricity generation efficiencies;
- Electric generation technology shares in power plants;
- Electric generation mixes.

As power generation technology shifts to renewable alternatives, the energy use and emissions associated with electric vehicle operation will gradually drop. Under that premise, GREET allows users to experiment with possible scenarios. Assumptions for future electric generation mixes can be incorporated per U.S. region, for transportation or stationary use, for California, and for a user defined mix. Electric generation efficiencies per method can also be included and varied on a 5 year basis up to 2020.

The next sheets: "Petroleum", "NG", and "Hydrogen" are beyond the scope of this report. In summary it can be said that all three sheets offer users very limited intervention as most cells should not be modified because they contain verified data and are linked to formulas. The next four sheets: "Ag_inputs", "EtOH", "E-D Additives", and "BD" are also beyond the scope of this report due to their complexity. These sheets contain data on the emissions and energy use associated with the manufacture of fertilizers and the production of biofuels.

The "Coal" sheet calculates energy use and emissions of mining, cleaning, and transportation of coal which serves as the primary fuel to generate over 20% of U.S.

power. It is divided in 3 tables: shares of combustion processes for each stage, calculations of energy consumption and emissions for each stage, and summary of energy consumption and emissions. Tables 1 and 3 within contain no yellow cells thus must not be modified as they contain verified data. Energy efficiency for coal mining and cleaning may be changed from its original preset value of 99.3 %, as well as the VOC and SOx emissions involved in coal cleaning.

The "Uranium" sheet is divided in 3 sections similar to the previous sheet, and also allows limited modification. It contains data on uranium for electricity generation and hydrogen production with thermo-chemical cracking of water. Table 1 in this sheet presents the scenario control and key input parameters. The user can modify values of energy use for uranium mining (mmBtu per ton of yellowcake), the weight conversion factor from yellowcake to U-235, and the U-235 concentration in the uranium fuel. The fraction of U-235 in waste and in feed can also be changed by the user. The final output of this sheet is a summary table of energy consumption and emissions in Btu or Grams per gram of U-235 available at the nuclear power plant or H_2 plant (depending on row).

The "Electric" sheet calculates energy use and emission rates associated with the generation of electricity which is used for the production of other fuels or for the operation of PHEV or BEV. It is possible for GREET to calculate electric power plant emission rates based on the predetermined emission factors or from user input. The model accounts for energy use and emission rates during the processing and transportation of power plant fuels as well as their operation. The results are displayed in

Btu or g/mmBtu of available electricity, reflecting transmission and distribution losses from the power plant to plug. It is possible to simulate various types of electricity generation, including:

- Oil power plants;
- NG power plants;
- Coal power plants;
- Nuclear power plants (LWR or HTGR);
- Hydro power plants;
- NG Combined-cycle turbine power plants;
- US generation mix;
- North-eastern US generation mix;
- California generation mix;
- User defined generation mix;
- Others.

Given that emissions produced by power generation plants will likely decrease as technology evolves, time-sheets have been included to account for this effect. Mass in grams per kilowatt-hour of electricity generated for the six criteria pollutants are included for each power generation types listed on a 5 year basis.

The logic flow used by GREET for this sheet can be seen in Figure B-2.

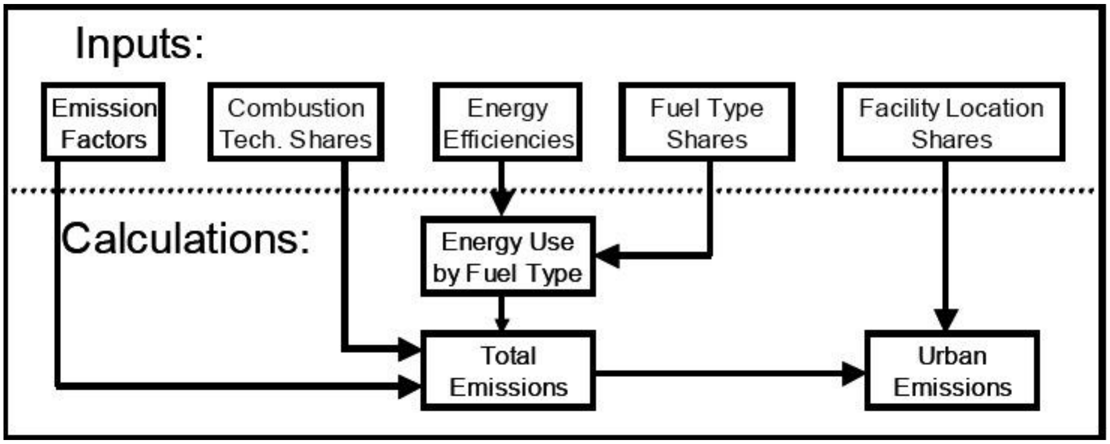


Figure B-2. Calculation logic for WTP energy use and emissions for activities related to power production. [24]

This portion is divided in 8 sections:

- Scenario control and key input parameters. Values for nuclear reactor technologies derive from the "Fuel_Prod" sheet;
- Electricity generation mix, power plant fuel combustion technology shares, and power plant conversion efficiencies;
- Electricity transmission and distribution losses, predetermined at 8 %;
- Power plant emissions in grams per kilowatt-hour of electricity available at power plant. GREET calculates emissions for 6 criteria pollutants in stationary and transportation applications. A user input table exists that takes data from section 8 of the same sheet;
- Power plant emissions in grams per kilowatt-hour of electricity available at outlets (user site). This table provides information on total and urban emissions for each generation method;

- Power plant energy use and emissions per mmBtu of electricity available at user sites;
- Fuel cycle energy use and emissions from electric generation in Btu or grams per mmBtu of electricity available at wall outlets;
- Time-series tables of emission factors from EPA database in grams per kilowatt-hour.

The "Car_TS" sheet calculates emissions and energy use for various vehicle/fuel combinations versus a baseline vehicle (gasoline and diesel fuel powered vehicles). The relative changes in fuel economy and emissions are also calculated. This sheet consists of two sections: The first is a set of 4 time-series tables that contain fuel economy in mpg and emission rates in grams per mile, of baseline gasoline and diesel powered passenger cars; the second contains time-series tables with fuel economy and emissions changes for alternative fueled vehicles (AFV) and advanced vehicle technologies (AVT). The fuel economy is relative to baseline gasoline vehicles. For spark ignition (SI) vehicles, the emissions are relative to gasoline vehicles, for compression ignition (CI) relative to diesel vehicles. The green colored cells in section one contain probability distribution functions built into them for stochastic simulations. Once again, this feature allows GREET to generate stochastic results rather than point estimations of energy use and emissions. An important thing to consider before running vehicle fuel economy simulations is that the lifetime mileage midpoint should be used, given that emission rates of vehicles will deteriorate over time.

The "Vehicles" sheet calculates energy use and emission rates related to vehicle operation. It is divided in three sections: Scenario control and key input parameters (from "Inputs" sheet), ratios of vehicle fuel economy and emissions by alternative fueled vehicles (AFV from "Inputs" sheet), and per mile fuel consumption and emissions of vehicle operations. The split of vehicle miles traveled (VMT) on grid electricity or onboard fuel can be specified in the first section as well as the percentage content of multiple fuel blends. The second section presents ratios that may change over time, therefore are linked to time-series tables in sheets "LDT1_TS" and "LDT2_TS". The third section calculates “per mile” fuel consumption (gasoline equivalent) and Btu/mile and emissions of vehicle operations in grams per mile.

The "Results" sheet presents the final outcomes for the specific vehicle/fuel being studied. It is divided in three sections:

- *Well-to-Pump Energy Use and Emissions:* This table presents the accumulated energy consumption and emissions resulting from all processes prior to the fuel arriving at the pump on a vehicle/fuel basis. Energy is expressed in Btu, and emissions in grams per mmBtu.
- *Well-to-Wheels Energy Use and Emissions:* Results are given on per mile basis for each vehicle/fuel combination. Energy and emissions for feedstock, fuel production, vehicle operation, and total accumulated energy consumption and emissions production is presented in separate tables for each vehicle architecture.

- *Well-to-Wheels Energy and Emissions Changes:* Results relative to gasoline vehicles fueled with CG or RFG are presented in this single table expressed as a percentage.

Emissions data for this study was taken directly from the GREET 1.8d Excel file rather than the GUI output file. The macros were executed in the spreadsheet after specifying the main parameters in the Input Sheet and data was extracted from the corresponding fuel results tab. The GUI is intended to be employed by users that are not carrying out a separate PTW simulations, which is not the case of this work. When using the GUI, the program allows users to provide assumptions for fuel economy, electricity consumption, whether it is grid-dependant or not, charger efficiency and AER (in case it is a PHEV or BEV). However, it does not allow users to select specific components for each vehicle, scale these components, modify the vehicle control strategy nor test the dynamic performance of these through drive cycles, acceleration and gradeability tests. Given that the power trains evaluated in this study were simulated using PSAT, GREET was employed to obtain WTP datum only. This was done in order to side step any vehicle assumptions buried within the GUI.

Appendix C

WTW Energy Use Results

The following graphs represent the total energy use of the vehicles presented in Chapter 5. They are shown as independently colored stacked bars for each region, vehicle technology and operating mode. The WTP On-board (blue) represents the energy that was used in each region to produce the fuel consumed by the combustion engine in CD and/or CS mode. WTP Electric (red) represents the amount of energy that was used to generate the electricity powering a vehicle in CD mode. PTW On-board (green) represents the fuel energy that was consumed by the combustion engine during operation in blended or CS mode. Finally, PTW Electric (purple) represents the electric energy use of vehicles operating in CD mode.

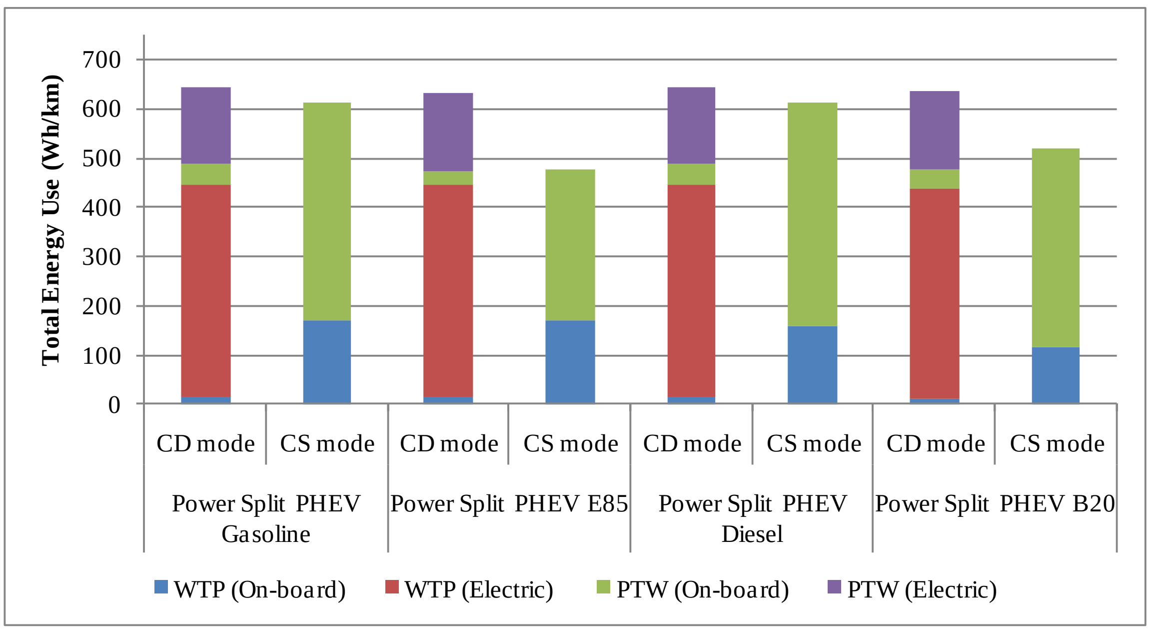


Figure C-1. Total WTW Energy Use for power-split PHEV configurations in Alberta.

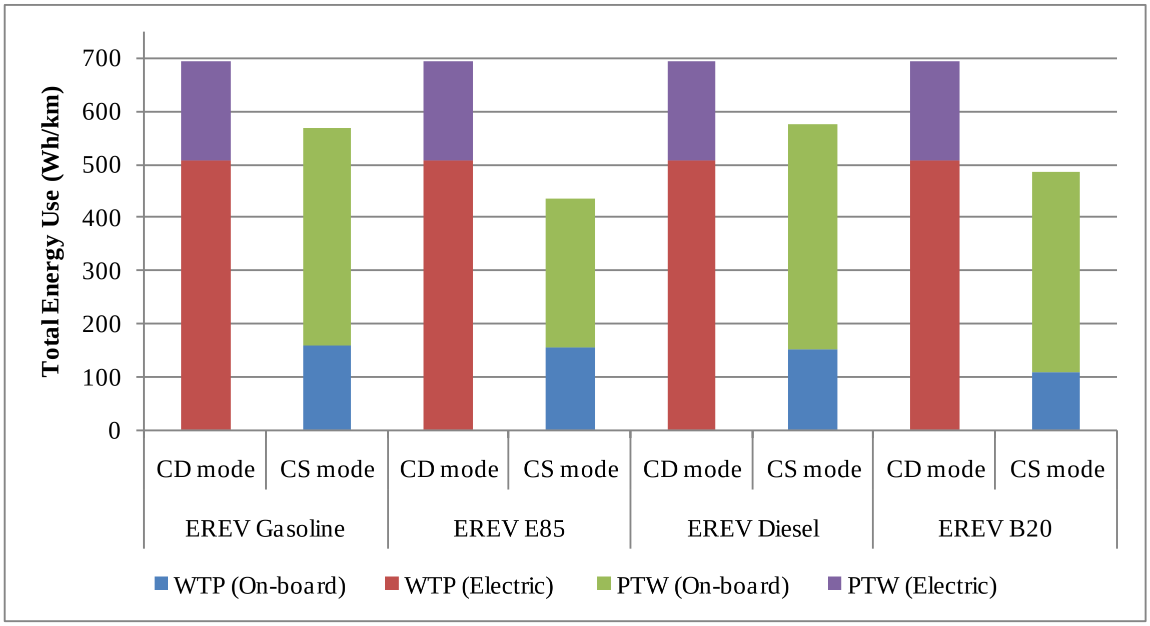


Figure C-2. Total WTW Energy Use for power-split EREV configurations in Alberta.

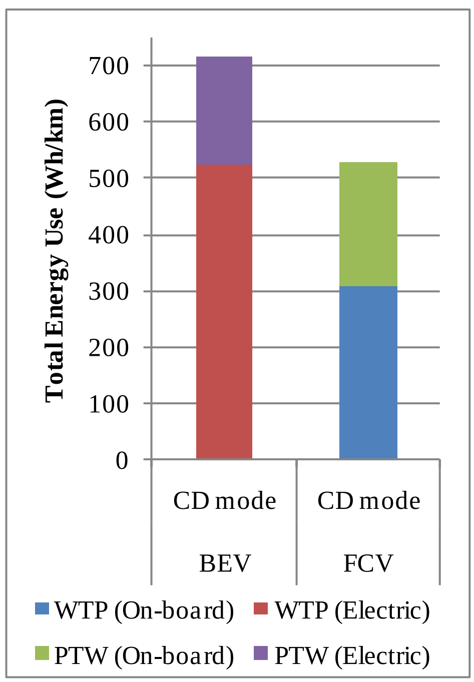


Figure C-3. Total WTW Energy Use for BEV and FCV configurations in Alberta.

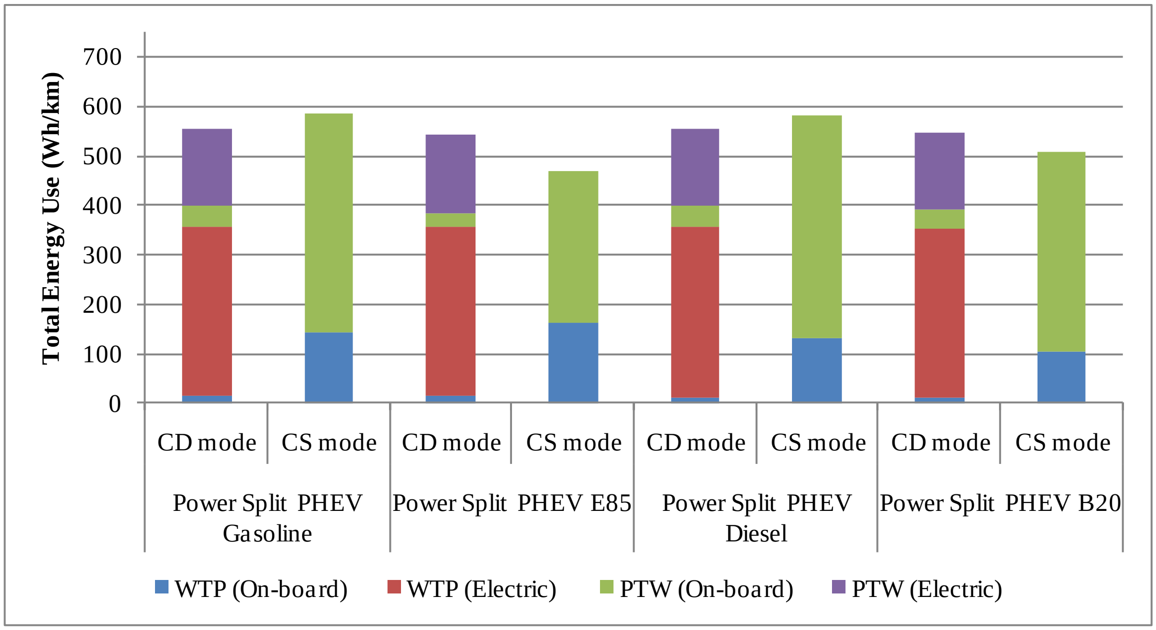


Figure C-4. Total WTW Energy Use for power split PHEV configurations in Ontario.

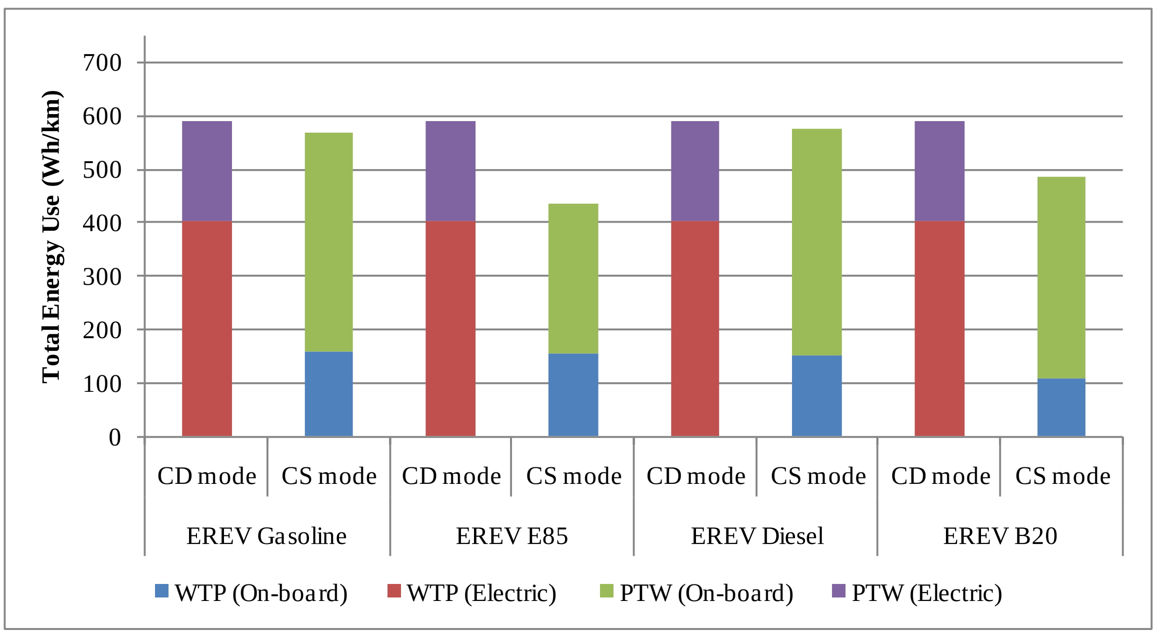


Figure C-5. Total WTW Energy Use for EREV configurations in Ontario.

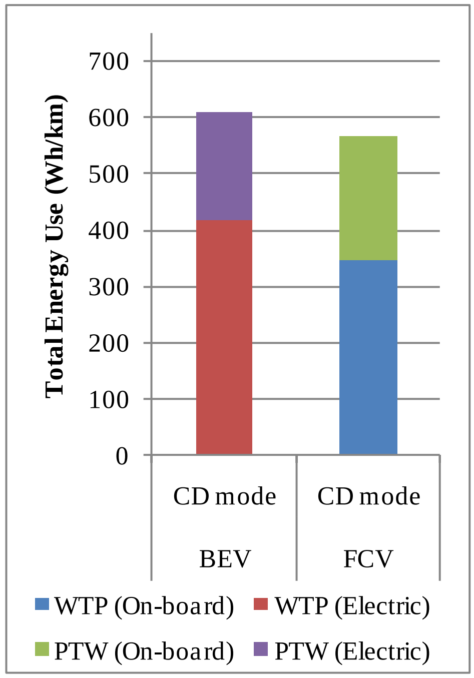


Figure C-6. Total WTW Energy Use for BEV and FCV configurations in Ontario.

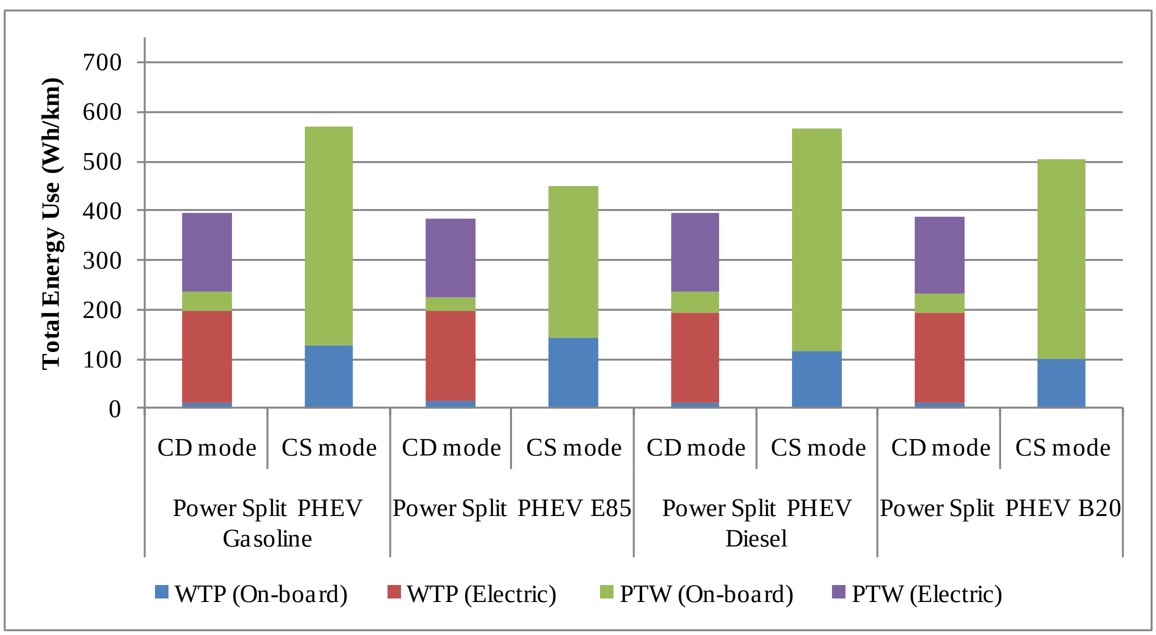


Figure C-7. Total WTW Energy Use for power-split PHEV configurations in Quebec.

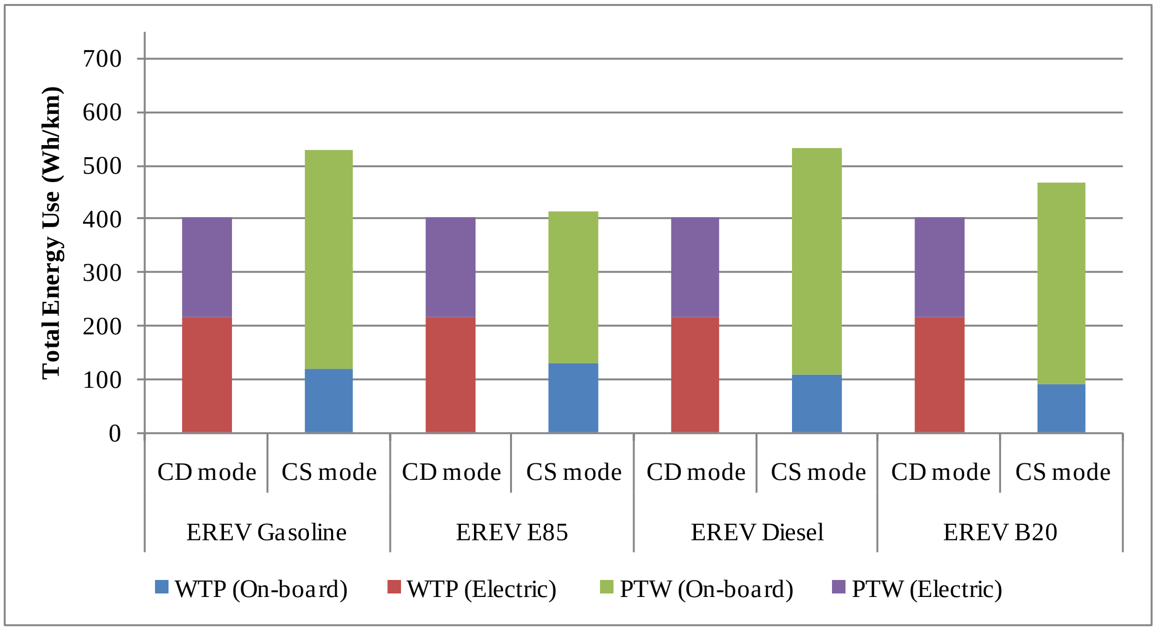


Figure C-8. Total WTW Energy Use for EREV configurations in Quebec.

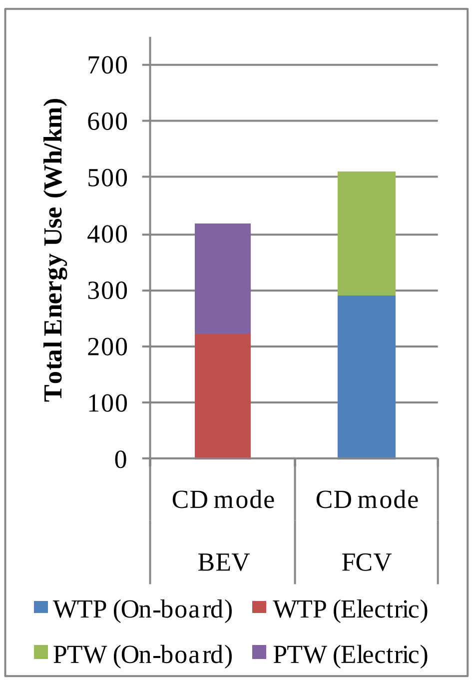


Figure C-9. Total WTW Energy Use for BEV and FCV configurations in Quebec.

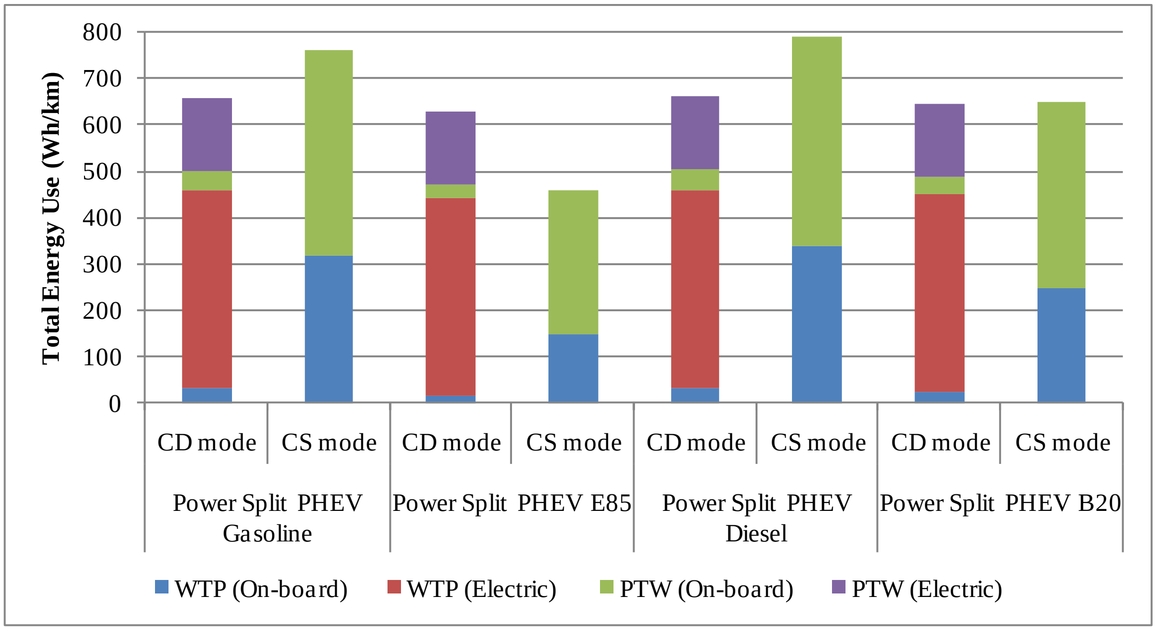


Figure C-10. Total WTW Energy Use for power-split configurations for US Mix.

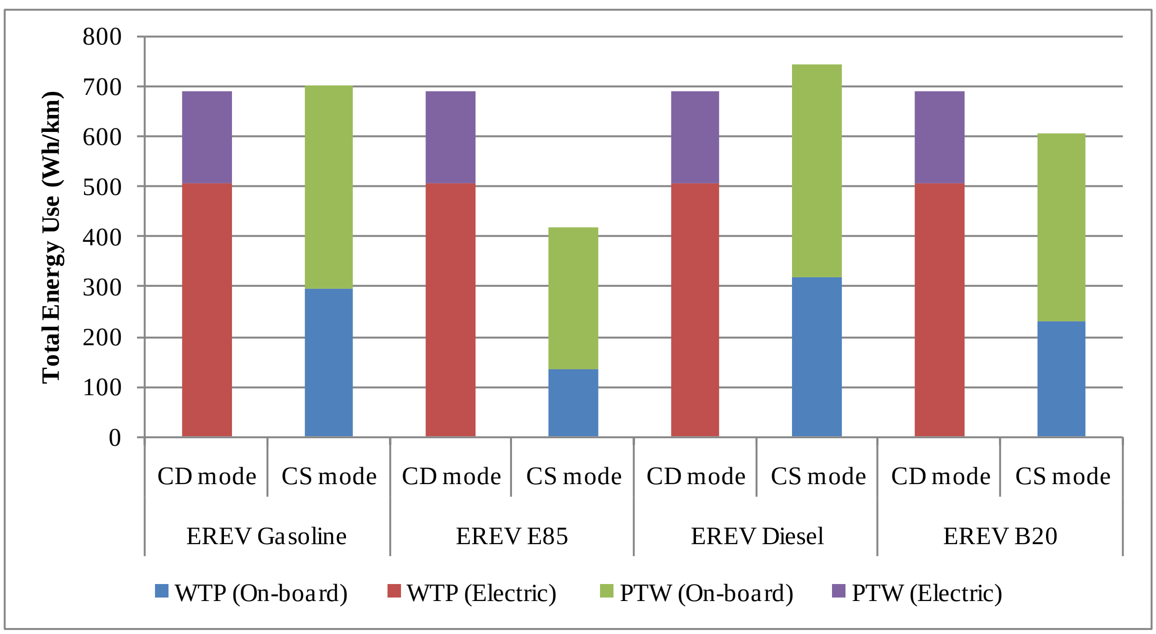


Figure C-11. Total WTW Energy Use for EREV configuration for US Mix.

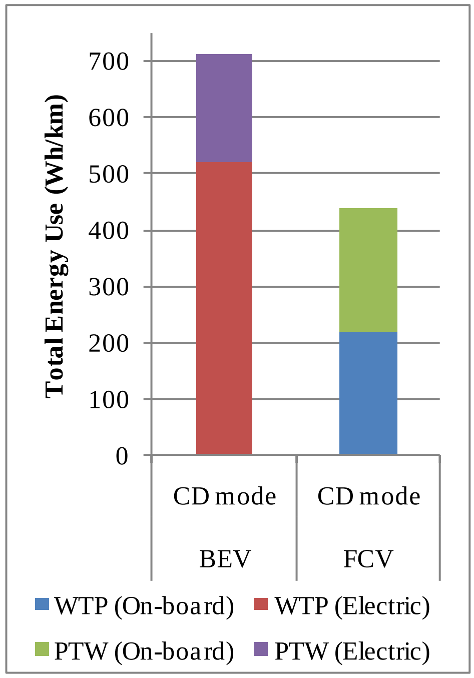


Figure C-12. Total WTW Energy Use for BEV and FCV for US Mix.

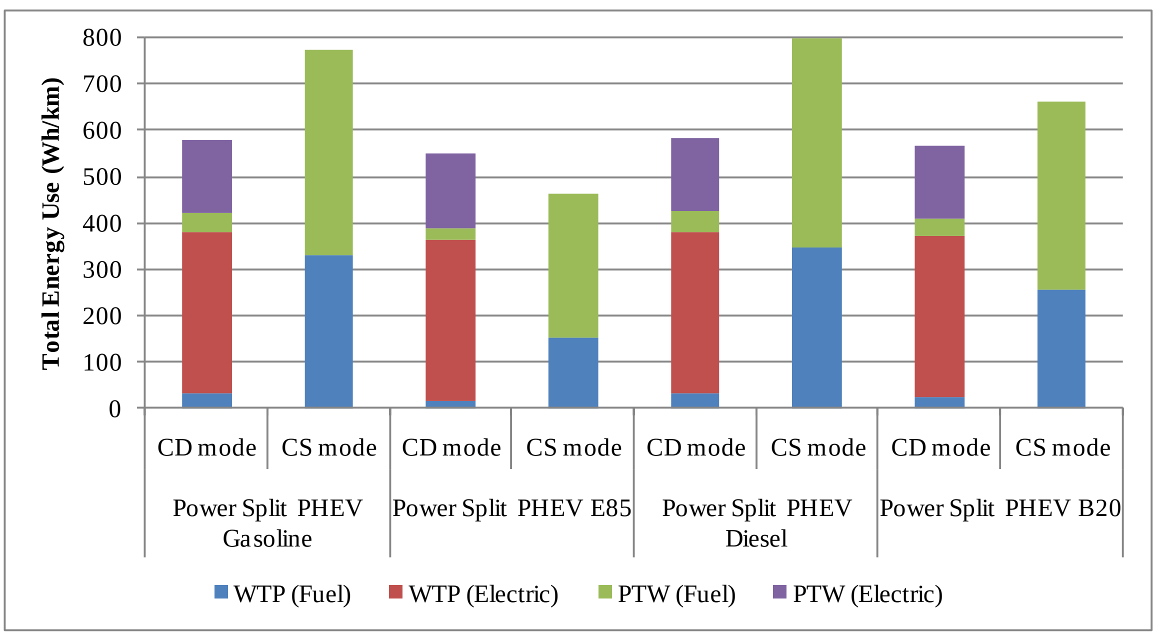


Figure C-13. Total WTW Energy Use for PS PHEV configurations for NE US Mix.

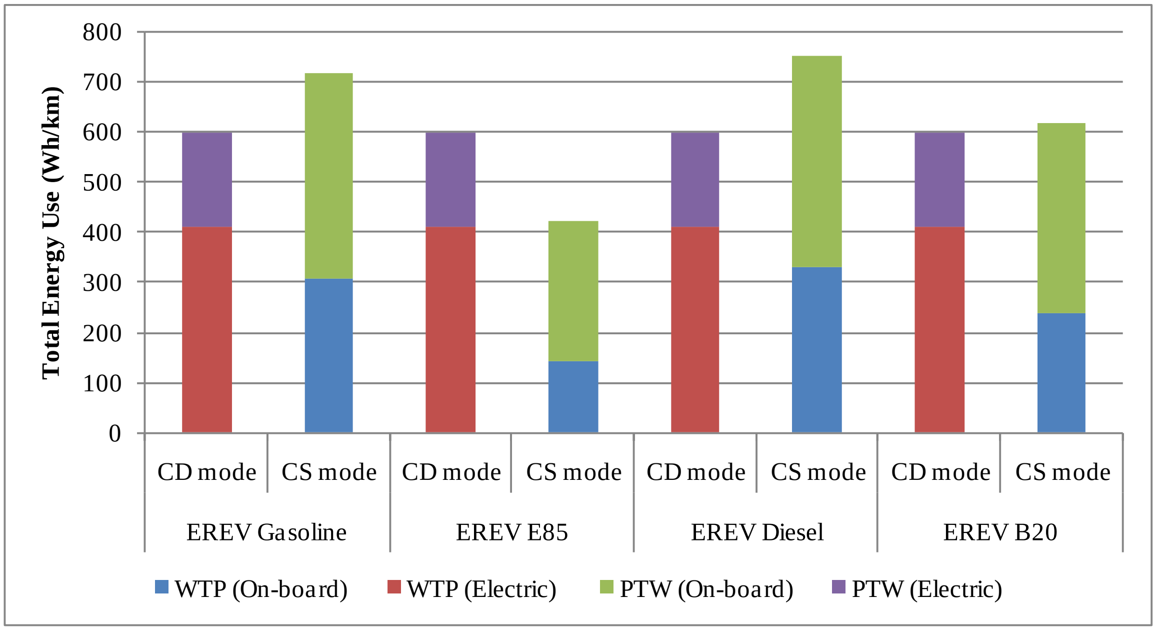


Figure C-14. Total WTW Energy Use for EREV configurations for NE US Mix.

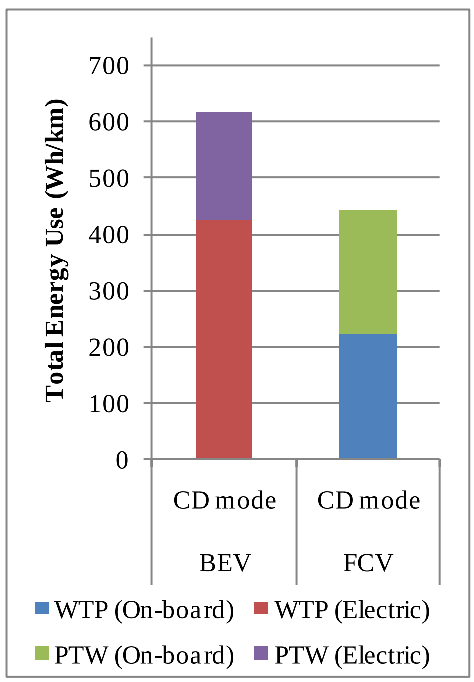


Figure C-15. Total WTW Energy Use for BEV and FCV configurations for NE US Mix.

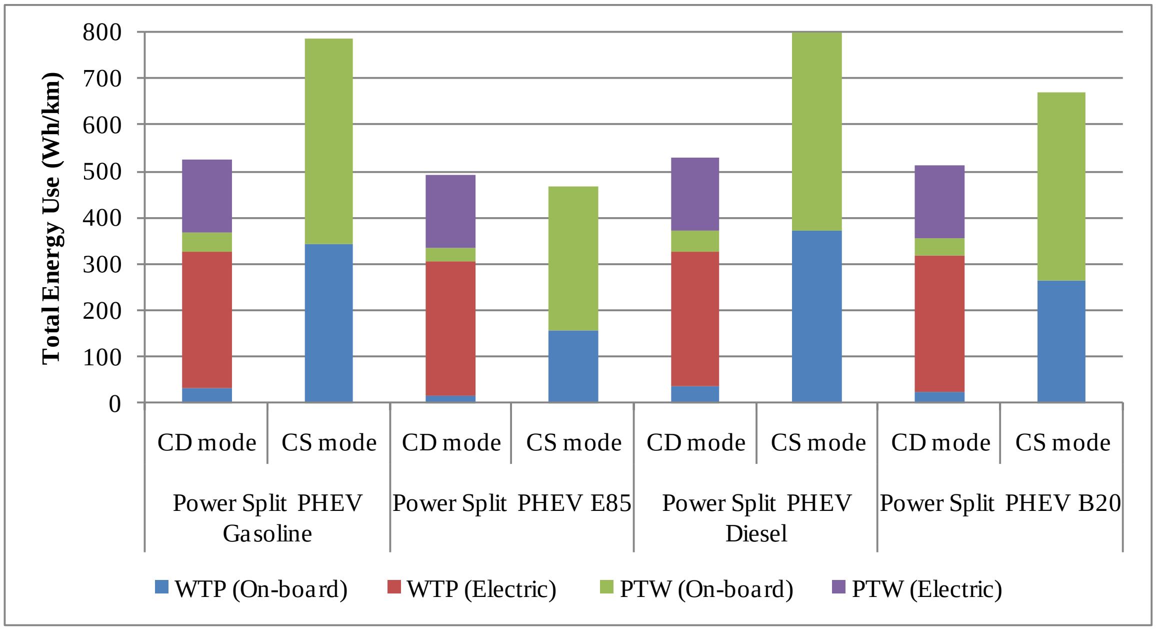


Figure C-16. Total WTW Energy Use for PS PHEV configurations for California Mix.

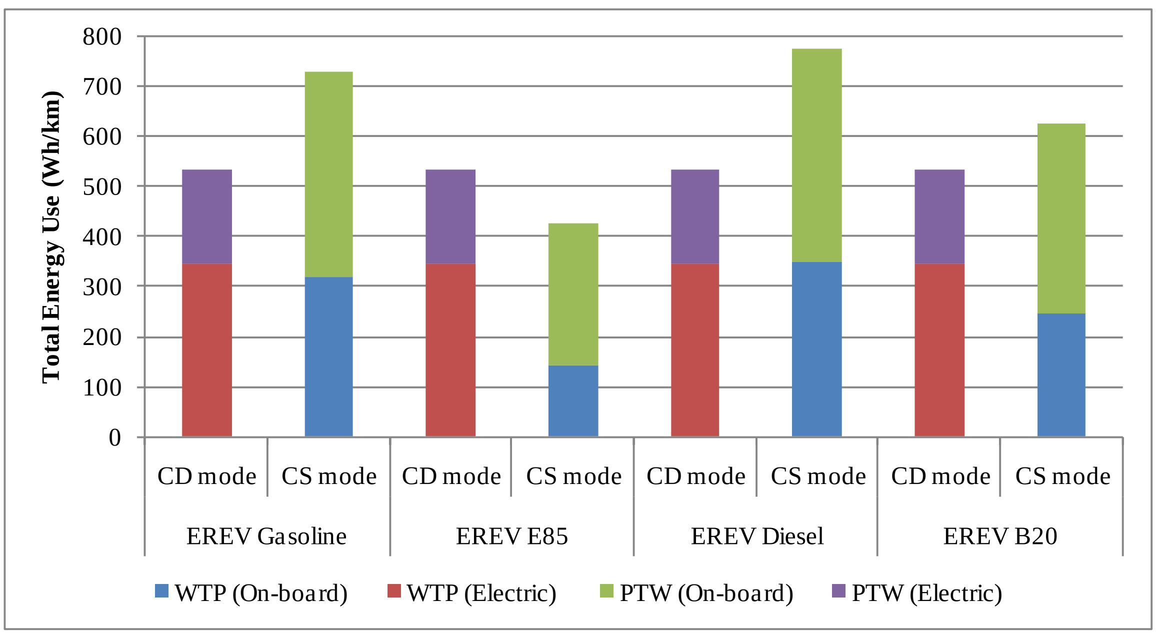


Figure C-17. Total WTW Energy Use for EREV configurations for California Mix.

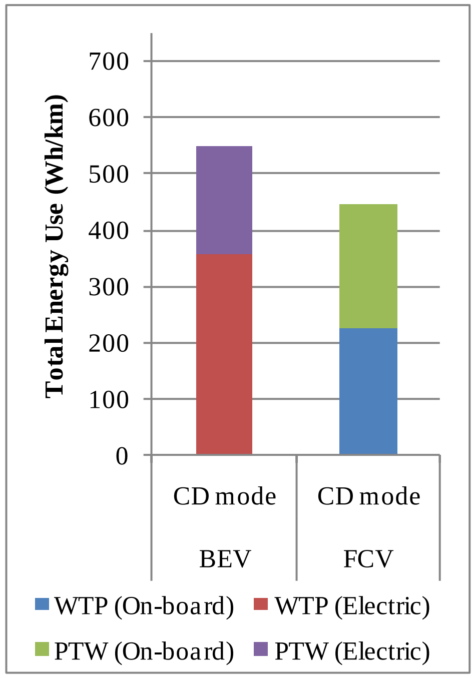


Figure C-18. Total WTW Energy Use for BEV and FCV configurations for California Mix.

WTW Greenhouse Gas Emissions Results

The following graphs represent the total greenhouse gas emissions generated through the use of the vehicles presented in Chapter 5. They are shown as independently colored stacked bars for each region, vehicle technology and operating mode. The WTP On-board (blue) represents the GHG emissions generated during the production of the fuel consumed by the combustion engine in CD and/or CS mode. WTP Electric (red) represents the GHG emissions generated by each power generation mix in order to produce the electrical energy used to power each vehicle in CD mode. PTW On-board (green) represents the tailpipe emissions during blended or CS operation. Given that vehicles operating in CD mode do not generate emissions, the PTW Electric (purple) value is zero for all architectures.

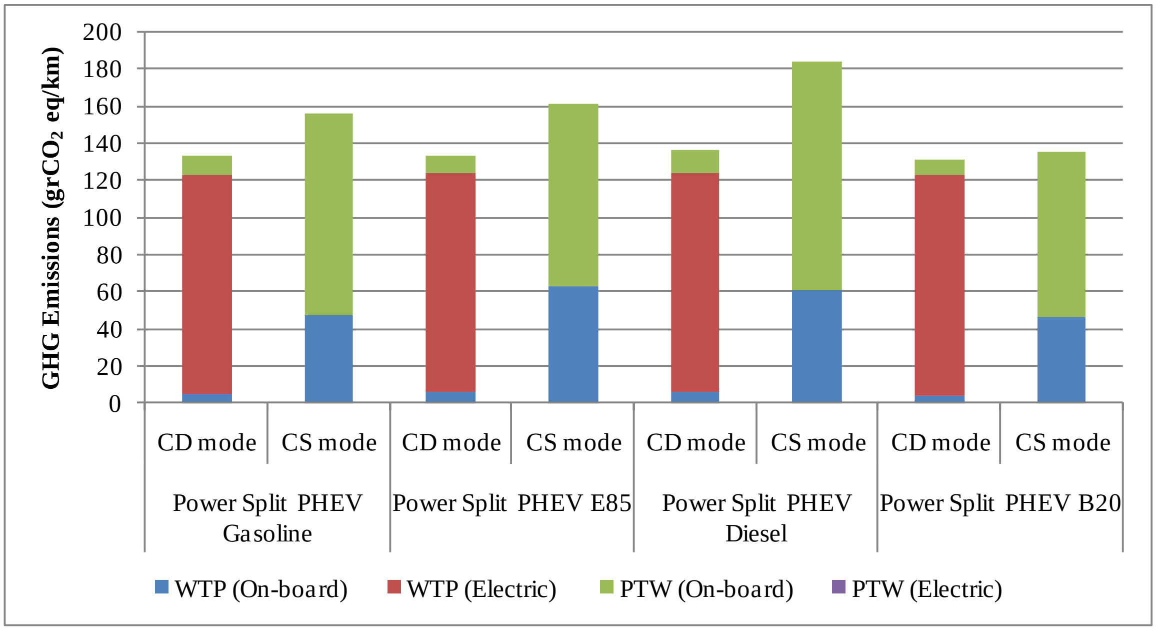


Figure C-19. GHG Emissions for power-split PHEV configurations in Alberta.

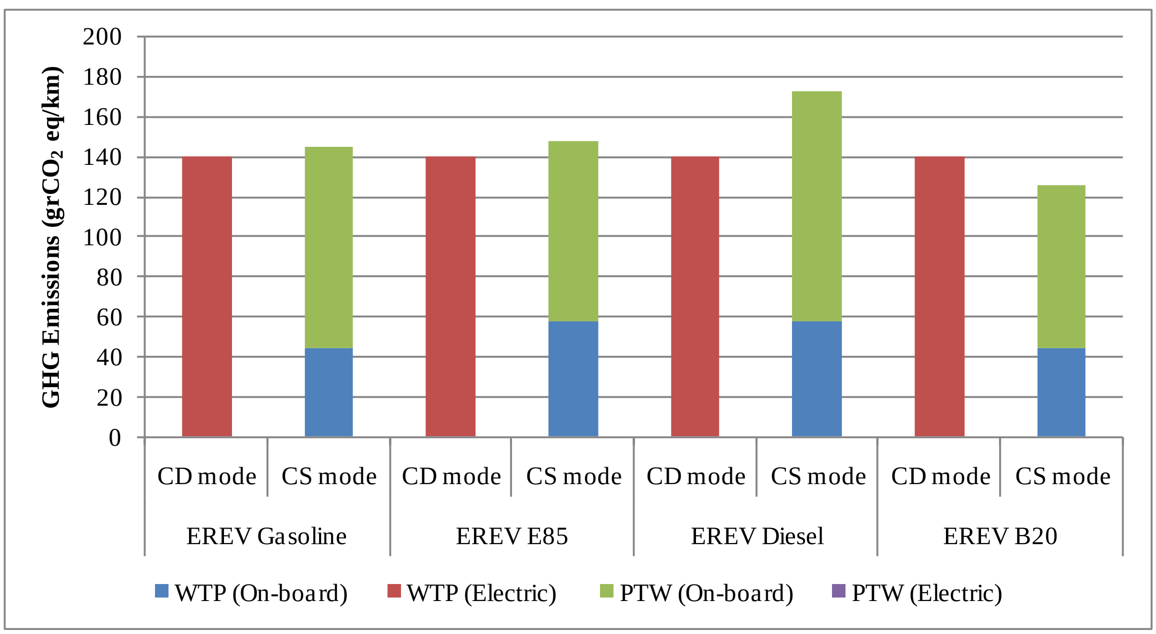


Figure C-20. GHG Emissions for EREV configurations in Alberta.

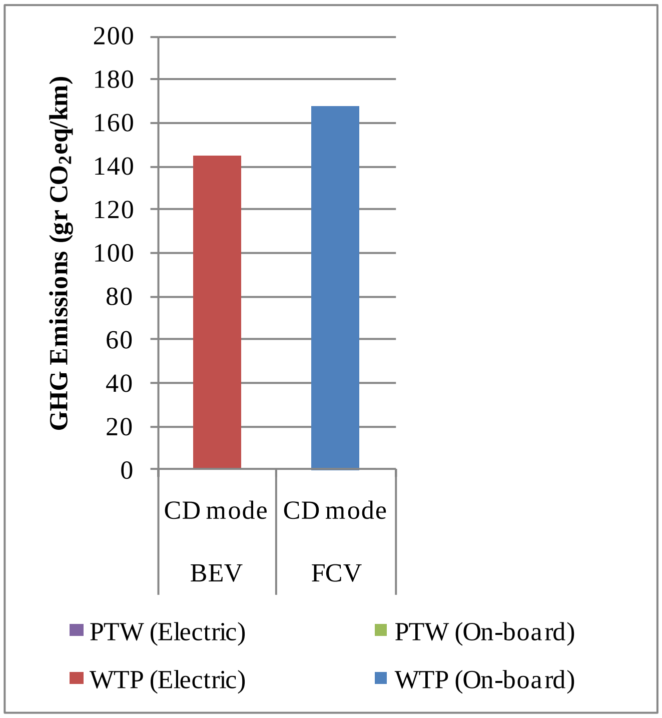


Figure C-21. GHG Emissions for BEV and FCV configurations in Alberta.

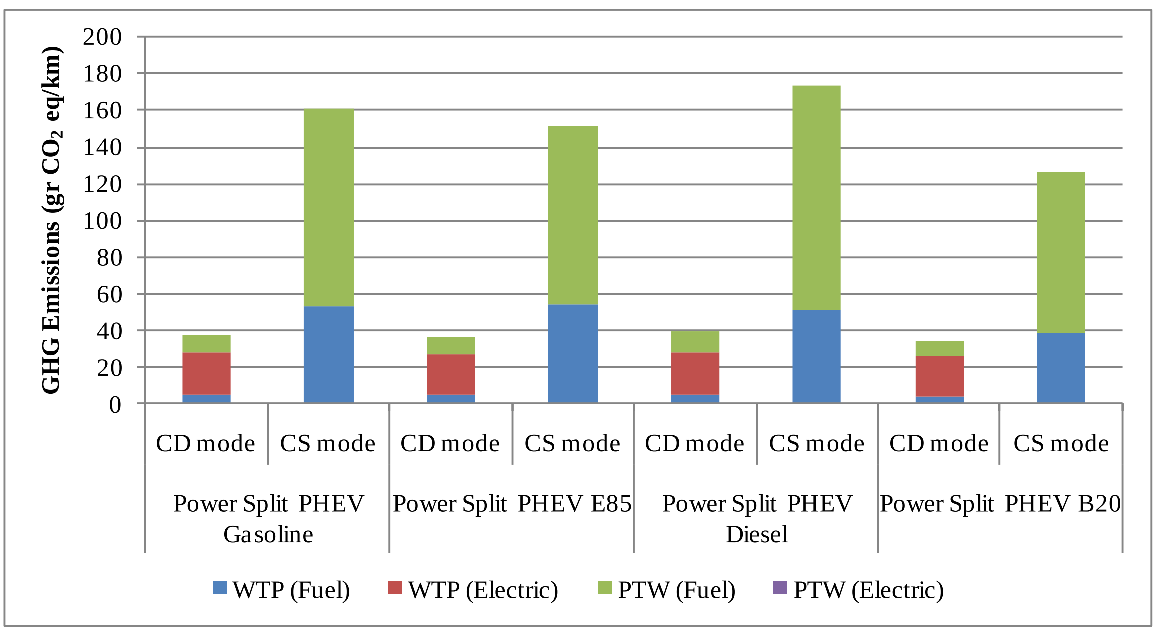


Figure C-22. GHG Emissions for power-split PHEV configurations in Ontario.

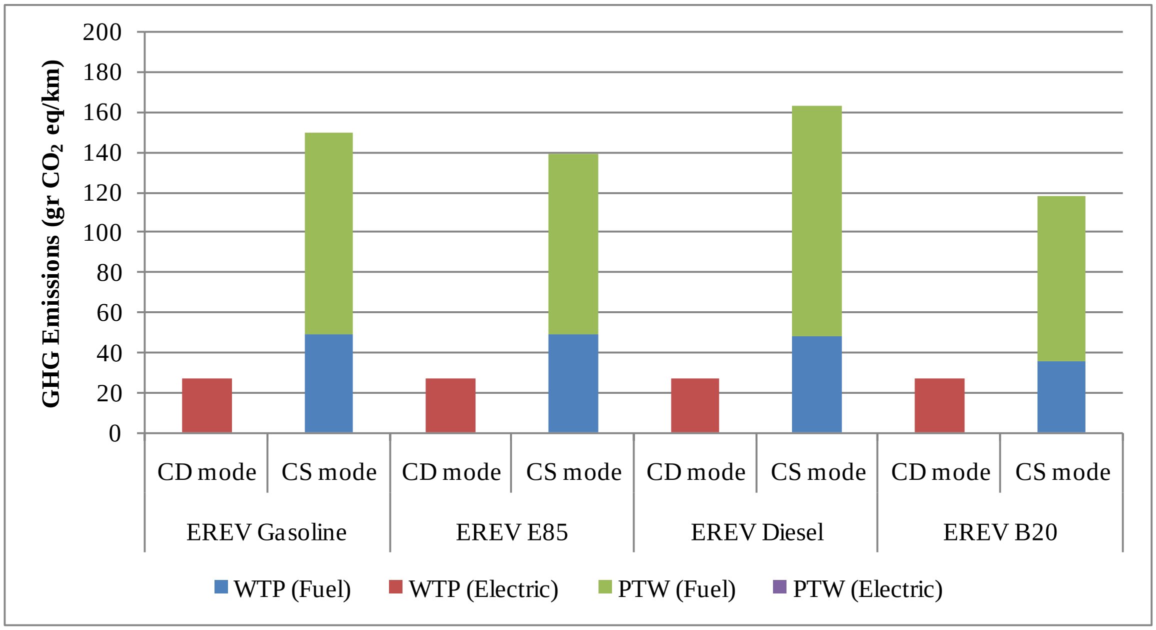


Figure C-23. GHG Emissions for EREV configurations in Ontario.

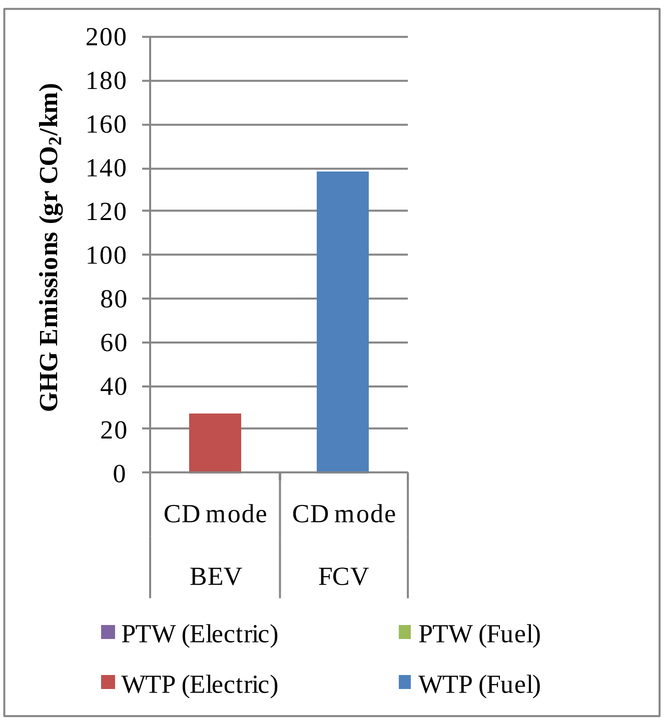


Figure C-24. GHG Emissions for BEV and FCV configurations in Ontario.

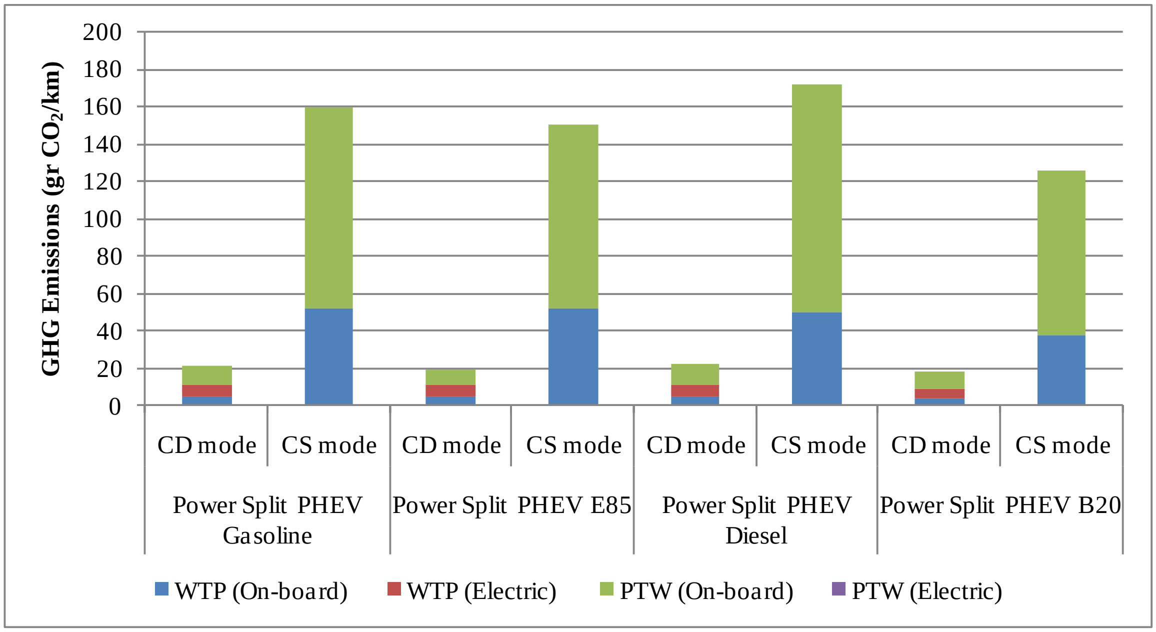


Figure C-25. GHG Emissions for power-split PHEV configurations in Quebec.

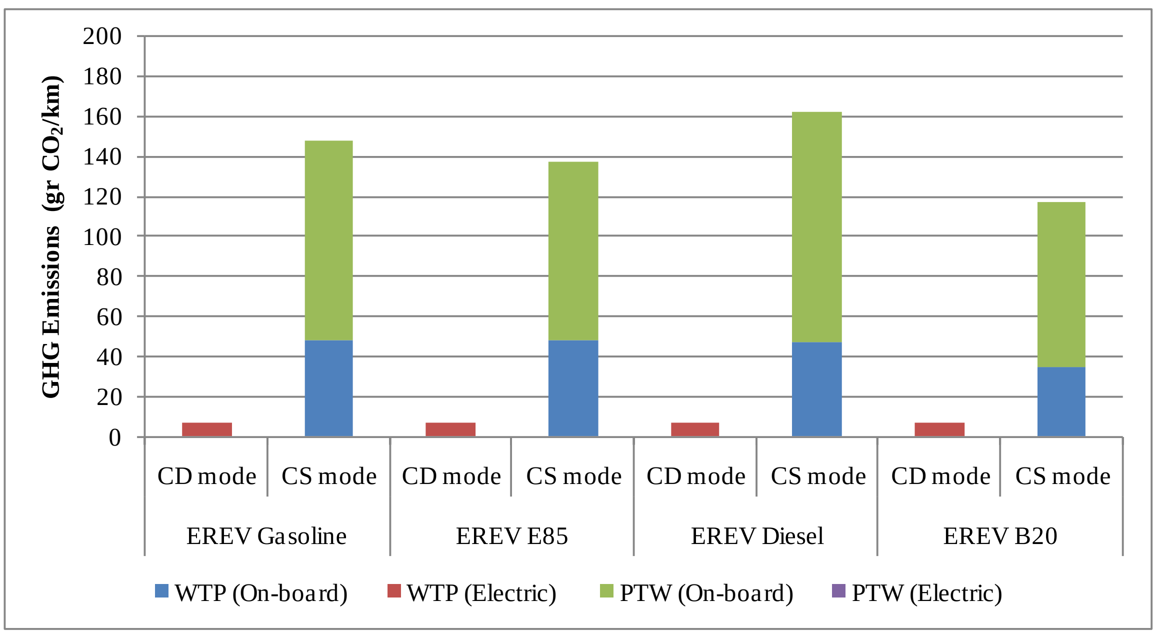


Figure C-26. GHG Emissions for EREV configurations in Quebec.

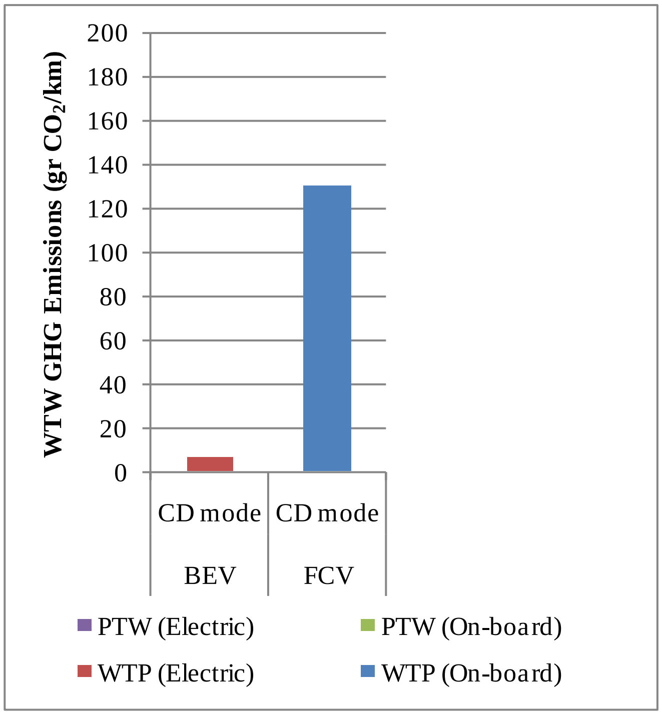


Figure C-27. GHG Emissions for BEV and FCV configurations in Quebec.

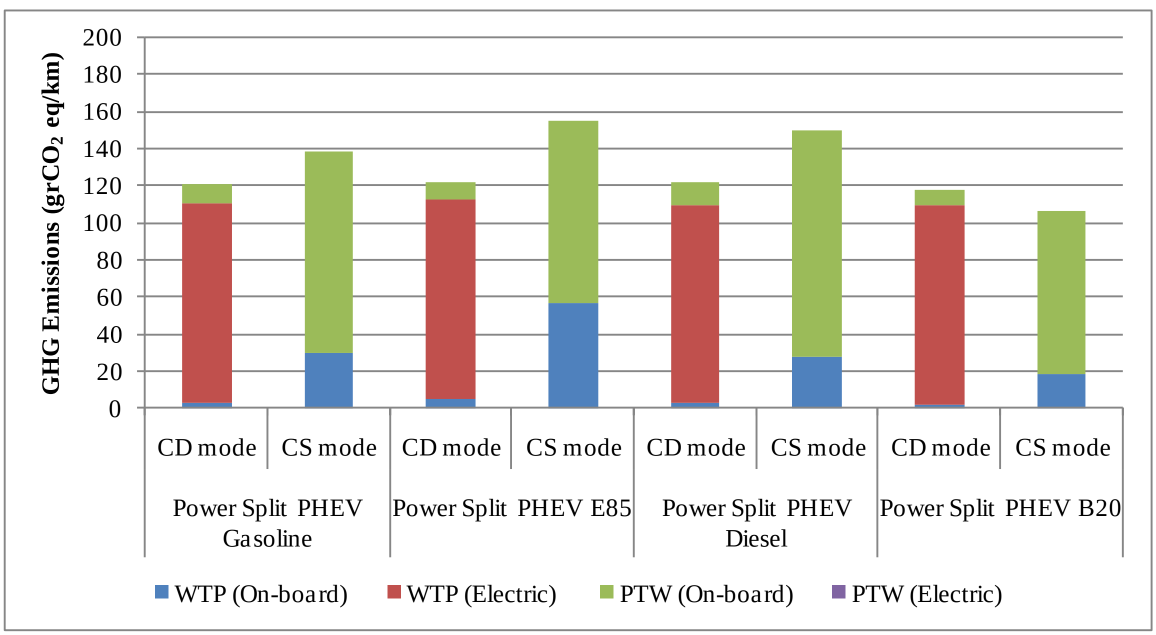


Figure C-28. GHG Emissions for power-split PHEV configurations for US Mix.

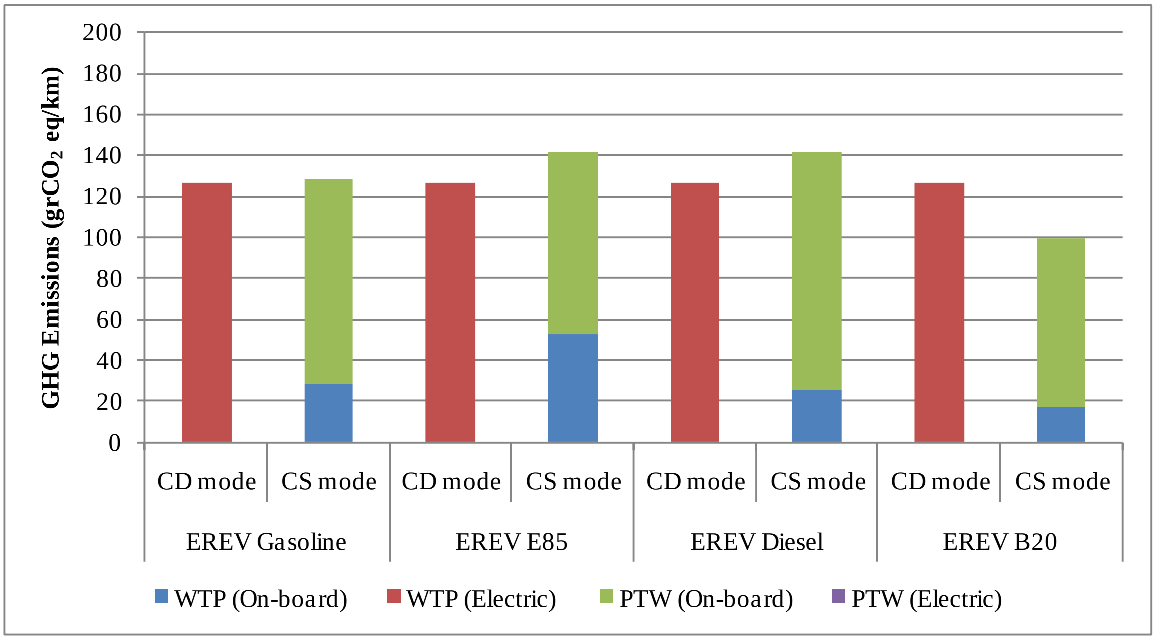


Figure C-29. GHG Emissions for EREV configurations for US Mix.

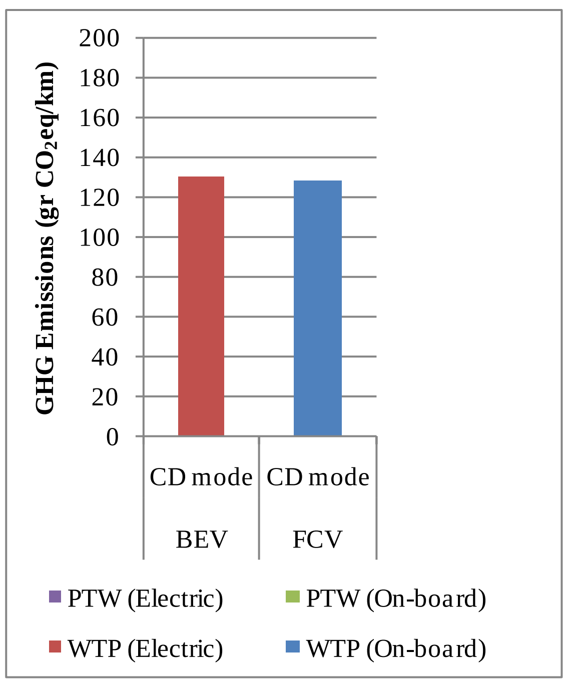


Figure C-30. GHG Emissions for BEV and FCV configurations for US Mix.

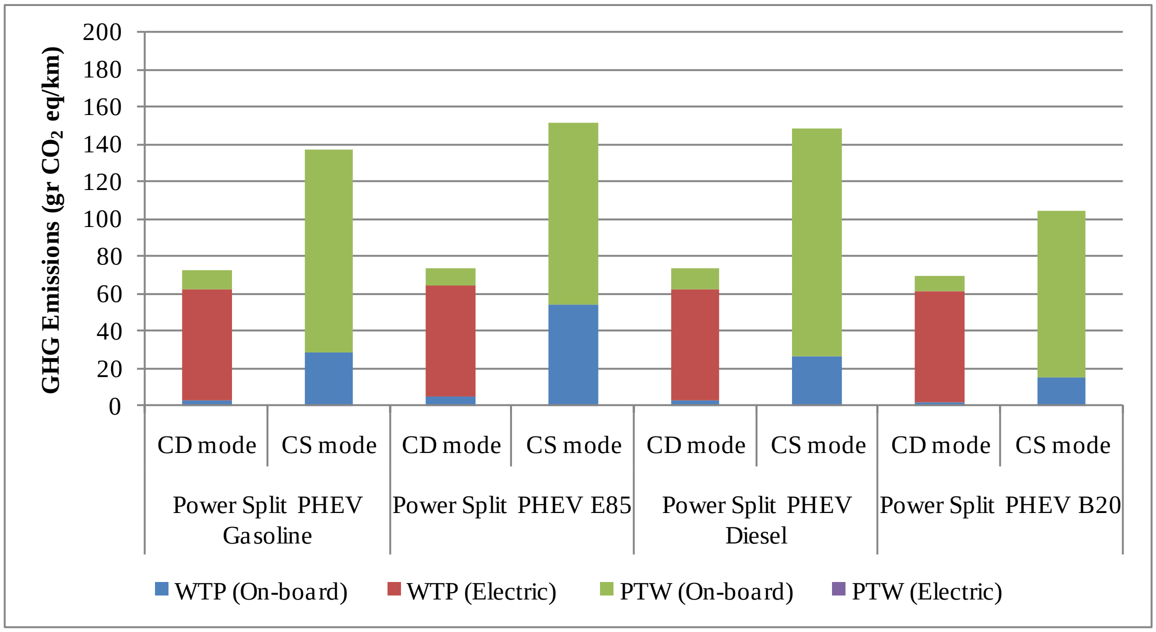


Figure C-31. GHG Emissions for PS PHEV configurations for Northeastern US Mix.

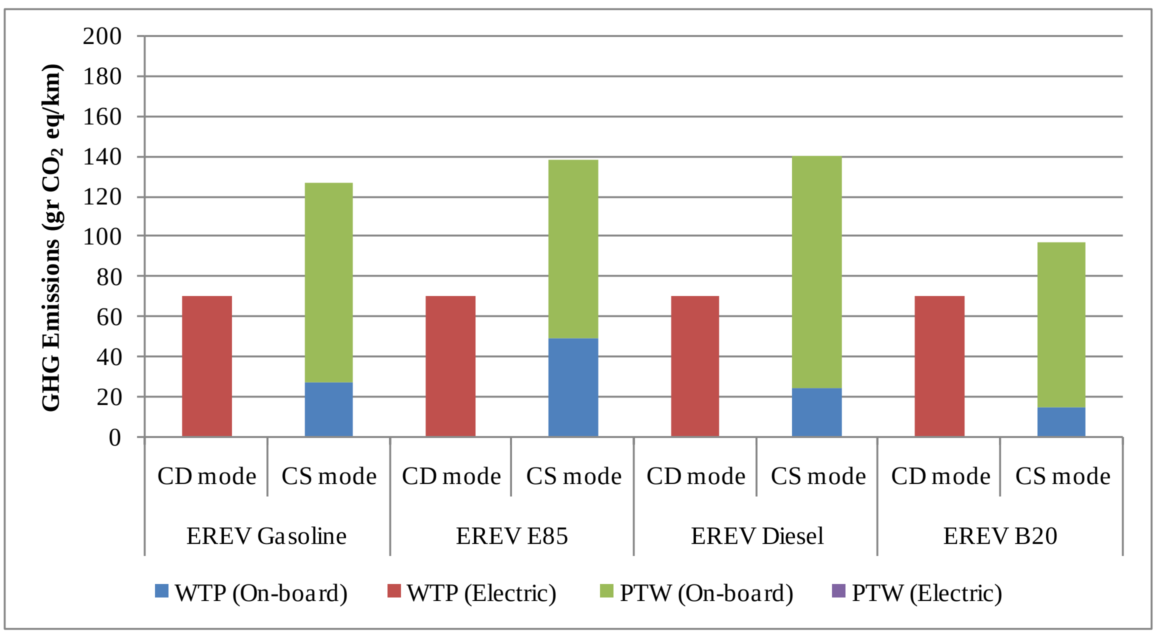


Figure C-32. GHG Emissions for EREV configurations for Northeastern US Mix.

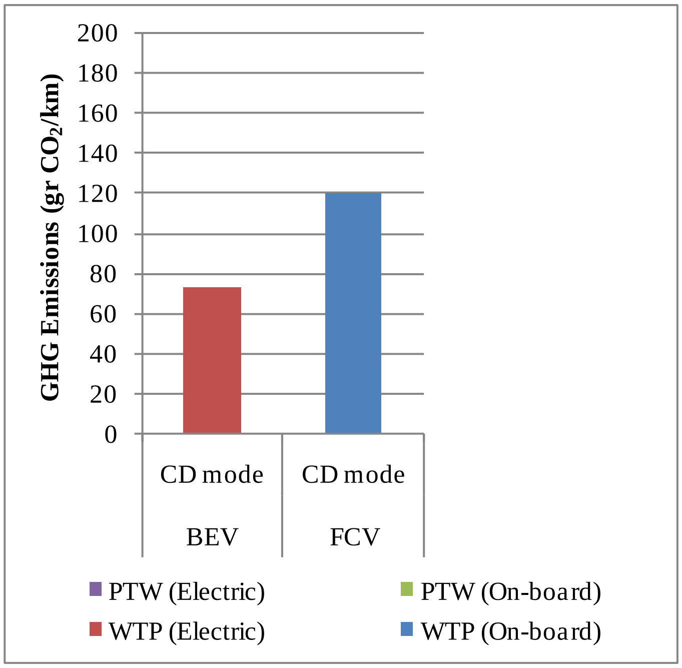


Figure C-33. GHG Emissions for BEV and FCV configurations for Northeastern US Mix.

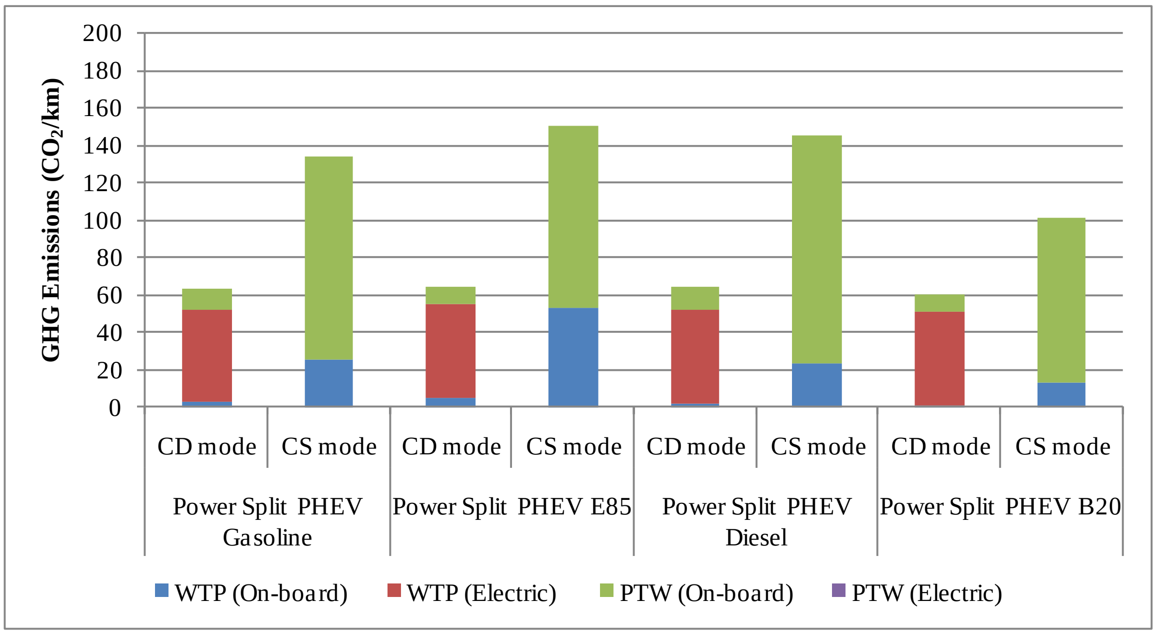


Figure C-34. GHG Emissions for power-split PHEV configurations for California Mix.

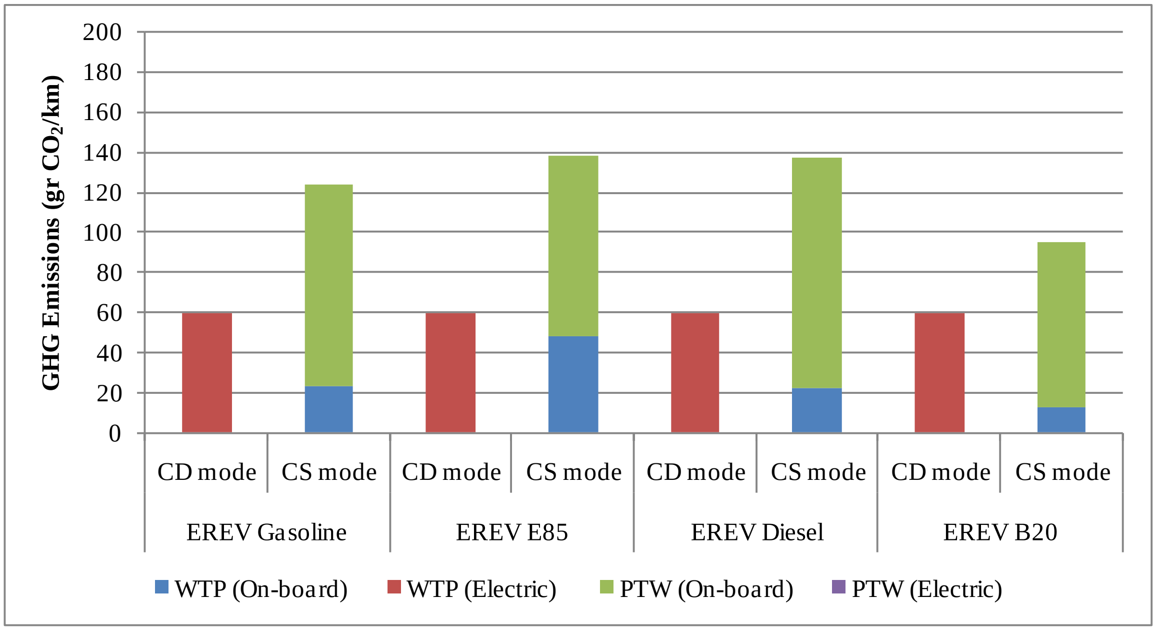


Figure C-35.GHG Emissions for EREV configuration for California Mix.

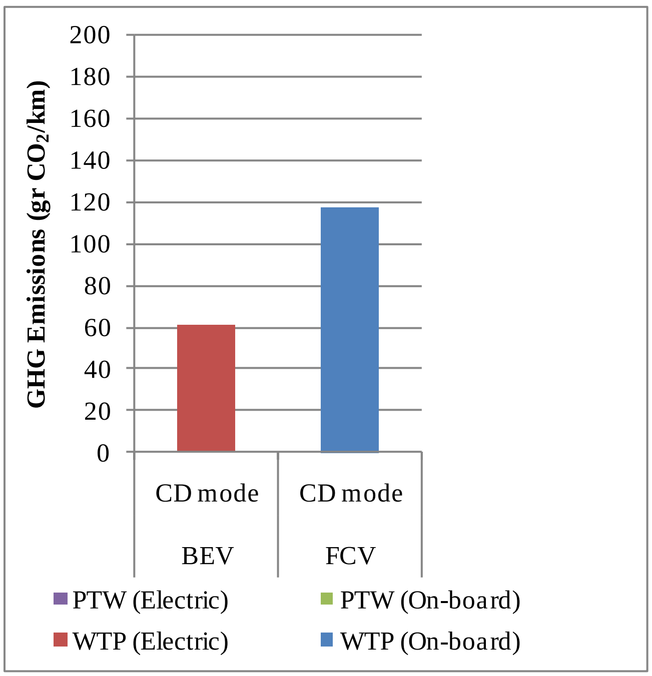


Figure C-36. GHG Emissions for BEV and FCV for California Mix.

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