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E555 – Final Paper
December 5, 2012

Plug-In Battery EVs vs. Conventional Vehicles: A CO_2 Equivalent Emission Analysis

Introduction

As countries throughout the world continue to debate the economic, political, and social impacts of global climate change, advancements in transportation technology are receiving attention for their potential to significantly reduce global greenhouse (GHG[1]) gas emissions. In the United States, the transportation sector accounts for 27% of GHG emissions, 35% of volatile organic compound (VOC) emissions, 58% of nitrous oxide (NO_x) emissions, 77% of carbon monoxide (CO) emissions, and 34% of carbon dioxide emissions (Thomas, 2009). Several policy options are being considered to reduce GHG emissions from U.S. transportation, including research and development, energy efficiency standards, infrastructure investments, and cleaner-burning fuel standards (Greene & Schafer , 2003). In fact, the Obama Administration recently announced new fuel-efficiency standards requiring the U.S. auto fleet to average 54.5 miles-per-gallon by 2025 (Eilperin, 2012).

Many analysts believe vehicle manufacturers will have to utilize electric vehicles (EV) technologies to meet the new fuel-efficiency standards. While these standards should reduce GHG emissions from the transportation sector, some studies show that powering cars and light duty trucks with electricity may result in a net increase of GHG emissions (Stenquist , 2012). As the following chart indicates, more GHGs are emitted by the electric power industry than any

[1] Note: Throughout this analysis we use the terms GHG and $CO_{2(eq)}$ interchangeably.

other sector in the U.S. Widespread adoption of EVs could simply result in an increase in demand for the electric power and emissions associated with electric power production, while decreasing the GHGs produced from the transportation sector emissions. If this were the result, it would defeat the purpose of adopting EVs as a means to reducing GHG emissions.

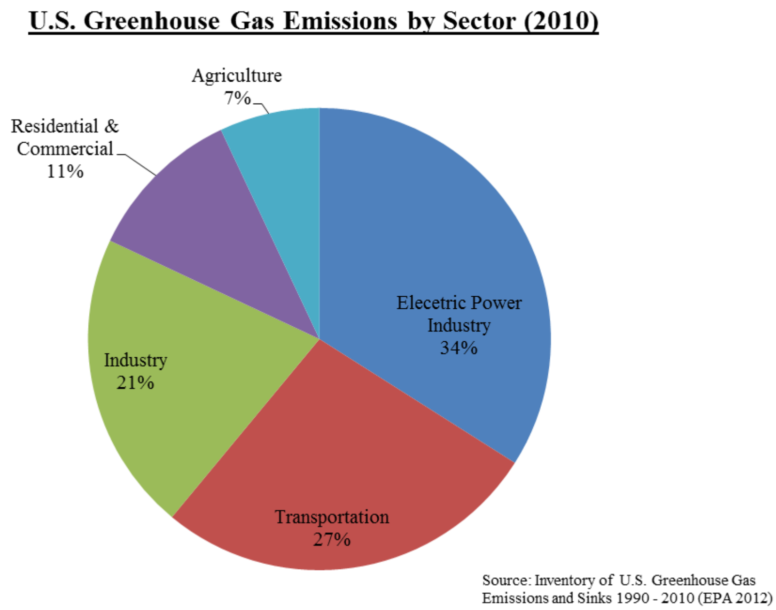

Figure 1. U.S. GHG emissions by sector

A significant proportion of U.S. GHG emissions also come from the transportation sector, specifically from burning motor gasoline. Although CO_2 emissions from the transportation sector originate from multiple sources, such as liquefied petroleum gas, jet fuel, distillate fuel, residential fuel, lubricants and aviation gasoline, the following table shows that the overwhelming majority of CO_2 emissions originate from motor gasoline combustion:

Table 1. U.S. Carbon Dioxide Emissions from Transportation Sector Energy Consumption 1990-2008 (U.S. Energy Information Administration 2009)

Table 10. U.S. Carbon Dioxide Emissions from Transportation Sector Energy Consumption, 1990-2008
(Million Metric Tons Carbon Dioxide)

Fuel	1990	1995	2000	2002	2003	2004	2005	2006	2007	2008
Petroleum										
Motor Gasoline	966.2	1,029.8	1,122.0	1,156.1	1,159.9	1,181.3	1,184.2	1,186.9	1,187.4	1,134.9
Liquefied Petroleum Gas	1.4	1.1	0.7	0.8	1.0	1.1	1.7	1.6	1.3	1.2
Jet Fuel	222.6	222.1	253.8	236.8	231.5	239.8	246.3	239.5	238.0	226.3
Distillate Fuel	267.8	306.9	377.8	394.5	414.5	433.9	444.4	469.2	472.3	445.7
Residual Fuel	80.1	71.7	69.9	53.3	45.0	58.3	66.0	71.4	78.3	74.1
Lubricants[a]	6.5	6.2	6.7	6.0	5.6	5.6	5.6	5.5	5.6	5.2
Aviation Gasoline	3.1	2.7	2.5	2.3	2.1	2.2	2.4	2.3	2.2	2.0
Petroleum Subtotal	**1,547.7**	**1,640.5**	**1,833.4**	**1,849.8**	**1,859.5**	**1,922.2**	**1,950.7**	**1,976.4**	**1,985.1**	**1,889.4**
Coal	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Natural Gas	**36.1**	**38.4**	**35.7**	**37.2**	**33.4**	**32.0**	**33.1**	**33.2**	**35.4**	**35.9**
Electricity[b]	**3.2**	**3.2**	**3.6**	**3.6**	**4.5**	**4.7**	**4.9**	**4.7**	**5.2**	**4.9**
Total	**1,586.9**	**1,682.2**	**1,872.7**	**1,890.7**	**1,897.4**	**1,958.9**	**1,988.7**	**2,014.3**	**2,025.7**	**1,930.1**

[a]Includes emissions from nonfuel uses of fossil fuels. See Table 12 for details by fuel category.
[b]Share of total electric power sector carbon dioxide emissions weighted by sales to the transportation sector.
Notes: Data in this table are revised from the data contained in the previous EIA report, *Emissions of Greenhouse Gases in the United States 2007*, DOE/EIA-0573(2007) (Washington, DC, December 2008). Totals may not equal sum of components due to independent rounding.
Source: EIA estimates.

For our analysis, we assume that determining ways to reduce GHG emissions from the transportation sector in a way that also reduces total GHG emissions from the U.S. is the ultimate goal of EV adoption.

Problem Statement

As indicated above, both the transportation sector and electric power sector contribute greatly to U.S. GHG emissions. If an important goal of contemporary U.S. energy policy is to reduce GHG emissions, the following questions need to be answered: Should the U.S. promote policies that encourage the adoption of EVs? Or would the decrease in GHG emissions from reducing motor gasoline combustion be offset by increased emissions from the electric power industry? Could the adoption of EVs actually increase GHG emissions? These central questions form the basis of our analysis.

Answering these questions is challenging because increases or decreases in GHG emissions are influenced by many variables. For example, research from the Union of Concerned

Scientists shows that increases or decreases in GHG emissions, *specifically related to EVs*, depends upon the sources of electricity generation. In a recent report, titled “State of Charge: EVs’ Global Warming Emissions and Fuel-Cost Savings across the United States,” the Union of Concerned Scientists show that reductions in GHG emissions from EVs are most pronounced in areas where electricity comes from renewable resources such as wind, hydro, and geothermal (Anair & Mahmassani, 2012). In areas that primarily burn coal for electricity generation, the reductions are much less significant.

The Concerned Scientists research team also demonstrates the global warming impact of EVs by calculating a miles-per-gallon emission equivalent between motor gasoline and electricity production. The team does this by determining the GHG emissions that would result at a power plant from charging an EV. This value is then converted into a gasoline miles-per-gallon equivalent, designated MPG_{GHG}. The team explains, "if an EV has an MPG_{GHG} value equal to the mpg of a gasoline-powered vehicle, both vehicles will emit the same amounts of global warming pollutants for every mile they travel” (Anair & Mahmassani, 2012). For example, if an electric car was charged using electricity generated by a coal-fired power plant, that car would have a MPG_{GHG} of 30. That is, the GHG emissions from driving the vehicle would be equivalent to a gasoline vehicle receiving a 30-mpg rating. The results are provided in the table below.

Table 2. Well-to-Wheels EV Miles Per Gallon Equivalent (MPG_{GHG}) by Electricity Sector

Well-to-Wheels EV Miles Per Gallon Equivalent (MPG_{ghg}) by Electricty Source	
Coal	30
Oil	32
Natural Gas	54
Solar	500
Nuclear	2,000
Wind	3,900
Hydro	5,800
Geothermal	7,600

Notes: (1) EV efficiency is assumed to be 0.34 kWh/mile, reflective of the Nissan LEAF (2) Production and consumption of gasoline are assumed to produce 11,200 grams CO2e/gallon

The purpose of our research project is to compare CO_2 equivalent emissions ($CO_{2(eq)}$) from an internal combustion engine (ICE) vehicle, where the emissions come from combusting motor gasoline, with a plug-in battery EV, where the emissions come from electricity generation. To accomplish this goal, we will examine emissions from: (1) vehicle production, (2) vehicle operation, and (3) vehicle disposal. We have chosen to examine two vehicles that have very similar specifications, except that one vehicle, the Nissan Versa, has an ICE, and the other vehicle, the Nissan Leaf, is powered solely by an electric battery. It should be noted that CO_2 emission equivalent refers to the global warming impact of a GHG, using the functionally equivalent amount of CO_2 as a reference.

Implications & Barriers When Considering an ICE Vehicle (ICE)

Current Market and Available Technology and Infrastructure:

The ICE was patented in 1893 by Rudolph Diesel, a young German engineer that used fossil fuels as the combustion material to produce energy engineer (Solvent Communications, 2012) Since the ICE was created so long ago, it has allowed for the expansive growth of the ICE market and the necessary infrastructure. In Bloomington, Indiana alone there are 76 gas stations

(Yellowpages.com, 2012). Another important factor is convenience, in one trip to the gas station, about 330 kWh of energy are pumped into a 10-gallon tank, this would take an equivalent 9 days to get the same amount of energy from a household electric current (Berman, 2010). Thus unlike the battery electric vehicles (BEV), ICE infrastructure is already in place and widely available.

Carbon Impacts of Oil:

The transportation sector accounts for 27% of total U.S. GHG emissions, 34% of all carbon dioxide emissions, 36% to 78% of the main ingredients of urban air pollution, and 68% of all oil consumption (Thomas, 2009). These aforementioned numbers are directly linked to the ICE vehicle as it typically burns carbon intensive fossil fuels, which when burned release high volumes of emissions. The emissions of the ICE vehicle are comprised of carbon dioxide, carbon monoxide, particulate matter, nitrogen oxides, sulfur and some uncombusted hydrocarbons (CDX Online eTextbook , 2009). Studies show that these anthropogenic emissions are directly linked to global climate change, and thus, it is necessary for both the transportation industry and society at large to find less oil and carbon intensive transportation alternatives.

The U.S. Department of Energy has produced information to aid consumers in researching fuel economy prior to purchasing a vehicle. Fueleconomy.gov gives consumers information on how fuel-efficient a specific car model is. Some of the most fuel-efficient versions of the ICE vehicle include the Honda CR-Z, Scion iQ, Audi A3 (diesel), Volkswagen Jetta (diesel) and the Toyota Prius (hybrid) (The Department of Energy, 2012). This website serves as a tool to easily allow consumers to take fuel-economy into account in their car purchasing decision.

Societal and Environmental Awareness:

One of the main reasons why consumers tend to purchase ICE vehicles is due to their relatively low up-front cost. Today an electric car costs anywhere from $10,000 to $20,000 more than compared to its ICE equivalent (Graham & Messer, 2011). For example, if a consumer were to purchase a Nissan Leaf as opposed to its ICE equivalent, the Nissan Versa, the buyer would need to drive it for almost nine years at today's gas prices or six years at $5 a gallon before the fuel savings outweighed the nearly $10,000 difference in price (Bunkley, 2012). Likewise, the ICE vehicle tends to have a higher total power output and better acceleration than compared to the more fuel-efficient vehicles. People also have a tendency to associate ICE vehicles with having better vehicle handling, as they are heavier than both hybrids and EVs. However as environmental awareness increases and people begin to place a heavier importance on fuel efficiency, the car market will see a shift from ICE vehicles to more fuel efficient models.

Implications & Barriers when Considering a Battery EV (BEV)

Current Market/Market Perceptions

Currently, EVs represent a very small proportion of the total number of passenger vehicles sold and driven; however, it is expected that the EV will experience growth over the coming decades (U.S. Energy Information Administration, 2012). The transition to the EV away from the ICE vehicle is expected to have a causal nexus where it is first led by the hybrid gasoline-EV, followed by the plug-in hybrid EV and then finally followed by the BEV (Ogden & Anderson, 2011). However as the industry transitions away from the ICE, it is important to consider how perceptions of the EV could affect its growth trajectory.

In general, consumers have negative perceptions of EVs. There are three important factors that affect the growth trajectory of the vehicle: cost, battery range, and unreliable charging. EVs are expensive relative to ICEs, and the Lundberg Survey, which tracks fuel prices, found that gas prices would need to reach $12.50 a gallon for the Chevy Volt to make sense purely on financial terms (Bunkley, 2012). Likewise the survey found that the Nissan Leaf would be competitive with gasoline at $8.53 a gallon (Bunkley, 2012). However, as EVs gains popularity and technological improvements occur, EV prices will continue to decrease, becoming more economically competitive with ICEs. Another factor impacting growth of the EV is the range of the vehicle that can be attained by the battery. EVs have a wide array of driving distances (Table 3). However with the exception of the Tesla Model S, all of the EVs have ranges much smaller than compared to the ICE vehicle, averaging only 32.9 miles per tank (U.S. Department of Transportation , 2010). Lastly, because the technology is new and the infrastructure is not in place to re-charge an EV anywhere in the U.S., as is possible with ICE vehicles, there is a perception that charging EVs can be unreliable and inconvenient. EV charging stations are considerably more sparse and inconvenient than gasoline stations. Depending on the voltage of the outlet, it can take between 8 and 21 hours for vehicles such as the Nissan Leaf to fully recharge.

Table 3. Battery EVs by Make, Model and All Electric Range

Make	Model	All Electric Range (mi)
BMW	ActiveE	100
BYD Auto	e6	205
Chrysler/Fiat	Fiat 500	100
Coda Automotive	Coda Sedan	90-120
Daimler	Smart ED	72-90
Daimler	Mercedes Benz BlueZero	120
Ford	Focus	100
Ford	Transit Connect	100
Ford	Tourneo Connect	100
Hyundai	i10 Electric	100
Mitsubishi	iMiEV	100
Nissan	LEAF	100
Rolls Royce	Electric Phantom	
SAIC	Roewe 750	125
Tesla Motors	Roadster	220
Tesla Motors	Model S	160, 230, 300
Th!nk	City	113

Available Technology and Infrastructure:

As mentioned previously, adequate batteries are a major limiting factor for the widespread adoption of EVs. In particular, the batteries of BEVs are at a disadvantage when compared to ICE vehicle as a result of their reduced energy density. Because batteries for EVs hold less energy than ICE fuel tanks, the range one is able to travel with one fully charged EV battery, is shorter than the distance one can travel on one take of gas with an ICE vehicle (Brown, Pyke, & Steenhof, 2010). In general, battery-size is also much smaller for BEVs and vehicle weight is also reduced to make the car from energy efficient. Nevertheless, the EV industry has seen great improvements in battery technology over the last decade, and it is projected that this technology will continue to improve.

The development of a public charging infrastructure is critical to the success of EVs. In order for EVs success, charging stations need to be present at residential areas, as well as work and public places of leisure (Electric Transportation Engineering Corporation, 2010). The Department of Energy has created a tool, the Alternative Fueling Station Locator, so that EV drivers can map out their routes in order to make sure they have charging stations available to them (U.S. Department of Energy, 2012). Currently there are 5,059 public EV charging stations within the United States. A fear, termed *range anxiety*, was coined to define the apprehension people have with re-fueling their EV before the battery needs to be recharged (Electric Transportation Engineering Corporation, 2010). This past September, an article was released by the Monroe County Government announcing that two public EV charging stations were installed downtown as part of a two-year pilot program with Duke Energy (Fox59, 2012). Programs like this are occurring all over the country, as a means of increasing the convenience of owning an EV.

Carbon Impacts on Electricity Used:

As previously discussed, there is controversy over whether or not the lifecycle GHG emissions of an EV are actually fewer than the conventional ICE. Ultimately, the climate change impact of the EV will differ significantly depending on where the vehicle is charged (Steenhof & McInnis, 2008). In areas where power grids are dominated by hydro, nuclear, natural gas or other zero or low carbon sources of electricity, the emission reduction benefits of the EV are significant relative to the ICE vehicle (Steenhof & McInnis, 2008). In contrast, for more emission intensive power grids (grids that get the majority of their energy from coal), such as the area stretching from Illinois to the Ohio Valley, the lifecycle of the EV could actually be more emission intensive than the ICE vehicle (Brown, Pyke, & Steenhof, 2010). If our goal in adopting EVs into the transportation market is to decrease national GHG emissions, using an EV in areas of the U.S. primarily powered by coal would not help in achieving this goal.

Impacts on Electricity Demand:

Concerning the impacts on electricity demand, much of the research on the expected impact of the EV on total electricity demand has indicated that an influx of these vehicles into the passenger vehicle sector will be manageable in terms of existing or planned generation sources in most power markets (Brown, Pyke, & Steenhof, 2010). Researchers at the Department of Energy concluded that current generating capacity would be sufficient for a large-scale conversion to PHEVs (U.S. Department of Energy, 2010). However, BEVs require higher energy inputs, as they run solely on electricity from the grid. Researchers have found that a primary reasons why the EV is not likely to have a large impact on requirements for additional electricity supply is that the majority of power transfer to EVs will likely be done during off-peak hours, or at night, when less electricity is used. (Webster, 1999).

Conventional Vehicle LCA

This section will look at the lifecycle analysis (LCA) of a conventional vehicle, specifically the 2011 Nissan Versa. To begin this section it is first necessary to describe how the ICE works, which is shown in Figure 2 below:

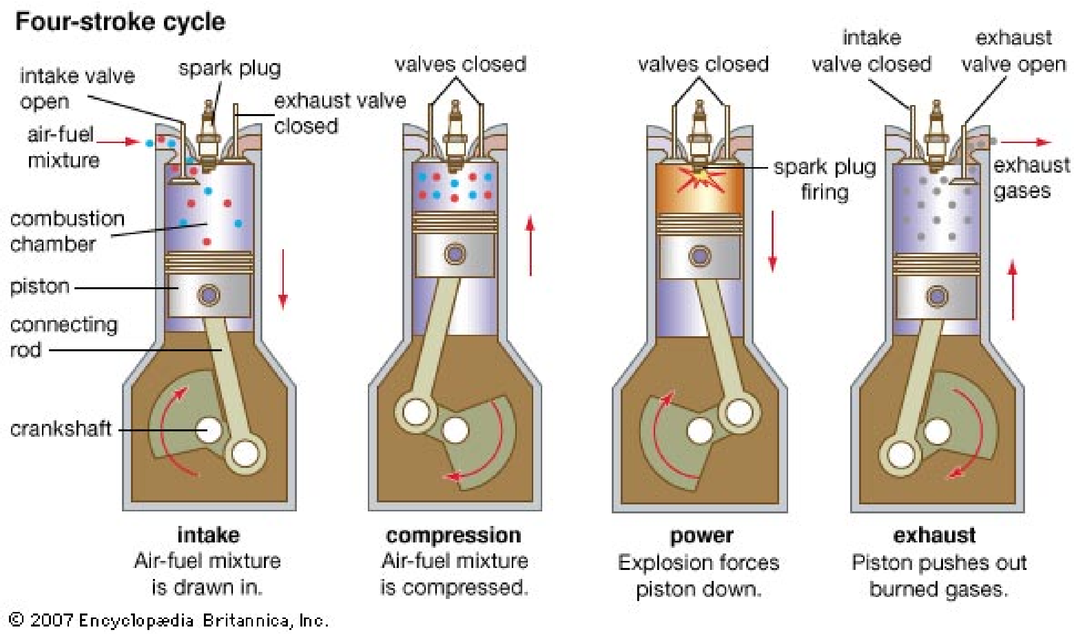

Figure 2. A Representation of the 4 phases of the Internal Combustion Engine (Encyclopedia Britannica , 2007)

As one can see from Figure 2 above the ICE goes through 4 main phases: intake, compression, power, and exhaust. The first phase the intake phase usually begins once you turn the car engine on. The intake valve opens, thus allowing the air-fuel mixture to enter the compression chamber (Encyclopedia Britannica , 2007). The second phase is the compression phase where the intake valves are closed, and the air-fuel mixture is contained within the compression chamber. Once an individual presses down on the accelerator, this causes the spark plug to fire, which drives the piston downward, rotating the crankshaft and thus propelling the vehicle forward. The final stage is the exhaust phase where the exhaust valves open and the exhaust gases are released from the engine and sent to the tailpipe (Encyclopedia Britannica , 2007).

The ICE has losses at each of the stages, and like many energy technologies, it is very inefficient. Rakopoulis & Giakoumis (2006), state that the efficiencies of the ICEs range from 20-25%. This number is very low and is indicating that the ICE is only about 25% efficient at converting gasoline into usable energy (Rakopoulis & Giakoumis, 2006). Below, Figure 3 shows where the energy losses occur in an ICE.

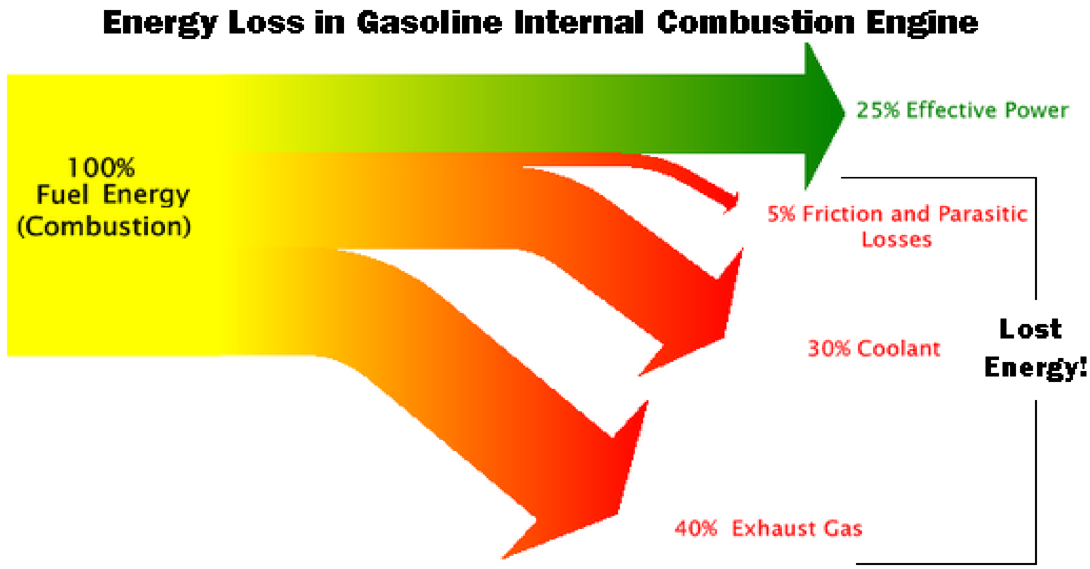

Figure 3. A sankey diagram showing the energy loses from combustion in the ICE (Cleargas.org, 2007)

Figure 3 does a good job of depicting where the energy loses occur in the combustion process for the ICE. As one can see, the efficiency is similar to what Rakopoulis & Giakoumis calculated, but the important numbers are the other 75% that is lost to either friction and parasitic loses (5%), coolant for the radiator and compressor (30%), and finally 40% as exhaust gas (Cleargas.org, 2007). This inefficiency is very important because, as consumers, we want vehicles that can travel further on a single tank of gasoline, and due to the inefficiencies of the engines, will need to refuel more often to travel longer distances (Rakopoulis & Giakoumis, 2006). This need to refuel more often will produce greater emissions, making the vehicles lifecycle carbon footprint even greater.

As was mentioned in the introduction section, the main reason why we decided to choose the 2011 Nissan Versa as our comparison model to the 2011 Nissan Leaf was due to the fact that the two vehicles are very similar. The Versa and the Leaf are basically the same model car, they are made by the same company, and have many of the same characteristics, except for their drivetrain (U.S. Department of Energy, 2012). It is because of this great similarity between the two vehicles that it was determined that it would be the perfect comparison model between an ICE and a fully EV.

In order to be able to compare the two vehicles it was first necessary to determine the Lifecycle emissions for the 2011 Nissan Versa. For the Versa the four stages of emissions are the Manufacturing, Petroleum Refining, Vehicle Operation, and Disposal. The results of the LCA for the 2011 Nissan Versa are shown in Figure 4 below:

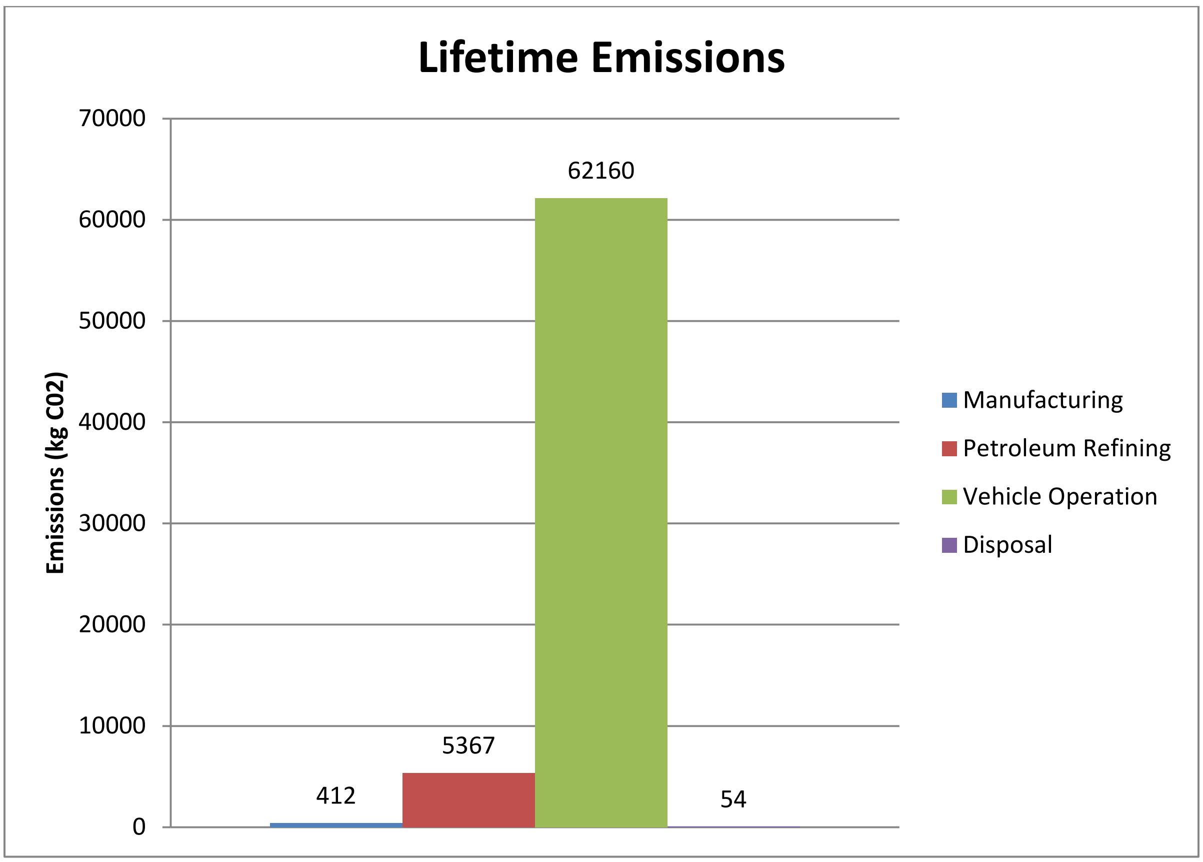

Figure 4. A figure showing the lifecycle emissions of the 2011 Nissan Versa in $kg\ CO_{2(eq)}$ (U.S. Department of Energy, 2012)

It is important to understand that the values shown above are represented in $kgCO_{2(eq)}$, not just $CO_{2(g)}$, other GHGs are included in the $kg\ CO_{2(eq)}$ as well. Looking at Figure 4 above, one can see that the manufacturing process creates 412 $kgCO_{2(eq)}$, while the petroleum refining emissions are represented as 5,367 $kgCO_{2(eq)}$ (Maclean & Lave, 2003). The petroleum refining value is a value that all vehicles that use gasoline share, because there are emissions produced when petroleum is refined into usable gasoline for our engines. While the manufacturing and petroleum refining values were taken from the literature, the vehicle operation value was more difficult to calculate. According to the US DOE, the average lifetime of a vehicle driven today is 14 years, and an average person drives 15,000 miles annually. Given that the 2011 Nissan Versa has tailpipe emissions of 0.296 $kgCO_{2(eq)}$, the lifetime vehicle operation emissions can be calculated (U.S. Department of Energy, 2012).

$$(14\ years)\left(\frac{15000\ miles}{1\ year}\right)\left(\frac{0.296\ kgCO_{2(eq)}}{mile}\right) = 62{,}160\ kgCO_{2(eq)}$$

The Nissan Versa disposal emissions were determined to be equivalent to a small sedan at 54 $kgCO_{2(eq)}$ used in the Aguirre et al. (2012) study. It is important to note that a full lifecycle analysis would likely have many more stages than the 4 that were used above, however these other stages are relatively small and insignificant to the project. Table 3 below does a good job of presenting a summary of the LCA for the 2011 Nissan Versa:

Table 4. A summary table of the LCA for the 2011 Nissan Versa (U.S. Department of Energy, 2012), (Maclean & Lave, 2003)

Vehicle Life (years)	14
Annual Miles	15,000
Miles per tank	350
Average MPG	32.3
Tailpipe emissions (kg C02/ mile)	0.296
Lifetime tailpipe emissions (kg C02)	62160
Manufacturing emissions (kg C02)	412
Petroleum Refining (kg C02)	5367
Disposal (kg C02)	54
Total Lifecycle emissions (kg C02)	67993

As one can see from Table 4 above, the 2011 Nissan Versa is a very fuel efficient vehicle averaging around 32.3 miles per gallon (MPG) combined (U.S. Department of Energy, 2012). The most important value for this project can be found in the last row of Table 4, where the full lifecycle emissions are calculated. For the 2011 Nissan Versa the total emissions are the summation of the 4 stages (Manufacturing, Petroleum Refining, Vehicle Operation, and Disposal), and equate to around 67, 993 $kgCO_{2(eq)}$. The next section will look at the lifecycle emissions of the 2011 Nissan Leaf.

2011 Nissan Leaf Drivetrain

The 2011 Nissan Leaf has a manufacturer's suggested retail price (MSRP) of about $35,000, which is $27,500 after the Federal EV tax credit. This is roughly a $10,000 premium over the Nissan Versa. However, with this premium, you receive a much more streamlined, efficient drivetrain, without a fuel tank, oil pan, exhaust system, or intensive cooling system. The most expensive and complicated component of the electric drivetrain is the very large, lithium ion battery pack. Each battery pack reportedly costs Nissan $18,000, more than the price of the 2011 Nissan Versa (Garthwaite, 2010).

The BEV's drivetrain is in stark contrast to that of the ICE. The Nissan Leaf's 24 kWh, 300 kg battery takes electricity from the grid and stores it until necessary use; then electricity travels from the battery pack to the controller, which receives the signal from the driver to send electricity to the 80 kW (110 hp) electric motor, which ultimately turns the front wheels (Nissan, 2012). The EV has 70% less moving parts than the ICE drivetrain, and minimal heat loss, so they convert about 59-62% of the electrical energy from the grid to power at the wheels (U.S. Department of Energy, 2012). As stated earlier, the ICE vehicle is only about 25% efficient.

Plug-in Electric Vehicle LCA

While battery EVs such as the Nissan Leaf are more efficient and have no tailpipe emissions, there are many other sources for potential emissions release through the manufacturing, operation, and disposal phases. We calculated the emissions for manufacturing and disposal of typical car parts; these parts include the tires, interior, frame, shell, axle, and other parts. We assumed these to be relatively consistent with that of the Nissan Versa.

The lithium ion battery pack is the most energy intensive component of the Nissan Leaf. Lithium ion battery requires mining, transit, and assembly, which dwarves the ecological costs of the rest of the automobile parts (Maclean & Lave, 2003).

During the operation phase, the EV's carbon footprint is largely determined by the electricity generation portfolio of the region the car is charged within. We calculated this using the national electricity generation portfolio as well as the Indiana regional portfolio to see how it affects the outcome.

Manufacturing

First, we calculated the emissions for traditional parts utilizing the weight and emissions of the 2011 Nissan Versa. The emissions for manufacturing the Nissan Versa were 412 kg $CO_{2(eq)}$. The curb weight of the average sedan is 1500 kg. Without battery, the curb weight of the 2011 Nissan Leaf is 1,275 kg. We estimated that these parts were similar to those in the traditional vehicle and calculated the emissions as the weight ratio times the emissions of Nissan Versa manufacturing to get 350 kg $CO_{2(eq)}$.

The manufacturing emissions of the battery were derived from the 24 kWh capacity of the lithium ion battery pack. We utilized assumptions made by Rydh and Sandén in 2005 on lithium ion battery production energy intensity. They found that lithium ion battery material production required 500 MJ/kWh and the actual battery manufacturing took 1200 MJ/kWh for a total of 1700 MJ/kWh. By multiplying this by the 24 kWh capacity of the battery we found a 40,800 MJ energy intensity. We found the emissions by converting to kWh and multiplying this number by the national average electricity emissions of 0.72 kg $CO_{2(eq)}$/kWh (ANL, 2012). We used the US national average emissions even though the Nissan Leaf is currently produced in Japan because the electricity generation portfolios of the two nations are very comparable. We added this number to our traditional parts emissions to reach a grand total of 8,511 kg $CO_{2(eq)}$ for the manufacturing phase.

Operation

We used the same use assumptions as the Nissan Versa analysis: 14 year vehicle life and 15,000 miles driven per year. This is assuming a daily operation of about 40 miles/day, well below the EPA estimated maximum range of 73 miles for the 2011 Nissan Leaf. Manufacturer specifications indicate the Nissan Leaf uses 0.34 kWh/mile (Nissan, 2012). We also used the 0.72 kg $CO_{2(eq)}$ / kWh national electricity emissions incidence from Argonne National Laboratory (2012) to complete the operation emissions equation seen below:

$$Use\ CO_2\ Emissions\ = \frac{14\ years}{vehicle\ life} * \frac{15{,}000\ miles}{year} * \frac{0.34\ kWh}{mile} * \frac{0.72\ kg\ CO_2}{kWh}$$

This yielded a lifetime operation emissions of 51,438 kg $CO_{2(eq)}$. In the Indiana region, the electricity emissions incidence is 0.85 kg $CO_{2(eq)}$ / kWh (Argonne National Laboratory, 2012), which changed the operation emissions total to 60,469 kg $CO_{2(eq)}$.

Disposal

The disposal of traditional car parts was held constant with the Nissan Versa. . It is very likely that current EV lithium-ion batteries will be recycled in some form, much like current car batteries, and they will not be left to rot in the scrap yard. How energy intensive and efficient the process will be is still a big unknown. Current lithium ion battery recycling has very limited data. The methodology is unproven and infrastructure is uncertain because most lithium ion battery applications in electric vehicles are still being used. It is currently cheaper to build lithium ion batteries from raw materials (Aguirre, et al., 2012). We assumed a net zero lifecycle emissions for battery disposal because the anticipated destiny of the battery can either increase or decrease the carbon footprint of the lifecycle. The recycled battery parts could reduce the emissions of future battery production or they could be recycled inefficiently, increasing emissions.

Comparison of Lifecycle $CO_{2(eq)}$ Emissions for Versa and Leaf

Using the base case, national scenario, the Nissan Leaf has a lower carbon footprint than the Nissan Versa by about 8,000 $CO_{2(eq)}$. However a couple factors would push the lifetime emissions of the Nissan Leaf higher than the Nissan Versa. The Indiana Electricity portfolio adds

9,000 kg CO_2 to lifecycle analysis. If the lithium ion battery needs replacement, this creates and additional 8,000 kg $CO_{2(eq)}$ (many analysts expect 1.5 batteries per lifetime (Aguirre, et al., 2012).) Battery recycling could lower the CO_2 requirement for battery production, but there is no solid data yet.

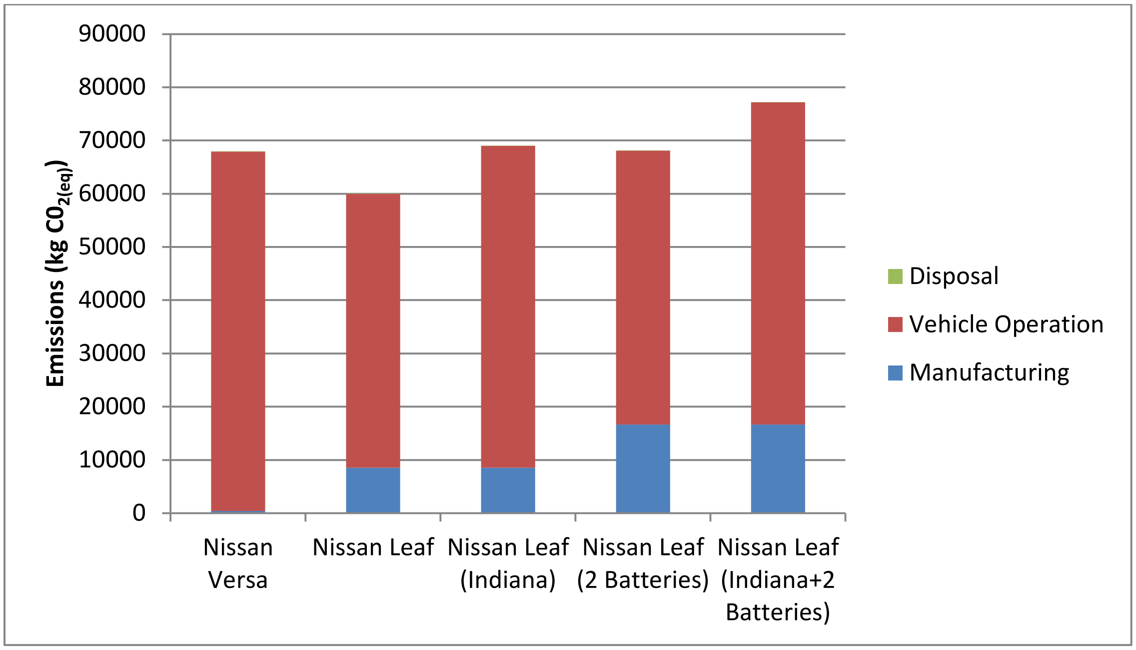

Figure 5. Lifetime $CO_{2(eq)}$ Emissions for the 2011 Nissan Versa and the 2011 Nissan Leaf

These estimates are very close. It might come as a disappointment to EV enthusiasts. The reason is probably because the Nissan Versa is very fuel efficient already at 32.3 MPG, thus very low carbon emissions during operation. Using electricity sources with lower emissions like wind, geothermal, hydro, nuclear, and even natural gas can reduce the operating emissions of the EV. This could possibly be achieved through renewable portfolio standards, upgrading the grid, and clean energy production tax credits. Building batteries that last the entire lifetime of the vehicle and can be efficiently recycled can also reduce emissions.

Future Projections of Vehicle Mix in the United States

As mentioned before, states which utilize a diverse portfolio of energy resources, as opposed to only relying on coal to meet their energy demand are the best places to own and operate an EV. EVs serve as a promising option for reducing the $CO_{2(eq)}$ emissions associated with transportation. A shift from ICE vehicles to EVs allow for future decreases in GHGs produced in the United States if the carbon intensity of electricity sources is reduced. While, internal combustion vehicles are still limited to gasoline as the primary source of power. For these reasons, it is useful to look into future projections of numbers of EVs in the United States.

Every year EIA produces an Annual Energy Outlook (AEO). The following discussion of the future of EVs is largely found in the AEO2012 projections. Figure 6 shows the AEO2012 reference case projections of light cars and trucks sold in the United States until 2035.

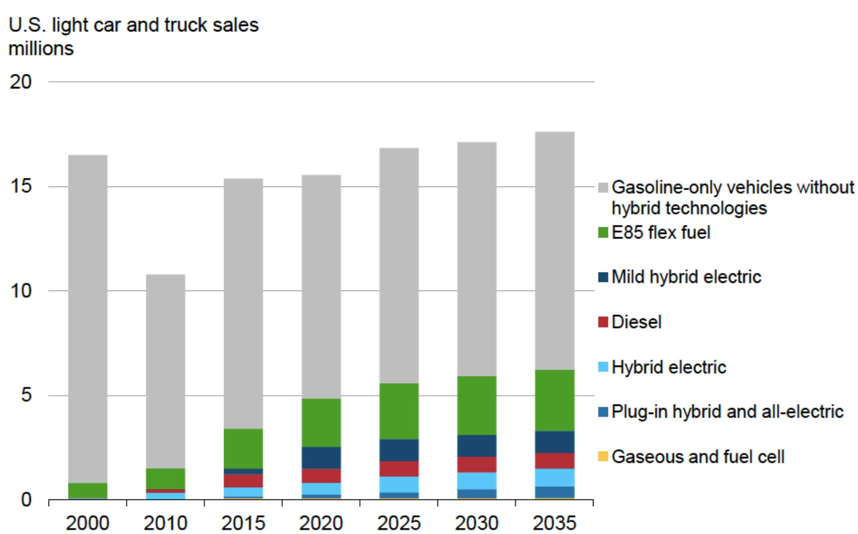

Figure 6. Annual Energy Outlook 2012 Reference Case (Turnure, 2012)

The AEO Reference case makes projections under the assumption that current laws and regulations remain unchanged throughout the projections (U.S. Energy Information Administration, 2012). Based on figure 6, it seems that the number of Plug-in hybrid and all EV sales increase every five years. However, the largest portion of the market is still dominated by gasoline-only vehicles into 2035. Certain regulations and advances in technology and technology availability would impact the future projections of EVs purchased.

CAFE Standard's Impact on EV Sales

In response to environmental, economic, and energy security concerns, EPA and NHTSA in December 2011 jointly issued a proposed rule covering GHG emissions and Corporate Average Fuel Economy CAFE standards for passenger cars and light-duty trucks (U.S. Energy Information Administration, 2012). In October 2012, the EPA and NHTSA passed the rule to increase standards for 2017 and beyond, these new standards will go into effect in December 2012 (U.S. Environmental Protection Agency, 2012). The average miles-per-gallon petroleum consumption of light-duty vehicles, passenger cars and light-duty trucks will increase by different percentages annually. CAFE standards lead to a change in the vehicle mix in future years. Figure 7 compares the projections of the number of cars sold by type in the reference case to the projection of the number of cars sold by car type in the CAFE standards case (Turnure, 2012).

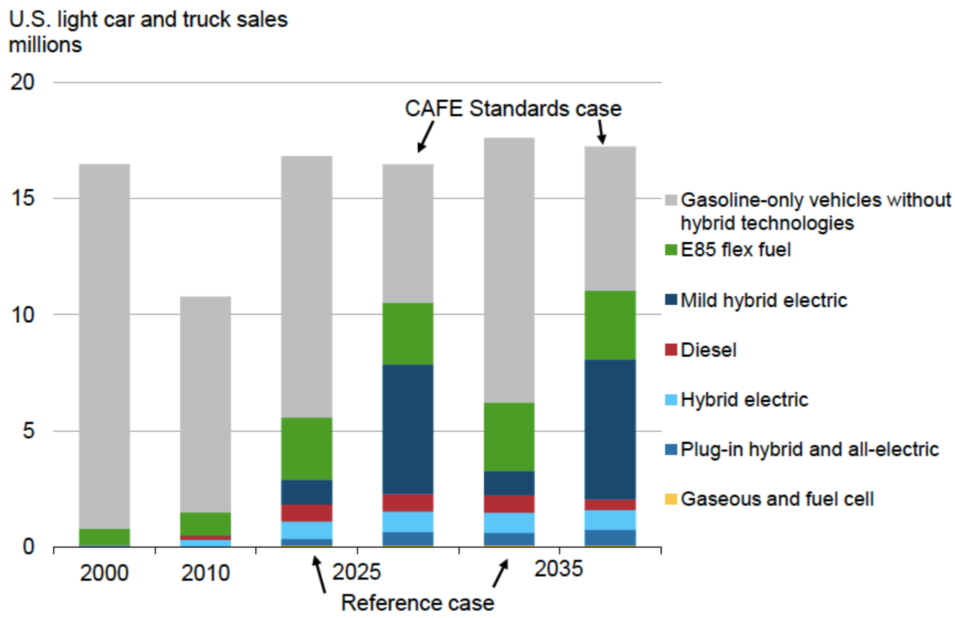

Figure 7. Annual Energy Outlook 2012 Reference Case and CAFE Standards Case (Turnure, 2012)

The above figure 7 shows a slight increase in the number of Plug-in hybrid and all-electric vehicles in the CAFE standards case. However, the number of Micro or "mild' hybrid vehicles increase to increase the fuel economy of cars. CAFE standards will increase the combined light duty vehicle fuel economy to 49.6 mpg by 2035, "though it could cause increased adoption of EVs, it could also significantly change the economic payback of electric vehicles by decreasing consumer refueling costs for conventional vehicles, thus lowering the fuel savings of electric vehicles and making the upfront incremental cost more prohibitive" (U.S. Energy Information Administration, 2012). AEO2012 defines mild hybrid EVs as vehicles with ICEs with larger batteries and electrically powered auxiliary systems that allow the engine to be turned off when the vehicle is coasting or idle and then quickly restarted (U.S. Energy Information Administration, 2012). These vehicles are recharged with fuel, not with electricity from the grid (U.S. Energy Information Administration, 2012). Since these are not pure EVs, we did not consider them in our analysis. Figure 8 makes it easier to see the difference in number of EVs on the road in 2025 in the two scenarios.

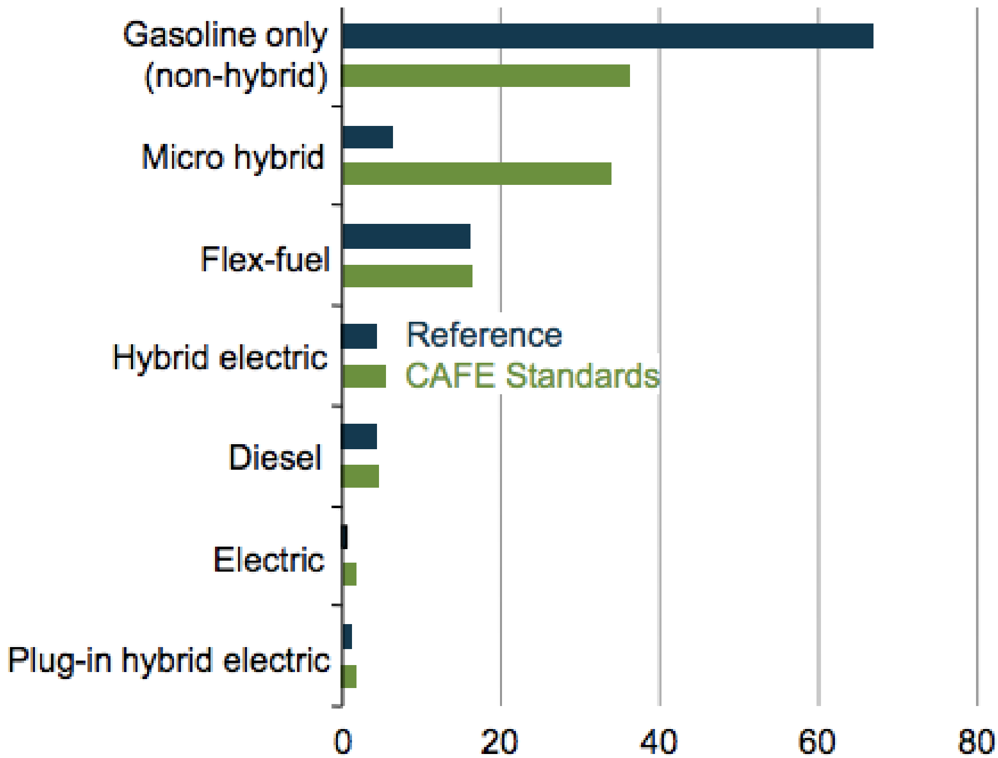

Figure 8. Light-Duty Vehicle Market Shares by Technology Type in the CAFE Standards case and the Reference Case in the year 2025 (Percent of all light-duty vehicle sales) (U.S. Energy Information Administration, 2012)

Based on the AEO2012 projections, it is predicted that CAFE standards will not have a large impact on the percentage of purely EVs on the road. In both the reference and the CAFE standard cases, the percentage of EVs on the road compared to other vehicle types is below one percent (U.S. Energy Information Administration, 2012). Because the proposed CAFE standards were passed and will go into effect this month, the future projections of the vehicle mix in the U.S. market is assumed to take the shapes of the projections in the CAFE standards case rather than the reference case.

Breakthroughs in Battery Technology

Another way to influence the market share of EVs in the future would be to have a significant breakthrough in battery technology. Breakthroughs in technology could make EV batteries less expensive (U.S. Energy Information Administration, 2012). EVs cannot penetrate the market when they are significantly more expensive than their ICE counterparts (U.S. Energy Information Administration, 2012). Some of examples of ways to bring down the cost of EVs would be to improve the manufacturing process, change the battery chemistry, or improve the electric motor (U.S. Energy Information Administration, 2012). In the AEO2012 High battery technology case, cost reductions are based on goals set by the Department of Energy (U.S. Department of Energy, 2012). These goals reduce the cost of batteries by 70% by 2014, based on 2009 costs, and reduce the cost of market-ready batteries by at least 35 percent (U.S. Department of Energy, 2012). With these goals in mind, figure 9 shows how the AEO2012 "High Technology Battery Case" compares to the reference case.

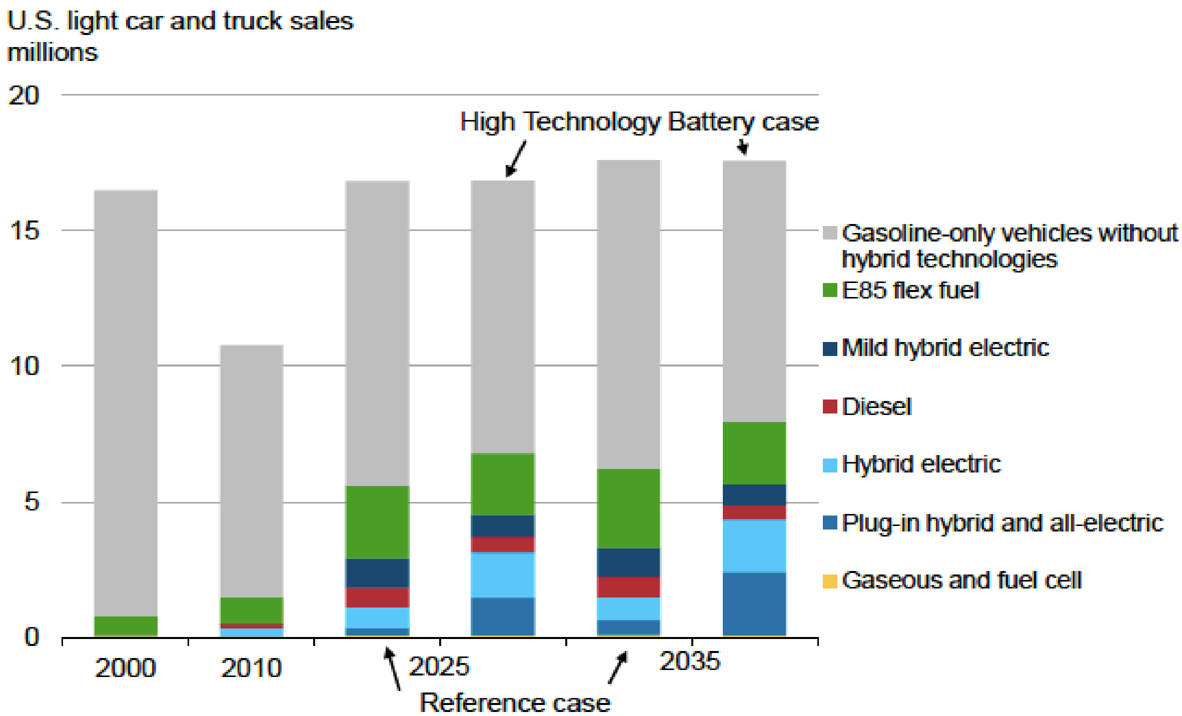

Figure 9. Annual Energy Outlook 2012 Reference Case and High Technology Battery Case (U.S. Energy Information Administration, 2012)

In this case, plug-in vehicle sales grow to about 13 percent of new vehicle sales in 2035, compared with 3 percent in the reference case (U.S. Energy Information Administration, 2012). Improving battery technology would have a much bigger impact on the number of electric cars driven in the future than passing of CAFE standards.

Expansion of Infrastructure

The EIA predicts that EVs would penetrate the market faster if high-speed vehicle re-charging stations were also available (U.S. Energy Information Administration, 2012). It is really a pairing better battery technologies and increases in high-speed charging stations that needs to occur in order to increase the number of EVs in the market. There are currently 5,059 charging stations in the United States (Figure 10 below shows where these stations are located). However, there are over 150,000 public gasoline re-fueling stations (U.S. Energy Information Administration, 2012).

Figure 10. U.S. Map Showing 5,059 curren electric vehicle re-charging stations.

When people make the decision to purchase a car, they weigh the benefits and costs of different models. One important consideration in these personal analyses is convenience. Without expansion of the public re-charging station network, people will have to rely on home charging stations, which are only available to people who are able to park their car within 20 feet of an electrical outlet. This only accounts for 40 percent of the residences in the United States (U.S. Energy Information Administration, 2012).

Figure 11 is based on data from a Source 1 Research study conducted in 2009 and confirms values given in a PikeResearch Study. It shows projections for the cumulative sales of re-charging equipment for EVs by type for 2010-2015.

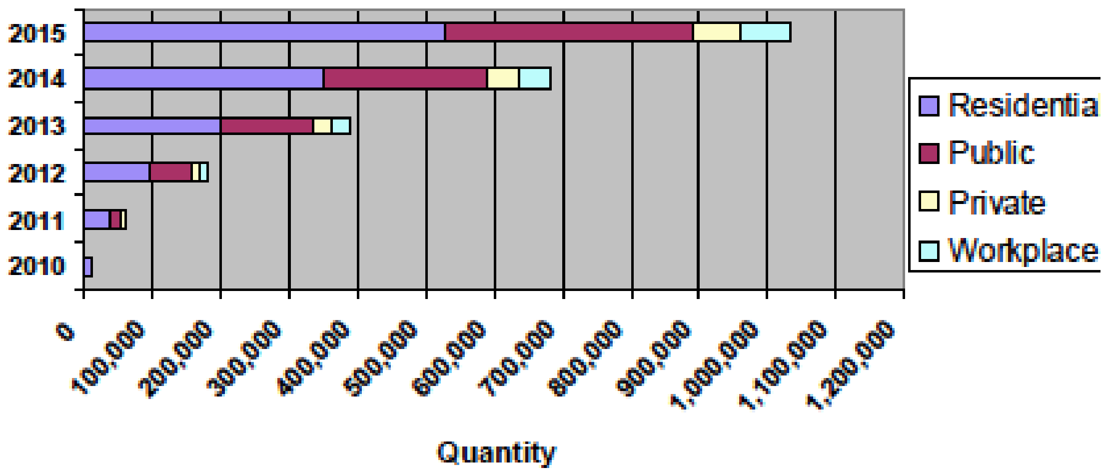

Figure 11. Cumulative Sales of charging stations in the United States 2010-2015 (Source 1 Research, 2009), (PikeResearch, 2010)

It is clear that projections predict that charging stations will increase significantly in the future. Source 1 Research predicts that there will be about 250,000 total charging outlets in the United States by 2015 (Source 1 Research, 2009). It is expected that if these projections actually occur, that more EVs will penetrate the market, due to increases in the convenience. An increased number of charging stations will help consumers to overcome their "range anxiety" over EVs (Electric Transportation Engineering Corporation, 2010). However, there are not projections available that actually show by how much this growth in number of charging stations will impact the percentage of EV sales in the future. These projections would be helpful to include in the AEO2013.

Electric vehicle recharging time serves as a significant barrier for future market penetration of EVs. Typical internal combustion vehicles take less than a minute to re-fuel, while for EVs, it depends on the voltage, but take significantly longer times. Recharging a battery with a 120-volt outlet could take up to 20 hours and a 240-volt outlet, about 7 hours (U.S. Energy Information Administration, 2012). There is discussion about building 480-volt quick recharging stations that would take about 30 minutes to recharge your vehicle, but there are safety issues associated with such high voltage outlets that create significant safety hazards (U.S. Energy Information Administration, 2012). This poses a significant convenience concern and may impact EVs being able to penetrate the market in the future.

New technologies are becoming increasingly available to overcome these refueling time barriers. One such technology is Tesla's solar powered charging station could help to overcome this barrier (Vance, 2012). The charging station, at 100 kW, will take about 30 minutes to fully revive a car that has been driven at 60 mph for 3 hours (Vance, 2012). Musk, one of the co-founders of Tesla says that he plans to cover most of the United States with these charging stations by 2014 (Vance, 2012).

Recommendations & Conclusion

With a low carbon intensive energy portfolio, EVs serve as a viable option for reducing the carbon footprint of the United States. However significant changes need to be made in order for people to adopt the new technology and for these vehicles to change the types of cars on the road. We have a few recommendations going forward that would increase the number of EVs on the road in a way that decreases the lifecycle $CO_{2(eq)}$ emissions of the transportation sector.

Our first recommendation is to maintain the federal income tax incentives available when purchasing a plug in EV. In the United States, there is a $7,500 income tax credit available for purchasing an EV. Tax incentives are important way for new technologies to gain a market share while the industry is still innovating and researching ways to decrease their production costs (Dahl, 2004). This will make electric cars more cost competitive with conventional vehicles while companies work on ways to decrease their costs of production, in order to have lower future consumer prices.

Another recommendation is to increase investment in battery technology. Improving lithium ion battery technology will increase vehicle range and make charging faster. Consumers value their time greatly and decreasing the time it takes to charge an EV will be critical to the future for the future market of EVs.

A third recommendation is increasing the number of public charging stations available. Drivers require the convenience of having more charging stations available in order to overcome "range anxiety". If owning an EV is less convenient than owning and ICE, it will be less likely for a consumer trying to decide between purchasing an EV or ICE, it is less likely that the consumer will purchase the ICE. In order for consumers to choose to purchase an EV more stations need to be available for easy re-fueling.

Our final recommendation is to invest more in renewable energy and low carbon energy alternatives. As seen in our analysis, if the primary source of electricity is coal, then the lifecycle $CO_{2(eq)}$ emissions of an EV are about the same as that of an ICE vehicle. Increased investment in renewable energy will help to decrease the carbon footprint of EVs and has the potential to ultimately reduce the carbon footprint of the entire transportation sector. Investment in technologies like Tesla's the solar charging stations would be very beneficial to the future of

EVs. Electric Vehicles have the potential to decrease the total U.S. carbon emissions, but to be done effectively, it is important that these recommendations be implemented.

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