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Economic and Environmental Impacts of Plug-in Hybrids and Battery Electric Vehicles: A Comparative Analysis

Trideep Ghosh
deepghosh15@gmail.com

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Economic and Environmental Impacts of Plug-in Hybrids and Battery Electric Vehicles: A Comparative Analysis

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Index

List of Acronyms and Abbreviations

BEV	Battery Electric Vehicle
BTU	British Thermal Unit
CCS	Carbon Capture and Sequestration
CO	Carbon Monoxide
CO2	Carbon Dioxide
CO2-eq	Carbon Dioxide Equivalent
CV	Conventional Vehicle
DOD	Depth of Discharge
ECU	Engine Control Unit
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IEA	International Energy Agency
kWh	Kilowatt Hour
LCA	Life Cycle Assessment
Li-ion	Lithium Ion
MJ	Millijoule
MPG	Miles per Gallon

MPGe	Miles per Gallon Equivalent
NiMH	Nickel Metal Hydride
NOX	Nitrogen Oxides
Pb	Lead
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
SOX	Sulfur Dioxide
UCS	Union of Concerned Scientists
USDOE	United States Department of Energy
USDOT	United States Department of Transportation
USEPA	United States Environmental Protection Agency
VOCs	Volatile Organic Compounds

List of Tables

List of Figures and Equations

Abstract

Greenhouse gas (GHG) emissions from anthropogenic sources are the leading contributors to global climate change. Over the past century, GHG emissions have increased tremendously due to causes such as deforestation and the burning of fossil fuels. In the US, about 28% of these GHG emissions come from the transportation sector. By replacing conventional gasoline powered vehicles with plug-in hybrid (PHEV) and battery electric (BEV) vehicles, the amount of GHG emissions released can be reduced significantly.

In order to make the transition to alternative fueled vehicle, consumers must be informed on the economic and environmental consequences of purchasing one. This paper compares PHEVs and BEVs for both GHGs and costs. By comparing the results of a lifecycle GHG analyses of PHEVs done by Samaras and Meisterling with one done on BEVs by Aguirre et al., this paper found that BEVs produce about 4,000 kg fewer lifecycle GHG emissions than PHEVs over the life of the vehicles, using the US average electricity grid mix. Additionally, a lifecycle cost comparison was done to calculate the payback periods of PHEVs and BEVs when compared to a conventional gasoline vehicle. The analysis showed that the BEV has the lowest lifetime costs due to its increased fuel and maintenance cost savings. With the $7,500 Federal tax credit, the payback period of the BEV will only be about four months, as opposed to 2-9 years for a PHEV, depending on the specific model purchased.

It should be noted that the GHG emissions associated with charging PHEVs and BEVs is completely dependent on the local electricity grid mix. In highly carbon-intensive areas, it may be possible to generate more GHG emissions by operating a BEV than a conventional gasoline car. Because of this, policy makers need to focus on implementing measures such as carbon-cap programs or clean energy initiatives in order to lower nationwide GHG emissions. By coupling these strategies with increased incentives for alternative fueled vehicles, it is possible to see a significant reduction in GHG emissions from the transportation sector.

Chapter 1: Introduction

1.1: Current Technologies and their Effects on Greenhouse Gas Emissions

Over the last century, human beings have progressively become more reliant upon passenger cars for meeting their daily needs. The majority of Americans need their cars to get to and from work, go out and purchase groceries or run other errands, take their kids to school, go to the doctor, or a myriad of other tasks that may not be possible without a vehicle. This reliance upon cars, and in particular the fossil fuel internal combustion engines that power the vast majority of them, comes with significant drawbacks. Greenhouse Gas (GHG) emissions from the burning of fossil fuels, along with other anthropogenic sources such as deforestation, are among the leading contributors to global climate change (Grahn et al. 2009). The transportation sector in the United States makes up 28% of the total annual GHG emissions. Of this, light-duty vehicles make up 63% of the emissions, with 34% coming from passenger vehicles and 28% from light duty trucks (sport utility vehicles, pickup trucks, and minivans) (DOT 2006). In addition, the annual vehicle miles traveled from all passenger vehicles in the U.S. has increased by over 100% from 1,144,673 miles in 1960 to 2,839,083 miles in 2011 (DOT 2013). Although efficiency technologies in passenger vehicles have improved greatly in this time, this increase in miles traveled has still led to greater annual GHG emissions from passenger vehicles.

1.2: The Shift to Alternative Fueled Vehicles

The global automotive industry is currently seeking to reduce emissions from the transportation sector for many reasons, including the increase in greenhouse gas and particulate emissions that affect climate change and human health, rapid oil depletion and the rising cost of fossil fuels, issues with energy security, dependency from foreign sources, and population growth (Pollet 2012).

This paper focuses primarily on the GHG emission impacts of plug-in electric (PHEV) and battery electric (BEV) vehicles. More than 60% of all US transportation emissions come from cars and light trucks (UCS 2014). Transport emissions are estimated to increase by 84% in 2030 due to increases in population and increased economic activity

(Tomlinson, 2009). By moving towards alternative energy powered vehicles, the amount of emissions released can be reduced in an effort to slow down and combat the effects of climate change.

This paper also examines how the shift to alternative energy vehicles can reduce impacts on human health, especially in an urban setting. Although the production of these alternative fuels and vehicles utilize fossil fuels, the harmful pollutants generated are usually emitted from power plants in areas of low population density rather than tailpipe pollutants from vehicles in highly populated areas.

1.3: Overview of the Types of Alternative Fuel Vehicles

The International Energy Agency (IEA) has considered three alternative powertrain technologies as capable of delivering a near-zero emission sustainable road transport system. The powertrains include biofuels, battery electric vehicles (BEVs), and hydrogen fuel cell vehicles (IEA 2009). This paper will focus on two of these technologies: PHEVs and BEVs.

PHEVs utilize a combination of rechargeable batteries and an internal combustion engine (ICE). They share characteristics with BEVs by needing to plug in to an external power source to connect to the electrical grid. They are generally more affordable than BEVs or HFCVs, but do create more emissions due to the ICE component in their powertrain.

BEVs use the chemical energy in rechargeable battery packs to power their electric drive motors. The battery packs must be recharged by connecting the vehicle to the electrical grid, usually through a modified wall outlet. They do not produce any emissions while running, but their total emissions depend entirely upon the electrical grid mix in their area of operation (i.e. the total emissions will be higher if most of the electricity generated in their specific area was generated from coal-fired plants versus renewable sources) (Offer et al. 2009).

1.4: Alternative Fuel Vehicles and Consumers

Consumers are faced with many choices when in the market for a new vehicle. It is becoming increasingly popular to buy more efficient vehicles because it will be economically beneficial in the long run, or because it contributes towards lowering emissions to combat climate change, or both. Since 2012, BEV sales are up 447.95% (33,617 vs 6,135), PHEV sales are up 35.86% (32,718 vs 24,082), and conventional hybrid electric vehicle (HEV) sales are up 21.03% (360,245 vs 297,656) (EVObsession, 2013). There are currently no HFC vehicles available to the public.

The Union of Concerned Scientist (UCS) advises that a consumer purchase the most fuel-efficient, lowest-emissions vehicle that meets the majority of their needs and fits their budget (UCS 2011). Evaluating the environmental impacts and cost savings of alternative fuel vehicles can be difficult, and consumers need more information on the types of vehicles and their energy sources to be able to find the one that meets their needs.

One reason that alternative fuel vehicles have not overtaken conventional fuel vehicles is because of the initial premium in price. The average price difference for a PHEV versus a conventional gasoline vehicle of similar size ranges from $8,900 to $13,095, depending on the size of the battery pack in the PHEV (NRC 2010). Initial costs for BEVs are also currently higher than their gasoline base models. The Ford Focus electric for instance starts at $29,995, whereas the gasoline fueled Ford Focus S starts at $15,135. Even the high-end gasoline model, the Ford Focus ST, starts at $21,950 (Ford Motor Company 2014). These prices are much higher than a similar gasoline version of the car would cost, although auto manufacturers foresee a significant decrease battery costs in the coming years.

1.5: Purpose of this Paper

This paper compares PHEVs and BEVs for both GHGs and costs. It examines which has the least environmental impacts in terms of their life-cycle analysis of GHG emissions, including vehicle manufacturing, fuel generation, and disposal of retired equipment. Additionally, it examines which type of vehicle provides the most economical benefits to consumers, taking into account purchase and operational costs, infrastructure availability, and safety measures. This analysis is based on a wide array of documents, fact sheets, and analyses from governmental agencies, automobile manufacturers, environmental organizations, and academic institutes that pertain to the two types of alternative energy vehicles. The results of this analysis can be used by consumers to aid them in purchasing decisions related to these two types of vehicles.

This paper starts with an introduction and an overview including terms and information that are relevant to both PHEVs and BEVs. Chapters 3 and 4 cover information pertaining to PHEVs and BEVs, respectively. These chapters include sections on technology, price, range, efficiency, lifecycle greenhouse gas emissions, and environmental impacts from each type of vehicle. Chapter 5 includes a comparative analysis on the lifetime costs and GHG emissions of PHEVs and BEVs, using information from two case studies. Chapter 6 summarizes the conclusions made in the paper and uses the findings to generate a recommendation for consumers.

Chapter 2: Overview

2.1: Miles per Gallon Equivalent (MPGe)

Efficiency of PHEVs (in electric-only operation) and BEVs is expressed as kilowatt hours (kWh) per 100 miles (kWh/100m). This value shows how efficiently the vehicle converts electricity into miles traveled. Although this calculation of energy unit per mile is common in Europe and other countries, the US uses a calculation of miles per energy unit (miles per gallon, or MPG). Since the battery components of PHEVs and BEVs do not use gallons of gasoline, the USEPA has created a way of converting kWh/mile to miles per gallon equivalent (MPGe).

MPGe measures the average amount of miles traveled per unit of energy consumed. The USEPA uses MPGe to compare energy consumption of alternative fuel vehicles with the fuel economy of conventional ICE vehicles expressed as miles per US gallon (USEPA 2011). The MPGe rating is based on a formula derived by the USEPA in which one gallon of unleaded gasoline is equivalent to 115,000 British thermal units (BTUs). This means if one gallon of unleaded gasoline was ignited, it would create 115,000 BTUs of heat. Creating this much heat from electricity would take 33.7 kWh (USEPA 2010). For example, if a PHEV could travel 50 miles on 10 kWh of electricity (no gasoline used), it would be rated at 168.5 MPGe (see Equation 2.1).

Equation 2.1: Example of MPGe using USEPA formula

$$\left(\frac{33.7\ kWh}{1\ gal\ gasoline}\right) * \left(\frac{50\ miles}{10\ kWh}\right) = 168.5\ MPGe$$

MPGe is only useful when comparing alternative fueled vehicles to conventional gasoline vehicles. For consumers more focused on cost, kWh/100m is a much better rating to examine.

2.2: Marginal Electricity Generation Mix – PHEVs and BEVs

The environmental performance of PHEVs and BEVs is largely based on the source of the electricity used to charge their batteries (Elgowainy 2009). Since different regions of the US employ different power generation methods, the GHG and pollutant emissions can vary by region. PHEV and BEV charging will have lesser GHG and criteria pollutant impacts in regions that incorporate a higher percentage of low-carbon fuels (such as natural gas) and renewable energy sources into their electricity generation mix.

2.3: Batteries

There are two main types of battery used in PHEVs and BEVs: nickel metal hydride (NiMH) and lithium-ion (Li-ion).

Up until recently, NiMH batteries were the main type of battery used in PHEVs and BEVs. They were known for their design flexibility, environmental acceptability, low maintenance, moderate power and energy densities, cost, and safety (Offer et al. 2011).

Currently, auto manufacturers are moving towards using Li-ion batteries in their PHEVs and BEVs. Li-ion batteries are lighter, more compact, and have higher energy densities (80-120 Wh/kg) than NiMH batteries. However, they face challenges such related to aging, cycle life, and high cost of manufacturing. As technology improves, Li-ion batteries will become cheaper and more efficient, making them a likely candidate for use in PHEVs and BEVs in the future. This paper will assume the use of a Li-ion battery in all PHEVs and BEVs.

2.4: Carbon Dioxide Equivalent Emissions (CO_2-eq)

CO_2-eq is a value used to compare the global warming potential of various GHGs over a certain amount of time (usually 100 years) relative to that of carbon dioxide (CO_2). For example, methane has a global warming potential of 21, meaning that one ton of methane would have the same global warming impacts as 21 tons of CO_2. Table 2.1 shows the CO_2-eq values for four major GHGs.

Table 2.1: CO_2-eq for four major GHGs (UNFCCC 2009)

Greenhouse Gas	Formula	CO2-eq
Carbon dioxide	CO_2	1
Methane	CH_4	21
Nitrous oxide	N_2O	310
Sulphur hexafluoride	SF_6	23,900

Chapter 3: Plug-In Hybrid Electric Vehicles (PHEVs)

3.1: Technology – How do PHEVs work?

Conventional hybrid vehicles are based on three basic powertrain architectures including series hybrids, parallel hybrids, and series-parallel hybrids, while plug-in hybrids use a modified series-parallel powertrain.

Series hybrids, also known as extended-range electric vehicles (EREV), utilize an electric motor to provide power to the drive motor. The motor receives electric power from either an internal combustion engine (ICE), or from a battery pack. The battery pack is recharged through the ICE coupled to a generator, as well as through regenerative braking. The engine control unit (ECU) determines how much power comes from the battery or ICE/generator set. The ICE on a series hybrid is usually very small, while the battery pack is larger to provide peak driving power needs. These large batteries, electric motors, and generators add to the cost of these vehicles.

Series hybrids perform best in stop and go traffic due to the fact that their ICE is not coupled to the wheels, allowing it to operate within a high-efficiency power range while also eliminating the need for a multi-speed transmission and clutch. Because of this, series hybrids are top contenders for urban buses and work vehicles.

Parallel hybrids utilize an ICE in combination with an electric motor to provide power to the wheels. The ECU, along with a transmission, allows the ICE and electric motor to work in parallel. Parallel hybrids use much smaller battery packs than series hybrids, and rely mainly on regenerative braking to recharge them. In times of low power demands, the drive motor can be used to recharge the battery packs, similar to an alternator in a conventional gasoline vehicle.

Since the ICE is directly coupled with the drive motor, it increases the efficiency of converting mechanical energy to electrical energy and back again, causing parallel hybrid vehicles to be very efficient in highway driving. However, this same coupling reduces the vehicle’s efficiency in stop and go traffic because the ICE has to operate at a wide power band range to meet varying power demands in city driving.

Series-parallel hybrids combine the advantages of series and parallel hybrid designs in which the ICE can be used to directly power the wheels (as in a parallel hybrid system), or it can be completely disconnected from the drive motor (as in a series hybrid system). This allows series-parallel hybrids to utilize the benefits of parallel hybrid systems during highway driving, as well as the benefits of series hybrid systems during city driving. The prices of series-parallel hybrids are higher than parallel hybrids due to the addition of a generator, larger battery pack, and a more powerful ECU to control the dual system.

This paper focuses on plug-in hybrid vehicles as they are more comparable to BEVs. PHEVs utilize a modified series-parallel hybrid drivetrain which uses a larger battery pack that can be recharged by plugging into the electrical grid. Plug-in hybrid electric vehicles typically use a “PHEV-x” notation, where “x” represents the vehicle’s theoretical all-electric range – defined as the distance in miles that a fully-charged PHEV can drive before needing to incorporate its ICE (Markel and Simpson 2006). For example, a PHEV-40 can drive approximately 40 miles in all-electric operation with an 8 kWh battery, and a PHEV-10 can drive approximately 10 miles in all-electric operation with a 2 kWh battery. PHEVs can also have a larger electrical motor which allows them to travel long distances with all-electric operation, as well as allowing them to use the electric motor at higher speeds and accelerations than non-plug-in HEVs. The ICE is still utilized during highway driving, when the vehicle ECU determines that it is more efficient to do so.

Current PHEVs can be charged at home using AC Level 1 or AC Level 2 electric vehicle supply equipment (EVSE). AC Level 1 EVSE uses a 120 volt (V) AC plug and usually does not require any additional infrastructure to be installed. Most, if not all, PHEVs will come with AC Level 1 EVSE equipment so that no additional charging equipment needs to be purchased (AFDC 2013). Level 1 charging is usually used when there is only a 120 V outlet available, and provides 2 to 5 miles of range per hour of charging time depending on the vehicle and circuit capacity (AFDC 2013). AC Level 2 EVSE can be used when there is a 240 V outlet available. It involves the installation of additional home charging equipment. AC Level 2 adds about 10 to 20 miles of range per hour of charging time, based on the vehicle and circuit capacity (AFDC 2013). AC Level 2

EVSE is usually used with people who commute longer distances or have irregular schedules. At certain public charging stations, DC Level 2 charging may be available. DC Level 2 uses a 480 V AC current, and can add 60 to 80 miles of range in 20 minutes (AFDC 2013). DC Level 2 can be harmful to certain batteries, and should only be used if the vehicle was made to accommodate it.

3.2: Price – Initial and Operational Costs of PHEVs

The initial purchase price of PHEVs remains very high in comparison to their gasoline counterparts (NADA 2013). The Chevy Volt, for instance, has a base MSRP of $34,185, making it the company's most expensive passenger car in its class. This reflects a manufacturer's additional cost of $13,095 when compared to a similar conventional gasoline vehicle such as the Honda Civic EX. The Toyota Prius plug-in reflects an $8,900 manufacturer's additional cost compared to the Honda Civic EX. Consumers who want the AC Level 2 EVSE will need to spend upwards of $1,000 for the additional equipment and installation (NRC 2010).

The price of charging a PHEV depends on local electricity rates and whether it is being charged in peak or off-peak hours. Using an average daily mileage of 40 miles driven per person (DOT 2013), and an average electricity price of $0.117 per kWh (USEIA 2013), it would cost approximately $0.23 to charge a fully depleted PHEV-10 vehicle (2 kWh battery), and $0.94 to charge a fully depleted PHEV-40 vehicle (8 kWh battery).

Gasoline costs will vary depending on the specific vehicle, driving habits, length of commute, and local gas prices. Someone with normal driving habits and a short commute may never need to utilize the ICE in their PHEV during their commute, whereas an aggressive driver with a long commute may use their ICE component much more.

Table 3.1 shows the EPA-rated combined fuel economy (MPGe) and annual fuel cost for 5 PHEV models.

Table 3.1: MPGe and Annual Fuel Costs for 5 PHEVs (USEPA and USDOE 2014)

Make + Model	MPGe (combined electricity + gas)**	Annual Fuel Cost
2013 Toyota Prius Plug-in Hybrid**	95	$950
2013 Ford C-MAX Energi Plug-in Hybrid**	100	$950
2013 Ford Fusion Energi Plug-in Hybrid**	100	$950
2014 Cadillac ELR	82	$1,100
2012 Chevrolet Volt	98	$1,000

* Based on 45% highway, 55% city driving, 15,000 annual miles and current fuel prices.

The maintenance costs for PHEVs do not vary much from conventional gasoline vehicles. The ICE on a PHEV has the same maintenance requirements as a conventional vehicle ICE. However, since PHEVs utilize regenerative braking, their brake pads typically last much longer than conventional vehicles and do not need to be serviced as often. The battery, electric motor, and associated electronics require little to no regular maintenance throughout the life of the vehicle (DOT 2013).

The payback period of purchasing a PHEV over a CV can be estimated by using this information. The Prius and the Volt have an initial premium of $8,900 to $13,095 over the Honda Civic respectively, not including any charging equipment and installation. This analysis will assume maintenance costs are the same for PHEVs and CVs due to servicing of the ICE and related components, although PHEVs costs may be slightly lower due to less brake wear. Average annual gasoline and electricity costs for the Prius and Volt range from $950 to $1,100, whereas the average annual gasoline costs for the Civic is about $1,634 (using 32 MPG combined, USEPA 2013). These fuel costs assume 15,000 miles driven per year, a price of $3.486 per gallon of gasoline, and $0.117 per kWh of electricity (USEPA 2013). Using these values, the payback period for a PHEV ranges from about 13 years for the Prius to almost 20 years for the Volt. However, increases in the price of oil or rapid reductions in lithium-ion battery costs could decrease the time needed for PHEVs to become cost-effective (NRC 2010).

3.3: Efficiency – Miles per Gallon Equivalent (MPGe)

Table 3.2 shows six 2014 plug-in hybrid vehicles and their respective MPGe and kWh/100m ratings. The MPGe correlates to the initial all-electric (or primarily electric) operation. Once the battery is depleted to the point that the vehicle cannot run in all-electric mode, it will begin to function like a conventional hybrid. This is how the MPG is calculated.

Table 3.2: kWh/100m, MPGe, and MPG of PHEVs (USEPA and USDOE 2014)

Make + Model	kwH/100m	MPGe (combined electricity + gas)**	MPG (conventional hybrid mode)
2014 Toyota Prius Plug-in Hybrid**	29 (+ 0.2gal/100m)	95	50
2014 Honda Accord Plug-in Hybrid**	29	115	46
2014 Ford C-MAX Energi Plug-in Hybrid**	34	100	43
2014 Ford Fusion Energi Plug-in Hybrid**	34	100	43
2014 Cadillac ELR	41	82	33
2014 Chevrolet Volt	35	98	37

* Based on 45% highway, 55% city driving, 15,000 annual miles and current fuel prices.

** Some models may use small amounts of gasoline in the "Electric" range, affecting their MPGe

For kWh/100m, a lower value is better, meaning the vehicle uses less electricity to travel 100 miles. For MPG and MPGe, a higher value is better, meaning the vehicle travels more miles using one gallon of gasoline-equivalent (33.7 kWh).

3.4: GHG Impacts from PHEVs vs. Conventional Vehicles – A Life Cycle Assessment

A life cycle assessment (LCA) measures the environmental impacts of a product's manufacture, use, and end-of-life (Samaras and Meisterling 2008). Two main factors are included when performing a GHG LCA on PHEVs; battery production and fuel use (for both gasoline and electricity). Vehicle manufacture, service, maintenance, and other fixed costs are omitted from the assessment either because they are similar across all vehicle types or because the differences are negligible. This analysis uses a LCA by Samaras and Meisterling to identify the GHG intensities of battery production, gasoline, and electricity associated with PHEVs. Although they included conventional HEVs in their analysis, this paper omits them.

3.4.1: Battery Production

Rydh and Sanden estimate that 1200 MJ of primary energy is needed to manufacture 1 kWh of Li-ion battery storage capacity. Additionally, they estimate between 310 and 670 MJ of primary energy is needed to manufacture the materials used for 1 kWh of Li-ion battery storage capacity (Rydh and Sanden 2005). This paper uses an average of 500 MJ for material production, leading to a total of 1700 MJ to produce 1 kWh of Li-ion battery capacity.

The GHG emissions associated with battery production are dependent on the fuel sources used in the primary energy demand, the portion of primary energy that is electricity, and the energy grid mix used for manufacturing.

The useful life of a Li-ion battery reduces with every charge cycle. Markel and Simpson estimate that a typical Li-ion battery may last about 2,500 cycles, or about 10 years if it is charged 5 times per week, under normal conditions (Markel and Simpson 2006). Depending on the vehicles usage and the driving patterns of the owner, Li-ion batteries may need to be replaced during the life of the vehicle. It is important to note that replacing the battery doubles the life cycle GHG emissions associated with the manufacture of the battery for that particular vehicle. Table 3.3 below shows the energy and GHG emissions from Li-ion battery production for PHEVs. Total battery capacity is 20% greater than energy required for PHEV propulsion to allow the vehicle to operate as a conventional HEV once the battery depletes 80% (Rydh and Sanden 2005).

Table 3.3: Energy and GHG emissions from Li-ion battery production for PHEVs. (values from Rydh and Sanden 2005)

	Unit	PHEV-30	PHEV-60	PHEV-90
All-Electric Range	km	30	60	90
Energy required (from battery) for range	kWh	5.4	10.7	16.1
Total battery capacity	kWh	6.7	13.4	20.1
Li-ion				
Battery Mass	kg	84	168	252
Production	MJ/battery	11,400	22,800	34,200
	kg CO_2-eq/battery	810	1,610	2,420
	MJ/km	0.05	0.09	0.14
	g CO_2-eq/km	3	7	10

3.4.2: Use-phase

The majority of the life cycle GHG emissions associated with PHEVs is a result of the liquid fuel or electricity used to power the vehicle (Maclean and Lave 2003).

About 2.3 kg of CO_2 is released when 1 L of gasoline is burned (67 g CO_2/MJ of fuel) (CARB 2009). In addition to combustion, upstream GHG emissions must also be included in the life cycle GHG from gasoline, including those associated with crude oil extraction and transportation, refining, and fuel distribution (Samaras and Meisterling 2008). These upstream GHG emissions are estimated at about 0.67 kg of CO_2-eq per liter of fuel (19 g CO_2-eq/MJ) according to the GREET 1.7 model (ANL 2001).

Although a PHEV does not emit any CO_2 while in all-electric mode, the GHG intensity (g CO_2-eq/kWh) associated with the electricity used to charge the vehicles battery pack must be taken into account. These GHG emissions are created and released during power plant fuel production, processing, and transport. Since the fuel types used in power plants vary throughout the country, this analysis will be assuming a US average. According to the Energy Information Agency, average direct emissions (from combustion only) were 171 g CO_2/MJ (615 g CO_2/kWh) in 2004 (EIA 2005). Average upstream sources of GHG emissions amounted to 15 g CO_2/MJ (55 g CO_2/kWh), yielding a total of 186 g CO_2/MJ (670 g CO_2/kWh) electricity produced (Samaras and Meisterling 2008).

In addition to using the US average scenario, Samaras and Meisterling also use a carbon-intensive and a low-carbon scenario to calculate the life cycle GHG intensities of electricity. The carbon-intensive scenario uses coal as the foremost fuel for electricity generation, emitting 950 g CO_2-eq/kWh. This scenario includes a mix of older, less efficient coal power plants along with newer, more efficient plants. The low-carbon scenario uses a combination of renewables, nuclear, and coal with carbon capture and sequestration (CCS) technology as the main sources of electricity generation, emitting 200 g CO_2-eq/kWh. Table 3.4 shows the GHG emissions from various energy sources and scenarios.

Table 3.4: GHG emissions from various energy sources and scenarios (values from Samaras and Meisterling 2008)

	GHG intensity of energy source (g CO_2/MJ)
Electricity	
US average (life cycle)	186 (615 g CO_2/kWh)
Carbon-intensive (life cycle)	250 (950 g CO_2/kWh)
Low-carbon (life cycle)	56 (200 g CO_2/kWh)
Gasoline	
US average (life cycle)	87

This LCA assumes that the gasoline consumption of a CV is 0.08 l/km (30 mpg), and 0.05 l/km (45 mpg) for a PHEV (USEPA 2006). EPRI assumes that a PHEV uses 0.18

kWh/km, and when combined with a 9% loss in electricity transmission and distribution (EIA 2006), results in 0.20 kWh/km of electricity from a power plant for a PHEV to travel one km in all electric mode (Samaras and Meisterling 2008). Additionally, the useful life of the vehicles used in the LCA is 150,000 miles (240,000 km). Please note that actual gasoline and electricity consumption will vary depending on the specific vehicle, its characteristics, and driving patterns, and that the numbers used in this assessment are averages.

As battery capacity increases, so does the weight and volume of the battery. A larger battery may require additional support within the vehicle, further increasing total vehicle weight. This increase in weight may have adverse effects on the fuel efficiency of the vehicle, although larger batteries and electric motors may make up for the added weight through increased drivetrain and motor efficiency (EPRI 2002). This assessment assumes that fuel consumption remains the same as battery capacity is increased.

Table 3.5 shows the gasoline and electricity consumption per kilometer for a PHEV. The electricity consumption values take into account a 9% loss in electricity transmission and distribution (EIA 2005). Both gasoline and electricity consumption per kilometer will vary with different types of vehicles, characteristics, and driving styles (Samaras and Meisterling 2008).

When evaluating the GHG impacts of PHEVs, the amount of electricity used by the vehicle’s electric components compared to the amount of fuel used by the ICE plays a large role. Figure 3.1, from the US Department of Transportation National Household Travel Survey, shows a cumulative distribution of daily vehicle kilometers traveled.

Using the data from the National Household Travel Survey, Samaras and Meisterling are able to estimate the daily percentage of all-electric and gasoline for different PHEV configurations, as shown in Table 3.6.

Table 3.5: Parameters for gasoline and electricity consumption during travel (values from Samaras and Meisterling 2008)

	Unit	Value
Gasoline-powered travel		
CV	MJ/km	2.5
	l gasoline/km	0.08
	(mi/gal)	(30)
PHEV	MJ/km	1.7
	l gasoline/km	0.05
	(mi/gal)	(45)
Electricity-powered travel and electric drive system (power plant-to-wheel)		
Electricity consumption during electric powered travel, including charging/discharging losses	kWh/km	0.18
	(kWh/mi)	(0.29)
Transmission and distribution efficiency		0.91
Electricity required to power travel	kWh/km	0.2
Battery depth-of-discharge (DOD)		0.8

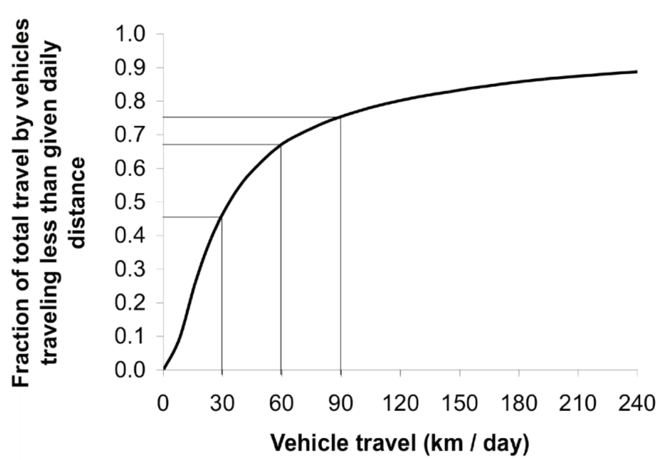

Figure 3.1: Cumulative distribution of daily passenger vehicle travel (km/day) (USDOT 2006)

Table 3.6: Fraction of total vehicle kilometers powered by electricity (α) and gasoline (1-α) (values from Samaras and Meisterling 2008)

	CV	PHEV-30	PHEV-60	PHEV-90
α	0	0.47	0.68	0.76
1-α	1	0.53	0.32	0.24

Samaras and Meisterling use the following equation to calculate the GHG emissions per kilometer of vehicle travel:

$$\frac{\mathrm{GHG}}{\mathrm{km}} = (\alpha)\left[\frac{\mathrm{kWh}}{\mathrm{km}} \times \left(\frac{\mathrm{GHG}_{\mathrm{powerplant+upstream}}}{\mathrm{kWH}}\right)\right] + (1-\alpha)\left[\frac{\mathrm{L}_{\mathrm{fuel}}}{\mathrm{km}} \times \left(\frac{\mathrm{GHG}_{\mathrm{fuel+upstream}}}{\mathrm{L}_{\mathrm{fuel}}}\right)\right]$$

Equation 3.1: GHG emissions per km of vehicle travel

α represents the fraction of total vehicle kilometers powered by electricity and (1-α) represents the fraction of total vehicle kilometers traveled powered by gasoline. The term multiplied by α represents the combustion and upstream impacts of electricity, while the term multiplied by (1-α) represent the combustion and upstream liquid fuel emissions (Samaras and Meisterling 2008).

3.4.3: Results

The total life cycle GHG impacts can be calculated by combining the GHG impacts from production and those from the use-phase (equation 3.1). Table 3.7 shows the life cycle energy use and GHG emissions from CVs and PHEVs using US Average GHG intensity of gasoline and electricity. The GHG impacts from PHEVs would become more severe in a more coal-powered energy infrastructure, such as the coal-intensive scenario. Likewise, the GHG impacts from PHEVs would reduce in a more renewable/nuclear-powered energy infrastructure, as shown in Figure 3.2.

Table 3.7: Life cycle energy use and GHG emissions from CVs and PHEVs using US Average GHG intensity of electricity (values from Samaras and Meisterling 2008)

		Units	CV	PHEV-30	PHEV-60	PHEV-90
Production Phase						
	Vehicle	MJ/km	0.4	0.4	0.4	0.4
		g CO_2-eq/km	35	35	35	35
	Battery	MJ/km	-	0.05	0.09	0.14
		g CO_2-eq/km	-	3	7	10
Use phase	Gasoline: site	MJ/km	206	0.9	0.6	0.4
		g CO_2-eq/km	177	63	38	28
	Gasoline: upstream	MJ/km	0.6	0.2	0.1	0.1
		g CO_2-eq/km	57	20	12	9
	Electricity: site	MJ/km	-	0.7	1	1.2
		g CO_2-eq/km	-	57	82	92
	Electricity: upstream	MJ/km	-	0.1	0.1	0.1
		g CO_2-eq/km	-	5	7	8
Total impact	**Energy use**	**MJ/km**	**3.6**	**2.3**	**2.2**	**2.2**
	GHG emissions	**g CO_2-eq/km**	**569**	**183**	**181**	**183**

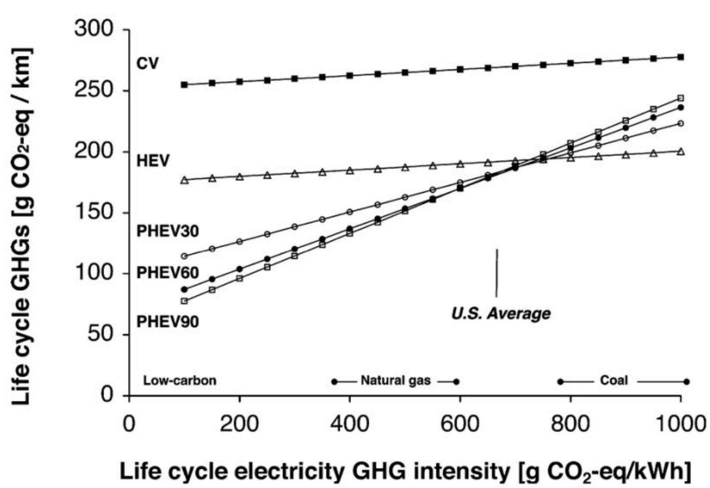

Figure 3.2: Life cycle GHG emissions from vehicles shown as a function of the life cycle GHG intensity of electricity generation (Samaras and Meisterling 2008)

3.6: Range of PHEVs

PHEVs can vary in their driving ranges depending on the vehicle and the battery pack that it is equipped with. Table 3.2 below shows the estimated all-electric and total range for six popular 2014 plug-in hybrid models.

The electric range is the theoretical range that the vehicle can drive in normal driving conditions without utilizing its ICE, determined by the USEPA. The total driving range is the theoretical distance that the vehicle can travel when it uses its battery in combination with its ICE. Real world range will vary depending on traffic conditions, driving style and patterns, and usage of electric components in the vehicle (air conditioner, headlights, radio etc.). The total driving range for PHEVs are similar to, if not exceeding, those of conventional gasoline vehicles. This eliminates the concerns that consumers may have with other alternative fueled vehicles regarding extended driving ranges.

Table 3.2: Driving range of PHEVs (USEPA and USDOE 2014)*

Make + Model	Range: Electric (miles)**	Total Driving Range (miles)
2014 Toyota Prius Plug-in Hybrid	11	540
2014 Honda Accord Plug-in Hybrid	13	570
2014 Ford C-MAX Energi Plug-in Hybrid	21	620
2014 Ford Fusion Energi Plug-in Hybrid	21	620
2014 Cadillac ELR	37	340
2014 Chevrolet Volt	38	380

* Based on 45% highway, 55% city driving, 15,000 annual miles and current fuel prices.
**Depending on driving style, these vehicles may or may not use any gasoline in the "Electric" range

Chapter 4: Battery Electric Vehicles (BEVs)

4.1: Technology – How do BEVs work?

Unlike HEVs and PHEVs, BEVs do not incorporate an ICE into their drivetrain. BEVs are equipped with multiple rechargeable batteries, one or more electric motors, a controller that provides electricity to the motor(s), and charging infrastructure that charges the batteries through external sources or regenerative braking (J.D. Power 2012). Current BEVs do not have a conventional transmission like those in CVs and PHEVs; instead, they have an electric traction motor that is directly coupled to the wheels, as seen in Figure 4.2.

Figure 4.1: Nissan Leaf (BEV) Powertrain (Nissan 2012)

BEVs require the same charging infrastructure as PHEVs. They can be charged at home using AC Level 1 or AC Level 2 electric vehicle supply equipment (EVSE), or through DC fast charging (DC Level 2) at public stations. Since the battery capacity of BEVs is typically much larger than PHEVs, the time it takes to charge the vehicle is significantly higher. The standard Nissan Leaf, for instance, requires 16 hours of AC Level 1 EVSE to be able to travel its full 100-mile range. However, if upgraded with a higher capacity on-board charger and using AC Level 2 EVSE, the Leaf can be fully recharged from empty in about 4 hours. If using

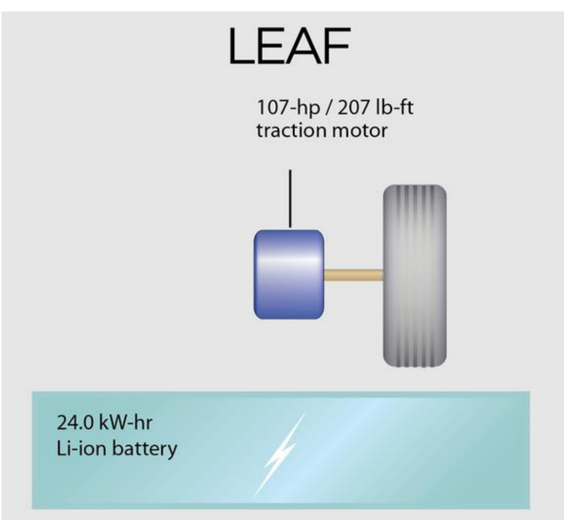

Figure 4.2: Nissan Leaf (BEV) Drivetrain (MotorTrend 2013)

DC Level 2 EVSE, the Leaf can be charged from empty to 80% in 30 minutes. Upgrading to a higher capacity on-board charger and AC Level 2 EVSE would cost the consumer an additional $2,200 to $3,200 (Nissan 2013).

4.2: Price – Initial and Operational Costs of BEVs

Like PHEVs, BEVs have a high initial price premium over comparable CVs. The Nissan Leaf has a base price of $28,980, which is about $7,890 more than a comparable gasoline car such as the Honda Civic EX.

Table 4.1 shows the kWh/100m rating, the fuel cost to drive 25 miles, the fuel cost to drive 100 miles, and the total annual fuel cost for 6 BEV models.

Table 4.1: MPGe and Annual Fuel Costs for 5 PHEVs (USEPA and DOE 2014)

Make + Model	kWh/100m	Cost to Drive 25 Miles	Cost to Drive 100 Miles	Annual Fuel Cost
2013 Mitsubishi i-MiEV	30	$0.90	$3.60	$550
2013 Ford Focus Electric	32	$0.96	$3.84	$600
2011 BMW ActiveE	33	$0.99	$3.96	$600
2013 Nissan Leaf	29	$0.87	$3.48	$600
2013 Smart ED	32	$0.96	$3.84	$600
2012 Coda	46	$1.38	$5.52	$800

*All estimated fuel costs based on 15,000 annual miles traveled, 45% highway and 55% city.

**Annual fuel cost values rounded to the nearest $50

Maintenance costs for BEVs are much less than that of CVs. This is due to the simplicity of the electric powertrain in BEVs. Like PHEVs, regenerative braking extends the life of the brake pads when compared to CVs. Due to the lack of an ICE and related components, the total maintenance costs of BEVs are estimated to be about 35% lower than that of a CV (LeSage 2013). The average annual maintenance costs for a CV in 2013 amounted to $745.50 (using $0.0497 per mile and 15,000 annual miles driven, AAA 2013), meaning that driving a BEV could save the consumer over $260 in annual maintenance costs.

The payback period of purchasing a BEV over a CV can be estimated using this information. The Nissan Leaf has an initial premium of $7,890 over the Civic, not including any charging equipment and installation. Annual maintenance costs for BEVs are about 35% lower than that of CVs. This equates to an estimated $485 per year for BEVs, a saving of about $260 per year when compared to CVs. Average annual electricity costs for the Leaf is about $600, whereas the average annual gasoline costs for the Civic is about $1,634. These fuel costs assume 15,000 miles driven per year, a price of $3.486 per gallon of gasoline, and $0.117 per kWh of electricity (USEPA 2013). Using these values, the payback period for a BEV is about 6 years, assuming it does not need to replace its battery over the course of its useful life. If the BEV does need a replacement battery pack (a cost of about $10,000), the payback period would increase to about 13 years. Auto manufacturers claim that the battery packs in BEVs are made to last the life of the vehicle, so this situation is likely a non-issue. Increases in the price of oil or rapid reductions in lithium-ion battery costs could decrease the time needed for BEVs to become cost-effective.

Total lifetime costs of BEVs and CVs will change depending on the future prices of electricity and gasoline. Figure 4.3 shows how the price difference between a BEV and CV increases as the price of electricity rises, making the BEV a worse economic choice. Alternatively, Figure 4.4 shows how the price difference between a BEV and CV decreases as the price of gasoline rises, making the BEV a better economic choice (Aguirre et al. 2012).

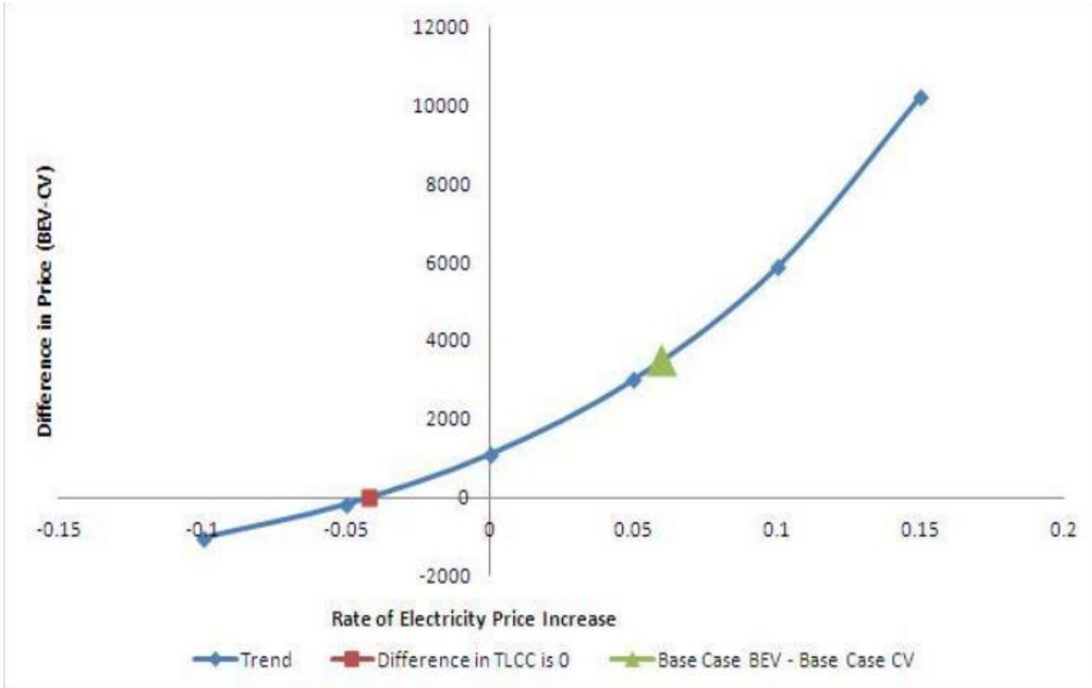

Figure 4.3: Change in lifetime costs for BEVs and CVs as electricity prices increase (Aguirre et al. 2012)

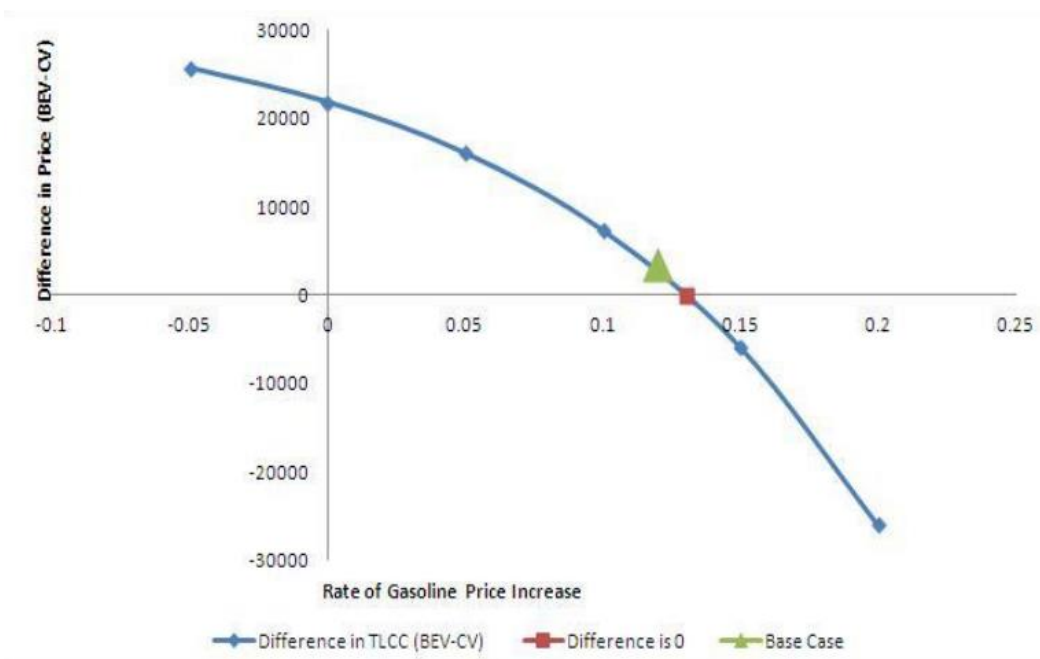

Figure 4.4: Change in lifetime costs for BEVs and CVs as electricity prices increase (Aguirre et al. 2012)

4.3: Efficiency – Miles per Gallon Equivalent (MPGe)

Table 4.2 shows six BEV models and their respective kWh/100m and MPGe ratings.

For kWh/100m, a lower value is better, meaning the vehicle uses less electricity to travel 100 miles. For MPGe, a higher value is better, meaning the vehicle travels more miles using one gallon of gasoline-equivalent (33.7 kWh).

Table 4.2: kWh/100m and MPGe of BEVs (DOE 2014)

Make + Model	kWh/100m	MPGe
2013 Mitsubishi i-MiEV	30	112
2013 Ford Focus Electric	32	105
2011 BMW ActiveE	33	102
2013 Nissan Leaf	29	115
2013 Smart ED	32	107
2012 Coda	46	73

* Based on 45% highway, 55% city driving, and 15,000 annual miles traveled

4.4: GHG Impacts from BEVs vs. Conventional Vehicles – A Life Cycle Assessment

The USEPA classifies BEVs as "zero-emission vehicles" due to the fact that they produce no tailpipe emissions. However, just like PHEVs, the emissions generated from vehicle/battery manufacture and transport, as well as those generated from power plants from which the BEVs get the electricity used to charge their batteries need to be taken into account. Calculating the GHG LCA for BEVs is similar to that of the PHEVs, except for the fact that direct and upstream emissions from gasoline do not need to be included. BEVs generally have much larger Li-ion batteries (ranging from 24 kWh to 85 kWh), so the GHG emissions associated with battery production and use-phase will be higher as well. The information in this chapter is sourced primarily from a LCA performed by 7 students at UCLA, and presented to the California Air Resources Board in June of 2012.

4.4.1: Assumptions

Several assumptions were made in order to complete this LCA. As with the PHEV LCA, vehicle manufacture, service, maintenance, and other fixed costs will be omitted from the assessment either because they are similar across all vehicle types or because the differences are negligible. Emissions associated with transportation and disposal of materials and vehicles were also omitted from the LCA because they were negligible in comparison to the overall emission impact.

The assumed weight of the CV and the BEV is 1,275 kg and 1,575 kg, respectively. The effective vehicle life for both vehicles is 180,000 miles. Since some BEVs will require a battery replacement during the life of the vehicle while others will not, the authors used an average value of 1.5 batteries in the LCA calculations. The fuel economy used for a CV is 31 MPG, and 100 MPGe for the BEV which is comparable to that of the Leaf battery (0.21 kWh/km) (Aguirre et al. 2012).

Since this LCA was prepared for CARB, the “base case” GHG impacts are based off the California electricity mix in 2011. However, the authors also include certain lifecycle impacts based on the US average electricity mix, allowing us to compare this LCA with the PHEV LCA by Samaras and Meisterling that was used in Chapter 3. The California electricity mix was composed of: coal (7%), nuclear (14%), natural gas (42%), total hydropower (13%), wind (5%), geothermal (5%), solar (0%), and biomass (2%) (CEC 2011). The US average electricity mix used in this LCA consisted of: coal (42%), nuclear (19.28%), natural gas (25%), hydropower (8%), wind (3%), geothermal (0.36%), solar (0.01%), and biomass (1.3%) (EIA 2013).

4.4.2: Lifecycle Energy Results from CVs and BEVs using the California Energy Mix

For the “base case,” the total lifetime energy requirements (including manufacturing, transportation, use, and disposal) for the CV amount to 858,145 MJ, whereas the BEV requires 506,988 MJ. The total lifetime CO_2-eq emissions generated from the CV is 62,866 kg, while the BEV generates 31,821 kg. As with the PHEV, the use-phase contributes most significantly to the total impacts of both vehicles. Tables 4.3 and 4.4

show the energy required and emissions generated by category for CV and BEV. Table 4.5 shows the energy use and GHG emissions per mile from CVs and BEVs using California GHG intensity of electricity.

Based on the 180,000 mile useful life of the CV and BEV in this LCA, each mile driven in a CV requires 4.77 MJ and produces 0.35 kg of CO_2-eq emissions, and each mile driven in a BEV requires 2.82 MJ and produces 0.18 kg of CO_2-eq emissions, showing that the CV requires 41% more energy and produces 49% more emissions than a BEV (Aguirre et al. 2012).

The difference in CO_2-eq emissions between CVs and BEVs reduces as the carbon intensity of electricity production increases, shown in Figure 4.5. Similarly, the difference in emissions between the two becomes greater with increased carbon intensity of gasoline, shown in Figure 4.6.

Electricity production would need a carbon intensity of 0.87 kg CO_2-eq/kWh for the overall emissions of a BEV to equal that of a CV (Aguirre et al. 2012). This means in certain regions where coal is the primary fuel used to produce electricity and the carbon intensity exceeds 0.87 kg CO2-eq/kWh, BEVs can actually generate more emissions than CVs (there are still benefits for operating BEVs in these regions that will be covered later in this chapter).

Table 4.3: Life cycle energy use and GHG emissions from CVs using California Average GHG intensity of electricity (values from Aguirre et al. 2012)

CV	Energy Required (MJ)	% Total Energy Required	Associated Emissions (kg CO2-eq)	% Total Emissions
Disposal, Transportation, and vehicle production	42,907	5%	2,515	4%
Use-phase	815,238	95%	60,351	96%
Battery Production	-	-	-	-
Total	**858,145**		**62,866**	

Table 4.4: Life cycle energy use and GHG emissions from BEVs using California GHG intensity of electricity (values from Aguirre et al. 2012)

BEV	Energy Required (MJ)	% Total Energy Required	Associated Emissions (kg CO2-eq)	% Total Emissions
Disposal, Transportation, and vehicle production	35,489	7%	2,227	7%
Use-phase	375,171	74%	21,956	69%
Battery Production	96,328	19%	7,637	24%
Total	**506,988**		**31,821**	

Table 4.5: Energy use and GHG emissions per mile (km) from CVs and BEVs using California GHG intensity of electricity (values from Aguirre et al. 2012)

	Energy (MJ/mile)	Energy (MJ/km)	Emissions (kg CO2-eq/mile)	Emissions (kg CO2-eq/km)
CV	4.77	(2.96)	0.35	(0.22)
BEV	2.82	(1.75)	0.18	(0.11)

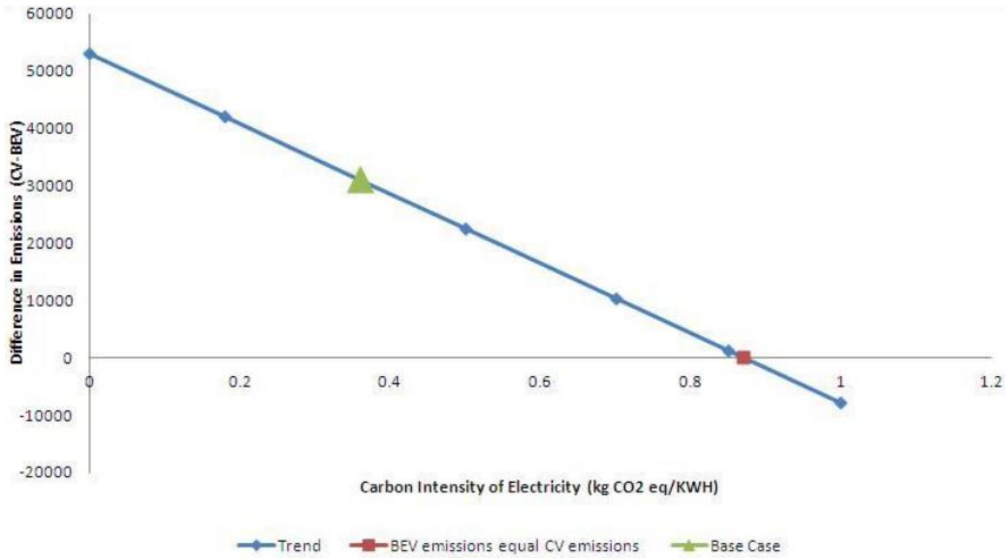

Figure 4.5: Difference in emissions of CVs and BEVs based on carbon intensity of electricity (Aguirre et al. 2012)

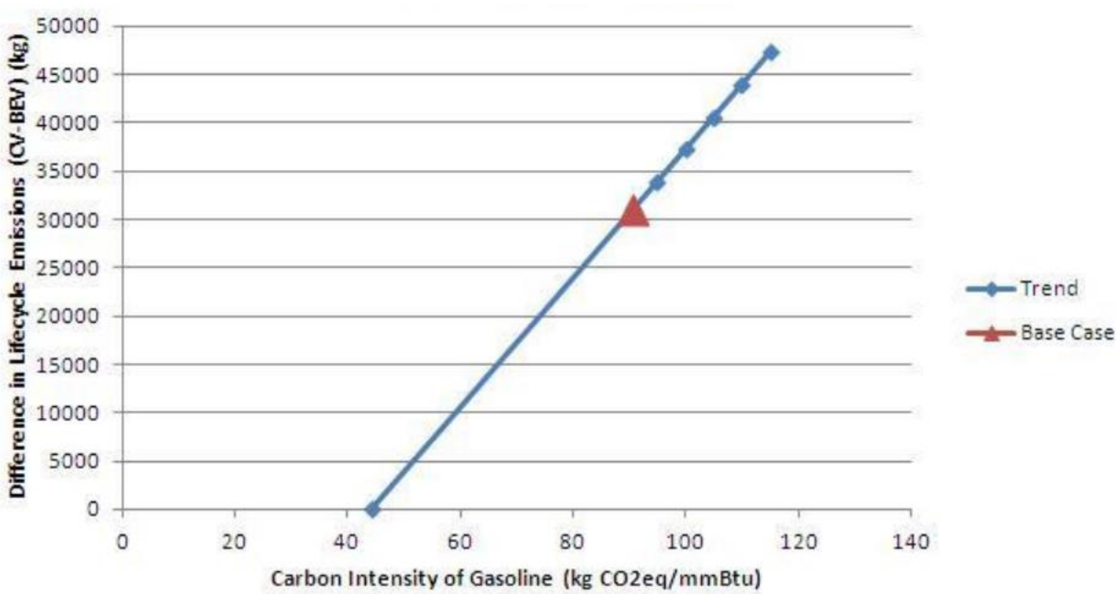

Figure 4.6: Difference in emissions of CVs and BEVs based on carbon intensity of gasoline (Aguirre et al. 2012)

4.4.3: Lifecycle Energy Results from BEVs using the US Average Energy Mix

The electricity mix in California is considerably less carbon intensive than the US average. California has the highest percentage of renewable energy sources, as well as the lowest percentage of coal-fired power plants, which decreases emissions greatly. Using the US average carbon intensity for electricity production, there is an increase of 29% in required energy and an increase of 61% in generated emissions when compared to the California electricity mix (Aguirre et al. 2012). Table 4.6 shows the energy use and GHG emissions per mile from BEVs using the US average GHG intensity of electricity.

Table 4.6: Energy use and GHG emissions per mile (km) from BEVs using US average GHG intensity of electricity (values from Aguirre et al. 2012)

	Energy (MJ/mile)	Energy (MJ/km)	Emissions (kg CO2-eq/mile)	Emissions (kg CO2-eq/km)
BEV	3.63	2.26	0.29	0.18

4.5: Range of BEVs

BEVs can vary in their driving ranges depending on the vehicle and the battery pack that it is equipped with. Table 4.7 below shows the estimated all-electric for six popular BEV models.

Table 4.7: Driving range of BEVs (USEPA and DOE 2012)

Make + Model	Total Range (mi)	Total Range (km)
2013 Mitsubishi i-MiEV	62	100
2013 Ford Focus Electric	76	122
2011 BMW ActiveE	94	151
2013 Nissan Leaf	73	117
2013 Smart ED	63	101
2012 Coda	88	142

Since BEVs do not have an ICE component, their total range is entirely dependent on their battery packs. Auto manufacturers typically use a target range of 100 miles for BEVs, mainly due to the high price, weight, and size associated with current Li-ion battery packs.

Over half of all household-based trips are between 1 and 10 miles, although these trips only account for 28.3% of all household-based vehicle miles traveled. Trips of over 100 miles account for less than 1% of all vehicle trips, but nearly 15% of all household-based vehicle miles traveled (USDOT and USFHWA 2008).

Chapter 5: Comparative Analyses – PHEVs and BEVs

This chapter contains a comparative analysis of PHEVs and BEVs based on price, lifetime GHG emissions, range, and the generation of criteria air pollutants which could impact human health. Although other criteria were examined earlier, the criteria used in this comparative analysis are the most relevant for consumers who are in the market to purchase an alternative fuel vehicle.

5.1: Price

Using the information outlined in Chapters 3.2 and 4.2, this analysis compares lifetime costs of PHEVs and BEVs. Table 5.1 outlines the total lifetime costs associated with three popular vehicles, the Toyota Prius Plug-in, Chevy Volt, and Nissan Leaf. These costs are based on 15,000 miles driven per year, average national gas and electricity prices, and a useful life of ten years or 150,000 miles.

Table 5.1: Total lifetime costs associated with PHEVs and BEVs

	PHEV-10 (Toyota Prius)	**PHEV-40 (Chevy Volt)**	**BEV (Nissan Leaf)**
Initial Cost	$29,990	$34,185	$28,980
Lifetime Fuel Costs	$9,500	$10,000	$6,000
Lifetime Maintenance Costs	$7,455	$7,455	$4,846
Total Lifetime Costs	**$46,945**	**$51,640**	**$39,826**

After combining fuel savings and lower maintenance costs, the total lifetime costs of the BEV range from $7,119 to $11,814 less than the PHEVs.

Another criteria to take into consideration is the payback period of these vehicles, or the amount of time it will take for the fuel savings (and maintenance costs, if applicable) to offset the initial price premium over a comparable CV. This analysis used a 2014 Honda Civic EX as the comparable CV, which has a base price of $21,090 and an USEPA combined MPG of 32.

The payback period for the PHEVs are longer than the useful life of the vehicles, meaning that a consumer purchasing either of these PHEVs would never be able to offset the initial premium they paid. However, a federal tax credit of up to $7,500 is currently available for the purchase of PHEVs and BEVs. Additionally, certain states may offer additional incentives of up to $2,500 for the purchase of a PHEV or BEV, such as the Clean Vehicle Rebate Program (CVRB) administered by the California Air Resources Board (CARB 2013). These incentives can significantly reduce the payback period for the high initial cost of PHEVs and BEVs. Using these incentives, all of the vehicles payback periods are shorter than their useful lives, with the BEV achieving cost-effectiveness within the first four months of purchase. Table 5.2 outlines the lifetime costs and payback periods of PHEVs and BEVs with and without the $7,500 Federal tax credit.

Table 5.2: Lifetime costs and payback periods of PHEVs and BEVs with and without the $7,500 Federal tax credit

Vehicle Type	Lifetime Costs	Lifetime Costs with Federal Tax Credit	Payback Period	Payback Period with Federal Tax Credit
Toyota Prius (PHEV-10)	$46,945	**$39,445**	13	**2**
Chevy Volt (PHEV-40)	$51,640	**$44,140**	21	**9**
Nissan Leaf (BEV)	$39,826	**$32,326**	6	**<1**

5.2: Lifecycle Assessment – GHGs

Using the GHG LCA of PHEVs done by Samaras and Meisterling outlined in Chapter 3.4, and the GHG LCA of BEVs done by Aguirre et al. outlined in Chapter 4.4, this analysis compares lifetime GHG impacts of PHEVs and BEVs. Two main factors are included when performing a GHG LCA on these vehicle types; battery production and fuel use (for gasoline, electricity, or both). GHG emissions associated with vehicle manufacture, service, maintenance, and other fixed costs are omitted from this analysis either because they are similar across both vehicle types or because the differences are negligible.

Samaras and Meisterling do not base their analysis on any specific vehicle, but instead focus on generic specifications of a PHEV-30, PHEV-60, and PHEV-90. This analysis uses the figures calculated for the PHEV-30, as they are most relevant to current commercially available PHEVs and will have a GHG intensity that falls between the Prius (PHEV-10) and Volt (PHEV-40) that were examined earlier. The figures used for the BEV are derived from the values calculated by Aguirre et al., based on the Nissan Leaf. The values used for the CV in this analysis are an average of the values calculated by Samaras and Meisterling and Aguirre et al.

In order to be able to compare the GHG intensities of PHEVs and BEVs, this analysis needs to normalize the assumptions used in the two LCAs. The first main difference was that the LCA performed by Samaras and Meisterling use a useful life of 150,000 miles, whereas Aguirre et al. use a useful life of 180,000 miles. For consistency purposes, this analysis recalculates the values obtained by Aguirre et al. based on a useful life of 150,000 miles. Secondly, Aguirre et al. assumes that half of BEVs would need a battery replacement during the life of the vehicle, and therefore multiply the GHG emissions associated with battery production by 1.5. Since this has been deemed a non-issue by auto manufacturers, this analysis assumes that no BEVs will need a battery replacement during their useful life, reducing the GHG emissions associated with battery production.

Table 5.3 shows the lifetime energy required, energy required per mile, lifetime GHG emissions, and GHG emissions per mile for a BEV and PHEV-30 after normalizing assumptions.

Table 5.3: Energy usage and GHG emissions associated with PHEVs and BEVs using US average electricity generation mix

	Lifetime Energy Required (MJ)	Energy Required per Mile (MJ/mile)	Lifetime GHG Emissions (kg CO2-eq)	GHG Emissions per Mile (kg CO2-eq/mile)
CV	**792,083**	5.28	**58,663**	0.39
PHEV-30	**555,224**	3.70	**44,177**	0.29
BEV	**510,015**	3.40	**40,020**	0.27

The BEV requires less energy and produces fewer GHG emissions over its useful life than a PHEV-30, although not by a significant margin. Battery production for the BEV uses substantially more energy and is much more GHG intensive than the PHEV, due to its larger size and capacity. However, the increased energy usage and GHG emissions generated from the ICE cause the PHEV-30 to use more net energy and produce more GHG emissions than the BEV over their useful lives.

If this analysis were to be done using the California average electricity mix, which relies on less coal-fired power plants, the difference in energy usage and emissions generated between the PHEV-30 and BEV would be larger.

5.3: Range

In terms of achievable driving range, PHEVs surpass BEVs by a significant margin. The typical range for a PHEV is at least 350 miles, and certain models can even exceed 600 miles on a fully charged battery and a full tank of gasoline. The typical range for a BEV is currently around 100-150 miles on a fully charged battery. Some BEVs, such as the Tesla Model S, can achieve ranges up to 265 miles but are priced higher than what average consumers can afford. As stated earlier, over half of all household-based trips in the US are between 1 and 10 miles, and trips of over 100 miles account for less than 1% of all vehicle trips, but nearly 15% of all household-based vehicle miles traveled (USDOT and USFHWA 2008). In conclusion, the 100 mile driving range of BEVs will be sufficient for the vast majority of household-based trips. As EV charging infrastructure continues to expand, the low driving range will become less of an issue for consumers. BEVs may not be a feasible choice for consumers that regularly drive more than 100 miles at a time.

5.4: Air Emissions Health Impacts

To examine the health effects associated with PHEVs compared to CVs, this paper examines the generation of six criteria pollutants, as defined by the USEPA and regulated under the Clean Air Act. These criteria pollutants include carbon monoxide (CO), lead (Pb), nitrogen oxides (NO_x), particulate matter ($PM_{2.5}$ and PM_{10}), ozone (created through a chemical reaction between NO_x and volatile organic compounds, VOCs), and sulfur dioxide (SO_x). This paper will be using the US Average Generation Mix, in which coal and natural gas make up the majority of fuel used for electricity production.

By replacing a CV with a PHEV, there will be a decrease in net CO emissions because gasoline has significantly higher total fuel cycle CO emission rates than electricity generation from any fuel type (Camere et al. 2010). Pb emissions from power plants will increase due to increased electricity demands for recharging PHEVs. NO_x and PM_{10} emissions from power plants increase as well, because coal-fired power plants emit higher amounts of these pollutants than gasoline. However, these increases in emissions are offset by the decrease in transportation sector emissions (Johnson 2008). VOCs emitted from power plants will increase, but will also be offset by the decrease in emissions from the transportation sector (Camere et al. 2010). Lastly, there will be a net increase in SO_x emissions from power plants, but these increases could be mitigated in the future due to the addition of federal SO_x emission caps.

Despite increases in Pb and SO_x emissions, PHEVs generate fewer total net criteria pollutant emissions than CVs.

BEVs will see similar reductions (and increases in the case of in Pb and SO_x) in criteria pollutant emissions, but on a larger scale since they rely completely on electricity produced from power plants. It is important to note that the emissions from power plants are stationary source emissions that are likely located in less population dense areas, whereas tail-pipe emissions are mobile source emissions located in and around population dense areas. Pollution from stationary sources can potentially be easier to mitigate. With future technological advances in carbon capture and sequestration or chemical removal of air pollutants, BEV’s will have an even lower impact on human health (Aguirre et al. 2012).

Chapter 6: Conclusions and Recommendations

GHG emissions from the burning of fossil fuels are one of the leading contributors to global climate change. By switching from conventional gasoline vehicles to alternative vehicles such as PHEVs and BEVs, the amount of emissions released can be reduced in an effort to slow down and combat the effects of climate change. The purpose of this paper is to compare PHEVs and BEVs in terms of which have the least environmental impacts in terms of their life-cycle analysis of GHG emissions, as well as determine which type of vehicle provides the most economical benefits to consumers, in an effort to better inform these consumers on their purchase of an alternative fuel vehicle.

This paper analyzes the lifetime costs associated with two PHEVs, the Toyota Prius Plug-in and Chevy Volt, and one BEV, the Nissan Leaf. It takes into account the initial price premium over a CV, fuel costs, and maintenance costs to determine which one would yield the consumer the most savings over the life of the vehicle. It then calculates how long it takes for the fuel and maintenance savings of the PHEVs and BEV to outweigh the initial price premium. Both of these analyses are done with and without incorporating the $7,500 Federal tax credit for purchasing an alternative fuel vehicle.

The BEV has the lowest lifetime costs in both scenarios due to its increased fuel and maintenance cost savings. With the $7,500 Federal tax credit, the Prius will take about two years to become cost-effective and the Volt will take about nine years, whereas the Leaf will only take about four months. If the Federal tax credit is discontinued in the future, the payback period for both of the PHEVs would exceed their useful life. This means that the consumer would never recoup the initial premium for these vehicles. The Leaf would still become cost-effective in about 6 years in the absence of the tax credit.

Next, this paper examined the lifecycle GHG emissions associated with PHEVs and BEVs. Although these vehicles are partially or fully powered by electricity, the GHG emissions generated from the power plants that supply the electricity need to be taken into account. To do this, this paper uses a GHG LCA on PHEVs performed by Samaras and Meisterling, and a GHG LCA on BEVs performed by Aguirre et al. The LCAs included GHGs generated from vehicle and battery manufacture, as well as fuel use. After normalizing the assumptions used in the two LCAs, the lifecycle GHGs of a PHEV-30 and a BEV were calculated based on a useful life of 150,000 miles and using the US average electricity generation mix. The results can be found in Table 5.3. Over the course of its life, the BEV generated 4,157 kg CO2-eq less than the PHEV.

Table 6.1 outlines the average lifetime costs and GHG emissions associated with PHEVs and BEVs.

Table 6.1: Average lifetime costs and GHG emissions associated with PHEVs and BEVs

Vehicle Type	Lifetime GHG Emissions (kg CO2-eq)	Lifetime Costs	Lifetime Costs with Federal Tax Credit
CV	**58,663**	$44,880	**-**
PHEV	**44,177**	$49,293	**$41,793**
BEV	**40,020**	$39,826	**$32,326**

Based on these findings, I would recommend that a consumer interested in purchasing an alternative fuel vehicle to purchase a BEV as it has fewer lifetime costs and GHG emissions associated with it. However, the PHEV still provides environmental benefits over a CV, and if utilizing the Federal tax credit, provides economic benefits to consumers as well.

It is expected that Li-ion battery technology will evolve to produce higher capacity, lighter batteries at a much cheaper cost to consumers in the near future. Hopefully this will allow BEVs to become increasingly popular and slowly displace the conventional gasoline vehicles that are so commonly used to today, effectively reducing the dependence on fossil fuels and combating the effects of climate change.

An influx of PHEVs and BEVs may pose problems for the electrical grid in some areas. This is not an issue when using AC Level 1 EVSE to slowly charge the vehicles, but becomes an issue when using dedicated electric vehicle charging circuits such as AC Level 2 EVSE. In California, where the majority of BEVs and PHEVs are sold, connecting an EV to an AC Level 2 EVSE is comparable to adding another house to the neighborhood circuit (Burris 2013). In temperate areas where air conditioning is rarely used, such as San Francisco, local electricity grids are sized for a much smaller peak electricity load. A home in San Francisco typically draws around 2 kW of electricity during peak hours, whereas charging a PHEV or BEV draws about 6.6 kW if using an AC Level 2 EVSE (Burris 2013). Some vehicles, such as the Tesla Model S, can draw up to 20 kW while using the optional home fast-charger. As a result, utility companies will be required to constantly upgrade local electricity grids to handle much higher electrical loads as PHEVs and BEVs become more popular, which can be costly. To try and avoid excessive strains on the grid, many utility companies are offering discounts for EV owners to charge their cars during off-peak hours.

In order to reduce nationwide GHG emissions, policy makers must focus not only on increasing incentives for alternative fuel vehicles, but rather on implementing targeted emissions policy. In a study done by Babaee et al., a CO_2 cap, similar to the Cap-and-Trade Program being administered in California, proved to be the most effective way to consistently reduce CO_2, SO_2, and NO_x emissions. These programs allocate a set amount of emission credits for all participating facilities, such as power plants, and allow them to trade their credits amongst themselves. The amount of credits allocated decreases annually, until the emission goals are met. If a CO_2 cap is not feasible, the implementation of clean energy policy can directly lower GHG emissions. Programs such as the EPA's proposed Carbon Pollution Standard for new and existing coal-fired power plants will limit the amount of CO2 these plants can emit, and can have a significant impact on nationwide GHG emissions as well as reduce the carbon intensity of EV charging (Babaee et al. 2014).

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Appendix

Table 2.1: Year 2010 Generation Resource Mix (USEPA 2014)

NERC region acronym	NERC region name	Nameplate capacity (MW)	Net Generation (MWh)	Generation resource mix (percent) Coal	Oil	Gas	Other fossil	Biomass	Hydro	Nuclear	Wind	Solar	Geo-thermal	Other unknown/ purchased fuel
ASCC	Alaska Systems Coordinating Council	2,235.4	6,747,178.4	9.1956	13.8801	55.5791	0.0000	0.0934	21.0649	0.0000	0.1868	0.0000	0.0000	0.0000
FRCC	Florida Reliability Coordinating Council	64,862.9	217,890,866.6	24.3846	4.1835	57.3321	0.6049	1.6658	0.0815	10.9853	0.0000	0.0369	0.0000	0.7254
HICC	Hawaiian Islands Coordinating Council	2,820.9	10,836,036.0	14.2627	74.8360	0.0000	3.4529	2.5212	0.6499	0.0000	2.4097	0.0163	1.8512	0.0000
MRO	Midwest Reliability Organization	64,222.0	235,949,817.8	65.8340	0.4266	3.2722	0.1223	1.4959	5.5230	14.3985	8.7586	0.0000	0.0000	0.1689
NPCC	Northeast Power Coordinating Council	81,460.2	271,537,220.9	10.1875	1.1710	41.3737	1.0543	3.4790	12.0206	29.5467	1.1621	0.0000	0.0000	0.0048
RFC	Reliability First Corporation	251,331.7	964,825,048.1	59.0980	0.4394	9.7183	0.5361	0.8424	0.6365	27.5585	1.1277	0.0056	0.0000	0.0376
SERC	SERC Reliability Corporation	299,094.9	1,131,186,728.1	50.7060	0.6328	19.1034	0.2443	1.6626	2.7715	24.7002	0.0822	0.0010	0.0000	0.0961
SPP	Southwest Power Pool	66,145.6	217,874,597.9	58.7426	0.9356	27.0248	0.1531	0.9944	3.0483	4.3859	4.7153	0.0000	0.0000	0.0000
TRE	Texas Regional Entity	100,595.3	345,382,525.6	34.8356	0.7898	44.9525	0.1266	0.1306	0.2040	11.9680	6.8938	0.0024	0.0000	0.0968
WECC	Western Electricity Coordinating Council	212,287.1	723,617,004.1	29.9840	0.4790	29.8737	0.1220	1.3204	22.4581	10.0387	3.3646	0.1436	2.0755	0.1404
U.S.		**1,145,056.0**	**4,125,847,023.5**	**44.7748**	**1.0174**	**23.9686**	**0.3498**	**1.3571**	**6.1730**	**19.5589**	**2.2864**	**0.0290**	**0.3689**	**0.1162**

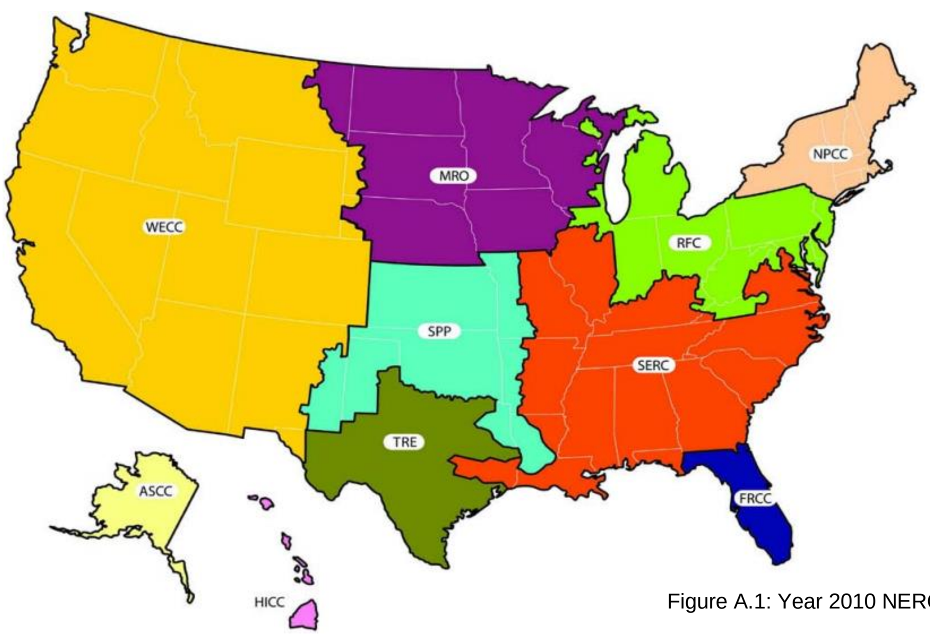

Figure A.1: Year 2010 NERC Regions (USEPA 2014)

Table 2.2: Year 2010 eGRID Subregion Emissions – GHG (USEPA 2014)

Year 2010 eGRID Subregion Emissions - Greenhouse Gases

eGRID subregion acronym	eGRID subregion name	Carbon dioxide (CO_2)		Methane (CH_4)		Nitrous oxide (N_2O)		Carbon dioxide equivalent (CO_2e)	
		Emissions (tons)	Total output emission rate (lb/MWh)	Emissions (lbs)	Total output emission rate (lb/GWh)	Emissions (lbs)	Total output emission rate (lb/GWh)	Emissions (tons)	Total output emission rate (lb/MWh)
AKGD	ASCC Alaska Grid	3,350,817.0	1,256.87	139,035.5	26.08	38,279.9	7.18	3,358,210.3	1,259.64
AKMS	ASCC Miscellaneous	317,398.6	448.57	26,527.0	18.74	5,208.6	3.68	318,484.5	450.10
AZNM	WECC Southwest	104,967,483.8	1,177.61	3,424,005.1	19.21	2,802,975.8	15.72	105,437,897.1	1,182.89
CAMX	WECC California	64,799,260.4	610.82	6,044,809.1	28.49	1,278,773.3	6.03	65,060,940.8	613.28
ERCT	ERCOT All	210,366,837.2	1,218.17	5,820,108.3	16.85	4,859,884.0	14.07	211,181,230.4	1,222.88
FRCC	FRCC All	130,376,587.7	1,196.71	8,478,102.7	38.91	2,995,217.6	13.75	130,929,866.5	1,201.79
HIMS	HICC Miscellaneous	1,963,642.7	1,330.16	218,438.7	73.98	40,985.9	13.88	1,972,289.1	1,336.02
HIOA	HICC Oahu	6,393,027.4	1,621.86	782,825.4	99.30	176,679.8	22.41	6,428,632.4	1,630.90
MROE	MRO East	26,009,237.7	1,610.80	784,331.9	24.29	888,770.5	27.52	26,155,232.6	1,619.84
MROW	MRO West	156,444,752.4	1,536.36	5,809,874.5	28.53	5,354,351.3	26.29	157,335,680.5	1,545.11
NEWE	NPCC New England	46,905,984.7	722.07	9,322,707.0	71.76	1,685,853.4	12.98	47,265,180.4	727.60
NWPP	WECC Northwest	112,891,853.5	842.58	4,300,901.6	16.05	3,502,980.9	13.07	113,479,975.1	846.97
NYCW	NPCC NYC/Westchester	12,733,660.7	622.42	974,161.1	23.81	114,582.6	2.80	12,761,649.6	623.78
NYLI	NPCC Long Island	8,115,858.7	1,336.11	989,929.6	81.49	124,943.6	10.28	8,145,619.2	1,341.01
NYUP	NPCC Upstate NY	24,165,154.6	545.79	1,443,157.6	16.30	641,283.5	7.24	24,279,706.7	548.37
RFCE	RFC East	137,558,868.7	1,001.72	7,434,984.1	27.07	4,210,267.5	15.33	138,289,527.5	1,007.04
RFCM	RFC Michigan	74,602,328.8	1,629.38	2,789,651.5	30.46	2,457,844.2	26.84	75,012,586.0	1,638.34
RFCW	RFC West	449,994,271.4	1,503.47	10,897,168.6	18.20	14,813,680.5	24.75	452,404,812.2	1,511.52
RMPA	WECC Rockies	61,839,528.9	1,896.74	1,477,560.7	22.66	1,904,448.4	29.21	62,150,232.8	1,906.27
SPNO	SPP North	62,457,258.2	1,799.45	1,444,401.4	20.81	1,986,994.1	28.62	62,780,408.5	1,808.76
SPSO	SPP South	117,325,297.0	1,580.60	3,444,187.9	23.20	3,095,469.5	20.85	117,841,258.7	1,587.55
SRMV	SERC Mississippi Valley	90,967,299.2	1,029.82	3,650,522.7	20.66	1,900,187.0	10.76	91,300,158.7	1,033.58
SRMW	SERC Midwest	123,042,911.4	1,810.83	2,783,643.6	20.48	4,019,051.2	29.57	123,695,092.6	1,820.43
SRSO	SERC South	183,236,856.9	1,354.09	6,176,437.4	22.82	5,653,138.2	20.89	184,177,945.9	1,361.05
SRTV	SERC Tennessee Valley	163,960,526.8	1,389.20	4,177,202.5	17.70	5,290,412.2	22.41	164,824,401.3	1,396.52
SRVC	SERC Virginia/Carolina	167,452,188.6	1,073.65	6,766,296.6	21.69	5,502,582.8	17.64	168,376,135.0	1,079.57
U.S.		**2,542,238,893.0**	**1,232.35**	**99,600,972.2**	**24.14**	**75,344,845.9**	**18.26**	**2,554,963,154.4**	**1,238.52**

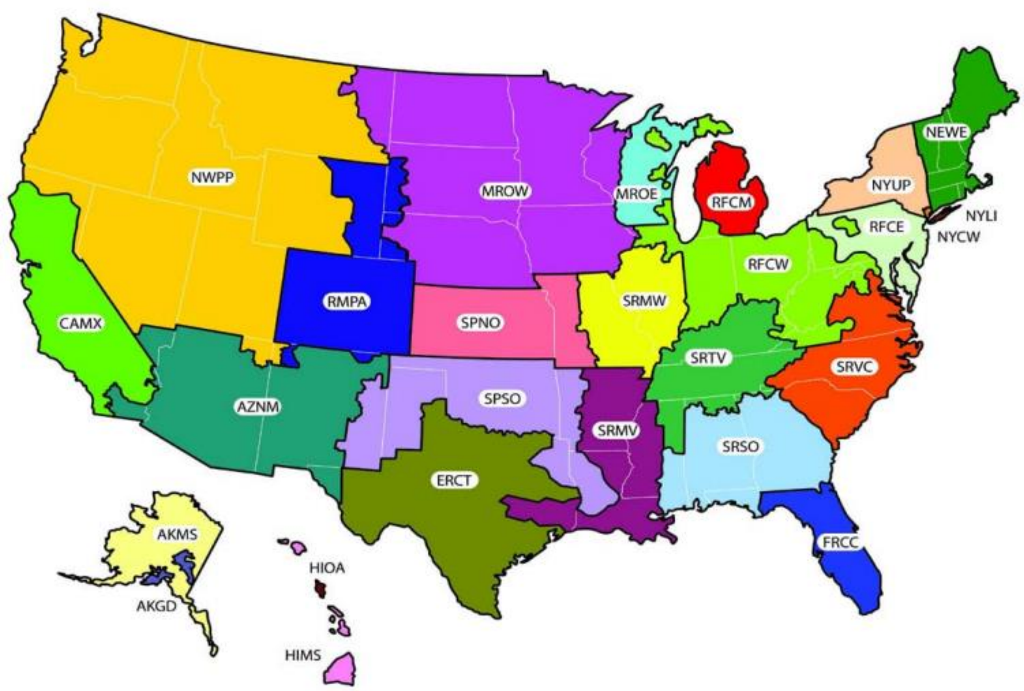

Figure A.2: Year 2010 eGRID Subregion - GHG (USEPA 2014)

Table 2.3: Year 2010 eGRID Subregion Emissions – Criteria Pollutants (USEPA 2014)

Year 2010 eGRID Subregion Emissions - Criteria Pollutants

eGRID subregion acronym	eGRID subregion name	Nitrogen oxides (NO_x) Emissions (tons)	Total output emission rate (lb/MWh)	Ozone season emissions (tons)	Ozone season total output emission rate (lb/MWh)	Sulfur dioxide (SO_2) Emissions (tons)	Total output emission rate (lb/MWh)
AKGD	ASCC Alaska Grid	6,747.78	2.5310	2,483.95	2.4531	1,218.16	0.4569
AKMS	ASCC Miscellaneous	4,190.35	5.9221	1,283.02	4.8215	119.64	0.1691
AZNM	WECC Southwest	126,803.83	1.4226	56,734.05	1.3558	54,384.88	0.6101
CAMX	WECC California	42,935.54	0.4047	18,951.31	0.3980	18,114.85	0.1708
ERCT	ERCOT All	112,686.33	0.6525	53,116.56	0.6318	388,236.16	2.2482
FRCC	FRCC All	77,861.56	0.7147	36,505.33	0.7058	154,674.97	1.4197
HIMS	HICC Miscellaneous	8,265.74	5.5992	3,655.16	5.6423	5,555.84	3.7635
HIOA	HICC Oahu	9,822.55	2.4919	3,473.29	2.0489	15,846.99	4.0203
MROE	MRO East	22,388.78	1.3866	9,773.05	1.3457	84,527.18	5.2349
MROW	MRO West	202,395.91	1.9876	83,125.52	1.9047	386,476.47	3.7954
NEWE	NPCC New England	33,872.13	0.5214	13,062.90	0.4453	91,903.02	1.4148
NWPP	WECC Northwest	136,341.44	1.0176	54,279.01	0.9348	134,623.44	1.0048
NYCW	NPCC NYC/Westchester	5,507.03	0.2692	3,174.62	0.3203	1,895.26	0.0926
NYLI	NPCC Long Island	5,739.65	0.9449	3,186.08	1.0224	3,346.78	0.5510
NYUP	NPCC Upstate NY	18,704.86	0.4225	8,393.89	0.4287	49,396.12	1.1156
RFCE	RFC East	118,630.07	0.8639	54,277.28	0.8714	293,625.57	2.1382
RFCM	RFC Michigan	76,828.93	1.6780	33,224.72	1.5480	240,734.60	5.2579
RFCW	RFC West	416,995.47	1.3932	180,238.54	1.3824	1,489,089.68	4.9752
RMPA	WECC Rockies	78,970.58	2.4222	32,666.01	2.3263	61,109.45	1.8743
SPNO	SPP North	66,593.95	1.9186	29,964.11	1.8933	88,544.89	2.5511
SPSO	SPP South	136,008.22	1.8323	64,420.86	1.7981	236,116.02	3.1809
SRMV	SERC Mississippi Valley	118,153.08	1.3376	59,670.07	1.4449	127,939.31	1.4484
SRMW	SERC Midwest	71,474.29	1.0519	31,153.17	1.0524	335,167.04	4.9327
SRSO	SERC South	150,786.79	1.1143	66,651.11	1.0437	484,599.01	3.5811
SRTV	SERC Tennessee Valley	134,430.67	1.1390	58,229.66	1.1400	387,669.47	3.2846
SRVC	SERC Virginia/Carolina	124,727.96	0.7997	57,608.45	0.8113	317,964.62	2.0387
U.S.		**2,307,863.49**	**1.1187**	**1,019,301.72**	**1.0885**	**5,452,879.41**	**2.6433**

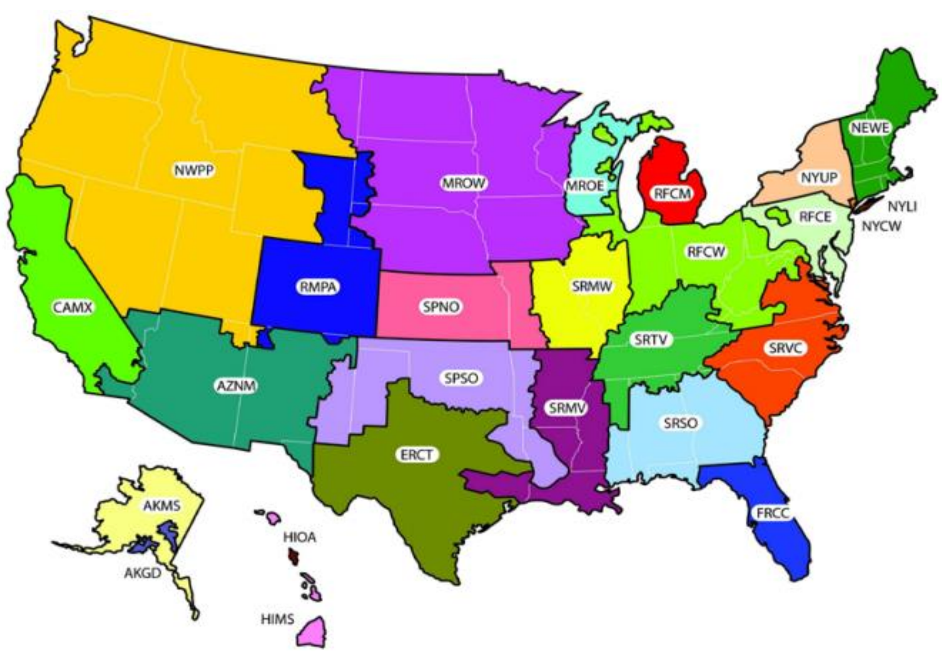

Figure A.3: Year 2010 eGRID Subregion – Criteria Pollutants (USEPA 2014)