Lifecycle Analysis Comparison of a Battery Electric Vehicle and a Conventional Gasoline Vehicle

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1. Abstract

California continues to be an environmental leader with the implementation of AB32. The California Air Resource Board (CARB) has enacted several programs to ensure the success of this groundbreaking bill. This study, in association with CARB, calculates the energy inputs and CO2 equivalents emissions of a conventional gasoline vehicle (CV), a hybrid vehicle, and a battery electric vehicle (BEV) to determine the lifecycle environmental costs of each specific to California. A hybrid model's results were generated based off of a weighted-average of CV and BEV results, using ⅙ of the battery from the BEV data. Data used were a compilation of the California GREET model, Argonne National Laboratory articles and other relevant peer-reviewed literature. The base cases of these models were then analyzed to test the sensitivity of a variety of assumptions, including carbon intensity of gasoline and electricity, varied electricity mixes, battery lifetime, and fuel economy. A cost effectiveness for each vehicle type was also calculated; the hybrid vehicle was found to be the most cost effective for reducing CO2. The net present cost of all vehicles was also calculated resulting in the hybrid being the least expensive over its lifetime, followed by the CV, and finally the BEV. The main purpose of this study was to examine the environmental impact of each vehicle type, taking into account the lifecycle energy usage and both CO2 equivalents and air pollution emitted. In terms of environmental impacts, the BEV was determined to have the least overall impact, followed by the hybrid, and lastly the CV.

2. Introduction

Climate change continues to become more of a driving force on different aspects of social living. Researchers are better able to understand, predict, and now witness the extreme weather events, rising temperatures, and subsequent resource shortages that will occur as climate begins to shift to a new equilibrium. With this in mind, we are witnessing a shift in how policymakers and scientists are addressing the best methods to mitigate these impending impacts.

One possible method for creating a more sustainable society is by reducing greenhouse gas emissions, which is measured by decreasing CO2 equivalents. Targeting the transportation sector as a major emitter of carbon dioxide equivalents is a step in the right direction in regards to reducing emissions. Revolutionizing the vehicle fleet that is currently on the road will be a key change by introducing an alternative fuel fleet. When looking at alternatives for fossil fuels, there needs to be an understanding of what type of vehicle requires the least amount of energy, produces the least amount of carbon dioxide emissions, and has the least overall impact on the environment.

Consequently, our research delves into examining and quantifying lifecycle energy requirements and emissions of a battery electric vehicle (BEV), a hybrid vehicle, and a conventional gasoline vehicle (CV). To collect all of the applicable data, we made a number of assumptions based on trends we saw throughout our literature review. We are interested in what scenarios a BEV will prove to be a better alternative to a hybrid and a CV. We conducted lifecycle assessments for both the BEV and CV, and used weighted averages and extrapolation to produce the data for a hybrid vehicle. We performed a sensitivity analysis to determine the effects on energy and emissions of changing several important variables, which included the carbon intensity of gasoline and electricity, the electricity mix, the life of the battery, and the fuel economy of the CV and BEV. We focus specifically on driving the vehicles in California (CA), but we also expanded our analysis to include the effects of charging the BEV with a United States (U.S.) average electricity mix and a Chinese average electricity mix.

Emissions and energy are two means of classifying a more sustainable vehicle fleet, but we also conducted cost analyses. From this we can determine if BEVs are not only environmentally sustainable but also economically sustainable. With this data we can weigh the BEV lifetime cost and compare it to the hybrid and CV lifetime costs to conclude which alternative vehicle is the most sustainable for the environment and the economy.

3. Methods

We defined our system boundary for this LCA to include all direct inputs and outputs from resource extraction to waste and recycling. We also included some indirect inputs such as the transportation needed to move the vehicle components from the manufacturing facilities, to the vehicle assembly factories, and finally to the dealership. The detailed flow diagrams of our systems are found in Appendix A and B. We then conducted an inventory analysis for each vehicle by collecting numerical data on the unit processes shown in Appendix A and B. The data came from various sources including published articles, government websites, and the California GREET Model, a large database released by the California Air Resources Board containing information on air pollutants and carbon and energy intensities for different transportation fuels. The entire list of unit processes and its corresponding sources are found in Appendix C.

Vehicle Assumptions

In the process of building our data inventory and creating our base case, we made several assumptions based on relevancy and the trends from the sources found in Appendix C. First, we assumed the design of the cars to be exactly the same, excluding the CV engine and the BEV battery. The total weight of the CV used in our LCA is 1500 kg, comprising of 1275 kg of vehicle parts and 225 kg for the engine. The BEV assumed weight is 1575 kg, consisting of the same 1275 kg of vehicle parts but also a 300 kg lithium-ion battery. According to the findings of Southern California Edison, the effective vehicle life assumed for both vehicles is 180,000 miles based. Most existing lifecycle assessments on BEVs imply no battery replacement. Moreover, the Nissan Leaf manufacturer states that the battery pack is designed to last the life of the car. Yet others such as Notter et al. accounted for a full battery replacement. We estimated an average value of 1.5 batteries for our calculations due to the need of partial replacement over the battery's lifetime. As a battery is continuously recharged and discharged, it slowly loses capacity resulting in reduced driving range. Hence, maintenance is required to maintain the BEV's performance. For contemporary electric vehicles, the batteries are composed of separate modules that can be replaced individually. Therefore, the whole battery does not need to be replaced. An LCA of a hybrid vehicle was also conducted based on a weighted average between the CV and BEV data, assuming ⅙ of a battery being used.

The fuel economy of the CV is 31 mpg, which is comparable to a Nissan Versa or compact equivalent, 50 mpg for the hybrid, which is comparable to a Toyota Prius, and 100 mpg-eq for the BEV, comparable to the efficiency of a Nissan Leaf battery (.21 Kwh/Km). To calculate the BEV miles per gallon equivalents, we began with the energy density of gasoline, 121 MJ/gallon. We multiplied 121MJ/gal * 1kwhr/3.6MJ * 1km/0.21Kwh * 1mile/1.609 km to get 100 miles/gallon of gasoline equivalent. A final assumption used was the Intergovernmental Panel on Climate Change (IPCC) conversions rates for carbon dioxide, methane, and nitrous oxides to carbon dioxide equivalents (CO2eq) in our final calculations of total CO2eq emitted.

Electricity Mix Assumptions

Because our base case assumed all charging will be done in California, we therefore used the current California electricity mix for our calculations. These values were taken from "California's Power Content Label" by the California Energy Commission, and consisted of: coal (7%), nuclear (14%), natural gas (42%), total hydropower (13%), wind (5%), geothermal (5%), solar (0%), and biomass (2%). Part of the sensitivity analysis, which is explained below, included projecting the effects of future electricity mix in California. We therefore decided to use the 2020 projected mix based off of the implementations of AB32. AB32 calls for California to generate 33% of its electricity from renewable sources. With the future projections to contain 33% renewables, there will mainly be an increase in solar and wind power. We assumed that electricity produced from coal would be the source that decreased the most drastically, as it is the the most carbon intensive. Thus the electricity producing energy mix in 2020 will comprise of: coal (1%), nuclear (11%), natural gas (36%), total hydropower (13%), wind (15%), geothermal (5%), solar (5%), and biomass (2%).

A national electricity mix was also used to compare BEV lifecycle impacts between CA and the US. Data of the national mix was found from the Energy Information Administration. This mix contained: coal (42%), nuclear (19.28%), natural gas (25%), hydropower (8%), wind (3%), geothermal (0.36%), solar (0.01%), and biomass (1.3%). We are also interested in the widespread use of BEV in China and thus performed a sensitivity analysis on China's electricity mix. Data of the electricity production mix of China came from the Institute for Energy Research's "What Can the U.S. Learn from China's Energy Policy?" China is overall more carbon intensive in their electricity production than the US, as a significant portion of their electricity source comes from coal. They also utilize less renewables in their production. The final mix used in our calculations were: coal (79%), nuclear (2%), natural gas (2%), hydropower (16%), oil (2%), wind (0%), geothermal (0%), solar (6%), and biomass (0%).

Transportation Assumptions

The three methods of transportation assumed in the movement of the vehicle parts, batteries, and whole cars are trucking, shipping, and rail. All methods of transportation utilize diesel fuel. The gasoline required was quantified by dividing the miles traveled by the average mileage per unit weight. This allowed us to scale everything down to the parts needed for one complete vehicle. We assumed batteries are made in China and shipped to San Pedro via large diesel cargo ships. Car parts are made in Mexico, transported to the US border via diesel trucks, and then shipped by rail to Detroit. Whole cars are then shipped by diesel train from Detroit to their final destination at dealerships in Los Angeles. Diesel trucks are used for short distances as well as to transport goods between the port and car dealerships. We assumed efficiencies of 99 ton-miles per gallon for diesel trucks, 380 ton-miles per gallon for trains, and 1,043 ton-miles per gallon for ships based on "Comparative Evaluation of Rail and Truck Fuel Efficiency on Competitive Corridors," a Federal Railroad Administration paper, and an Iowa State University study by Baumel et al. Distances between destinations were calculated using Google Maps and emissions of these modes of transportation were calculated using the California GREET model.

Disposal and Recycling Assumptions

We assumed that all the car parts for both vehicles were recycled and disposed of in the same manner. From the literature, we discovered that there were a number of steps that went into disposal. These steps include: dismantling, shredding, separation, and transportation of the car parts to the junkyard. We accounted that these steps were the same for each of the BEV and CV only varying them slightly by weight. Where the two vehicles differ is in the recycling of the battery from the BEV. We included recycling of the lithium ion battery in the lifetime of the battery cycle from production to recycling. We did not include disposal of engine because we assumed that each engine was not disposed of and was instead remanufactured to be reused in other vehicles.

As mentioned earlier, we assumed that disposal of the BEV and CV only differ in their disposal of the BEV battery. The disposal of the car parts was held constant at 1297.33 MJ of energy and 53.51 kg of CO2. Currently battery recycling is a new and unproven technology, especially for batteries specifically tailored for BEVs. We are assuming lithium ion batteries to be the future method for battery technology in electric vehicles. While it is true other battery types such as nickel metal hydride were used in older models, most current models in the market as of this writing use lithium ion batteries. Our research on battery recycling yielded very limited data. Most studies show that battery recycling is not economically feasible due to the lack of demand for the raw material. Moreover, it is currently cheaper to use virgin battery raw material than recycled battery material since the latter is more energy intensive. But in the interest of future development of recycling, we included recycling in the lifetime of the battery.

Based on our findings in Ishihara et al., Nemry et al., and Staudinger and Keoleian, we determined that battery recycling required 31 MJ/kg, which, with a 300 kg battery per vehicle and operating under the assumption of 1 battery with partial replacement per vehicle life, equates to 13950 MJ of energy required to recycle the battery. We calculated, based on an emission intensity of energy of 1.51 kg CO2 per kg of battery, that this would lead to emissions totaling 680.76 kg CO2. Based on comparing our base case numbers, disposal remains an insignificant percentage of the overall totals. Disposal of a BEV is less than 1% of the total lifecycle energy and emissions. Limitations of this is the fact that our analysis assumed battery recycling to be included in a subset battery lifecycle analysis. Thus disposal remains an insignificant part of vehicle lifecycle energy and emissions. For CV, this is also true and only represents <1% of the overall lifecycle energy and emissions. Instead, including battery recycling in the battery lifecycle analysis provides a significant boost to the battery manufacturing sector of the base case thus accounting for its significant representation of approximately 20% of the total energy and emissions for the vehicle.

Sensitivity Analysis Methodology

After completing the base case, we performed sensitivity analysis on the various lifecycle stages and on several parameters to test for uncertainty. First, tornado graphs were created for both the CV and the BEV to display the sensitivity of MJ/mile and kg CO2eq/mile to the different lifecycle stages. The lifecycle stages that influence overall MJ/mile and kg CO2eq/mile for the BEV are manufacturing of vehicle parts, battery manufacturing, transportation of vehicle parts, charging, and disposal. The lifecycle stages that influence overall MJ/mile and kg CO2eq/mile for the CV are manufacturing of vehicle parts, engine manufacturing, transportation of vehicle parts, the fuel cycle, and disposal. The tornado graphs further below demonstrate which stages are the most influential. Furthermore, four individual parameters were tested: the carbon intensity of gasoline, the electricity mix, the life of the battery, and the fuel economies of the CV and BEV. We performed the sensitivity analysis by keeping the values of the rest of the unit processes constant, only changing each of the above parameters independently. The first parameter tested in a sensitivity analysis is the carbon intensity of gasoline. Because the carbon intensity of gasoline is increased with marginal supplies coming from tar sands, we assumed that gasoline would become at least 15% dirtier. This 15% assumption is justified because it falls within an expected range of 8-37% from a Natural Resources Defense Council study by Mui et al. The next parameter tested was electricity mix variation. Four variations were compared when analyzing how the electricity mix affects our final results: base case (California's current electricity mix), the US national electricity mix, the current mix in China, and a future California mix based on the projections of AB32.

The third parameter tested was the life of the battery. In the BEV base case it was assumed that one individual lithium ion battery had a lifetime of 120,000, therefore a total of 1.5 batteries would be needed for a vehicle lifetime of 180,000 miles. This 1.5 battery presumption was tested by calculating the lifecycle energy and emissions impacts of alternative scenarios where the battery does not have to be replaced at all (1 battery over the lifetime) or where the battery would have to be completely replaced once (2 batteries over the lifetime). The fourth parameter is the fuel economy of the BEV and CV. The base case fuel economy of 31 mpg for the CV was manipulated to find the mpg at which total lifecycle energy requirements and CO2 equivalent emissions were equal to those for the BEV. The fuel efficiency for the BEV in terms of km/KWH was also manipulated to see how a 10% battery efficiency change would affect lifecycle energy and emissions.

Monte Carlo Assumptions

We did a Monte Carlo analysis, via an excel add-in tool, in order to account for uncertainty in addition to the variability we covered in sensitivity analysis. We chose to perform the analysis on areas that were determined to be the most uncertain and sensitive to change. We determined the area that was most uncertain in a CV was the use phase. Performing the uncertainty analysis allowed us to determine how the range will change based on different scenarios. Uncertainty differs from variability because uncertainty allows us to change within a given set of unknowns compared to variability which is a known change. For a BEV, we figured the most uncertain variables to be battery manufacturing, in addition to use phase. Battery manufacturing is an uncertain variable because there is little literature available on how to project more efficient manufacturing into the future. An uncertain aspect of BEV charging is how different carbon intensities affect the BEV, much like a sensitivity analysis. We want to see where the mean and most likely event will occur as our scenarios change within given uncertainties.

Cost Effectiveness and Net Present Cost Assumptions

To determine the cost effectiveness, we performed a net present value calculation. The base prices used were $35,000 for the BEV, $15,000 for the CV, and $20,000 for the Hybrid. These prices were based off of Kelly Blue Book fair purchase prices for a Nissan LEAF (BEV), a Nissan Versa (CV), and a Toyota Prius C (hybrid). The effective base price of the BEV is lowered by $7500 after federal tax incentives, however this is not included in our calculations. A $3,000 mandatory home charger is included, however. We also predicted the BEV battery would need to be partially replaced for $10,000 after 8 years, based on a current price of $30,000 for a full replacement which should fall with improving technology. The interest rate was assumed to be 5%. A gasoline base price of $3.82 per gallon was based off of the California average for 2011. We used an electricity price of 12 cents per KWH based off of California averages. We calculated a gasoline price increase rate of 12.6% based on a 15 year California average from "U.S. Gasoline and Diesel Retail Prices" by the U.S. Energy Information Administration and found that electricity increased at a rate of 6% based on residential electricity prices provided by EIA. Finally, we decided that the 180,000 miles would be traveled equally over 15 years.

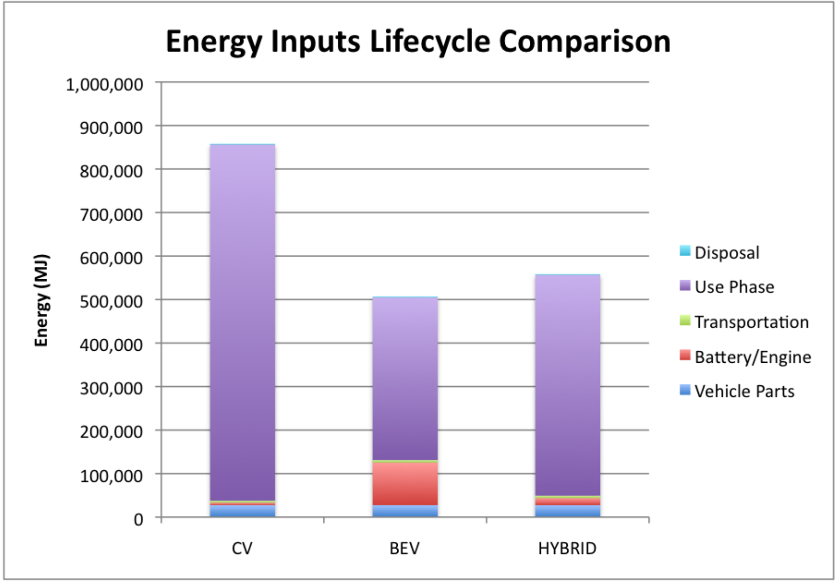
4. Results and Discussion

Our results begin with our base cases for energy inputs and CO2 equivalents emissions for our three vehicle types. Then we show the corresponding air pollution emissions for the CV and the BEV. Next, the results of our sensitivity analyses are shown with corresponding graphs and tables, which illustrate the sensitivity of our base case to changing assumptions. Monte Carlo Uncertainty analysis and cost studies are also included.

a. Base case

i. Lifecycle Energy Results

Figure 1. Energy Inputs Lifecycle Comparison



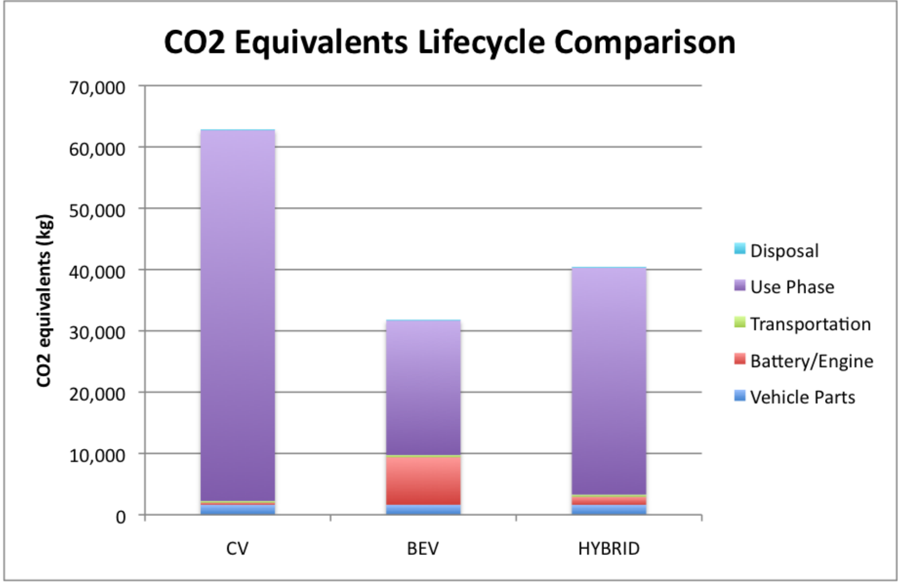
Our preliminary results, or “base case,” for the energy requirements of each vehicle type show that over their lifetime (manufacturing, transportation, use, and disposal), the CV requires 858,145 MJ, the BEV requires 506,988 MJ, and the hybrid requires 564,251 MJ of energy. Figure 1 shows this lifecycle comparison, categorizing the phases by color within each bar on the graph. The use phase contributes most significantly to the energy use of all three vehicle types. Battery production, included in the lifecycles of the BEV and hybrid vehicle, also played a major role in lifecycle energy requirements.

Our base case results suggest that a BEV uses the least amount of energy of all the vehicle types analyzed in this study, followed by a hybrid and a CV. The results of the CV lifecycle analysis show that by far the greatest source of energy intensity is the use phase, at 95% of the lifecycle energy. This is due to the amounts of energy required to extract and process the gasoline and the energy intensity of the gasoline itself. Other life stages such as the manufacturing of vehicle parts, engine manufacturing, transportation, and disposal contribute minimal energy requirements. Similarly for the BEV model, the use phase, which consists of generating the electricity needed to charge the battery, requires the most energy of all phases: 74% of the total energy used over the lifetime.

Interestingly, the battery manufacturing phase also contributes significantly, with 19% of the lifetime energy requirements. Vehicle parts manufacturing, transportation, and disposal are not significant to the overall lifecycle energy inputs of a BEV. A hybrid's energy requirements, as predicted, all in-between the CV and BEV, with the greatest energy needs coming from the use phase at 89%. Due to the smaller size of the hybrid battery, our calculations suggest that a hybrid's battery manufacturing only accounts for 4% of the lifecycle energy inputs. For all cases, transportation, vehicle parts manufacturing, and disposal phases were negligible.

ii. CO2 Equivalents Results

Figure 2. CO2 Equivalents Lifecycle Comparison



Our base case of emissions produced over the entire lifecycle of the vehicles (measured in CO2 equivalents), reveals that a CV produces 62,866 kg CO2 equivalents, a BEV produces 31, 821 kg CO2 equivalents, and a hybrid produces 40,773 kg CO2 equivalents (Figure 2). The lifecycle emissions results follow the same trend as lifecycle energy results, revealing that the BEV is the most efficient, followed by the hybrid and the CV.

For all three vehicle types, the use phase contributes the most CO2 equivalents emissions; the use phase can be attributed to 96% of CV emissions, 91% of hybrid emissions, and 69% of BEV emissions. Battery manufacturing is accountable for 24% of the BEV's lifecycle emissions, but only 3% of hybrid's lifecycle emissions. The BEV produces the lowest amount of emissions and is therefore the best in terms of environmental impacts overall.

iii. Energy and Emissions Per Mile Driven

Table 1. Energy and Emissions Per Mile Comparison Table

	Energy (MJ/mile)	Emissions (kg CO2eq/mile)
BEV	2.82	0.18
CV	4.77	0.35
Hybrid	3.14	0.23

Table 1 shows the per mile comparison of a BEV, CV, and hybrid with respect to lifetime energy and emissions. Given a vehicle lifetime of 180,000 miles, each mile driven in a BEV requires 2.82 MJ and produces 0.18 kg CO2 equivalents, each mile driven in a CV requires 4.77 MJ and produces 0.35 kg CO2 equivalents, and each mile driven in a hybrid requires 3.14 MJ and produces 0.23 kg CO2 equivalents. The CV is 41% more energy intensive and 49% more emitting than the BEV. The CV is also 34% more energy intensive and emitting than the hybrid. The hybrid is 10% more energy intensive and 22% more emitting than the BEV.

iv. Air Pollutants

Figure 3. CV Lifecycle Air Pollutants

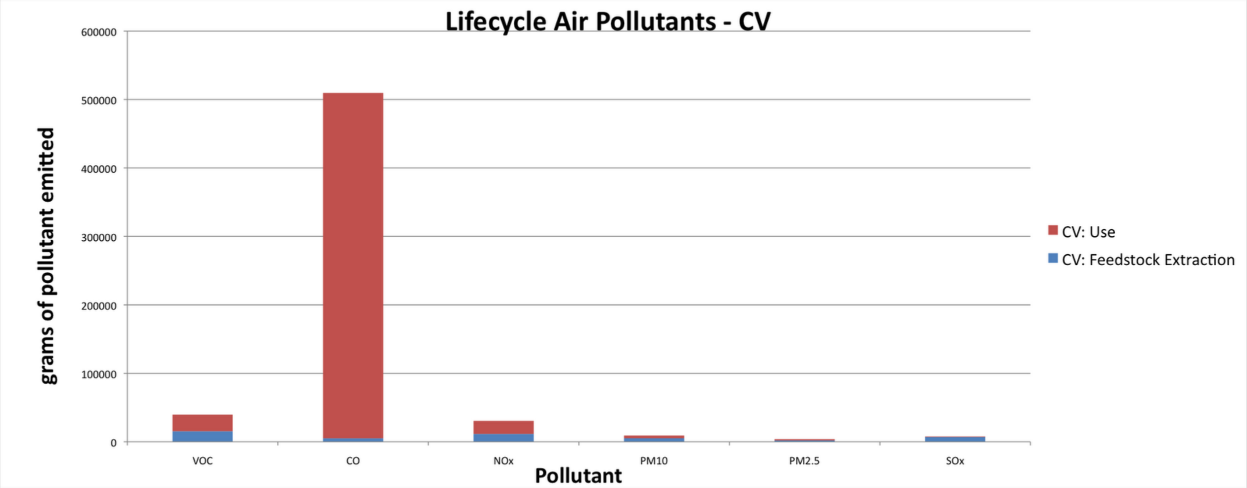


Figure 3 displays lifecycle air pollutants of the CV. Use phase (red) dominates over the lifecycle. Note the values of grams polluted over the lifecycle. Emissions for the CV (figure 3) are an order of magnitude higher than that of the BEV. It may seem deceiving. Figure 5 is a more accurate way to compare lifecycle air pollutants of the CV vs BEV.

Figure 4. BEV Lifecycle Air Pollutants

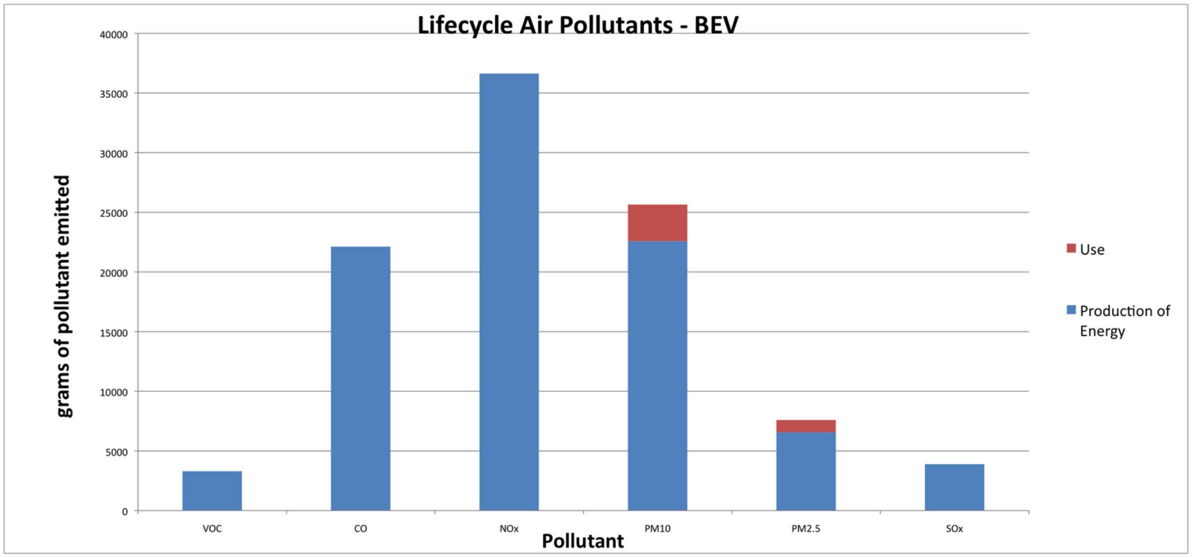


Figure 4 illustrates air pollution over the lifecycle of the BEV. The majority of pollution comes from the production of electricity (shown in blue). Air pollutant emissions during use phase are only PM10 and PM2.5 (see figure 4). This is due to brake and tire wear while in motion. There is no pollution during use for VOCs, CO, NOx, or SOx. Pollution occurs during electricity production, and thus is a point source. This has potential for facilitated trapping of pollutants. If technology moves in a way to allow air pollutants to be trapped, stored, or removed by reactions, use of the BEV has even more potential to reduce air pollution.

Figure 5. Lifecycle Air Pollutants Comparison

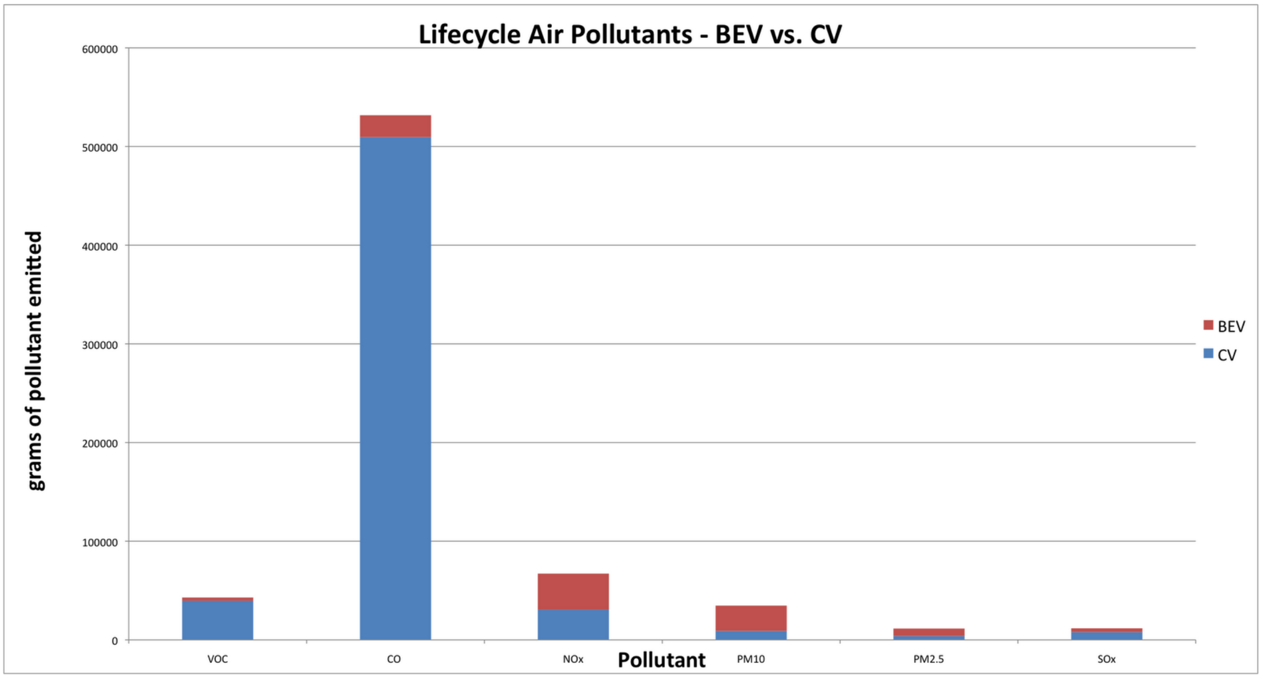


Figure 5 is a combined graph of the lifecycle air pollutants for the CV and BEV.

Air pollution has serious impacts on the environment and human health. VOCs, CO, NOx, PM10, PM2.5, and SOx make up the non-greenhouse gas pollution from each vehicle type.

- VOCs react with NOx in the presence of sunlight to form ozone. In the troposphere, ozone is a serious air pollutant, causing smog. Ozone prevents the human lung from inhaling to full capacity. High concentrations of ozone inhibit plants rate of photosynthesis.
- CO also contributes to the formation of smog, reducing visibility. To the human body, carbon monoxide reduces the amount of oxygen delivered to vital organs.
- NOx has minor human health impacts, mainly respiratory related. It also reacts with VOCs in the presence of sunlight to form ozone.
- PM10 & PM2.5 are a main factor in visibility reduction. High concentrations also may have some effect on the human respiratory system.
- SOx can react in the atmosphere and form small particles. Particulate matter may have respiratory effects if exposed to high concentrations.

b. Sensitivity Analysis

i. Energy and Emissions Sensitivity

Tornado graphs were created for both the CV and the BEV to display the sensitivity of MJ/mile and kg CO2eq/mile to the different lifecycle stages. The lifecycle stages that influence overall MJ/mile and kg CO2eq/mile for the BEV are manufacturing of vehicle parts, battery manufacturing, transportation of vehicle parts, charging, and disposal. The lifecycle stages that influence overall MJ/mile and kg CO2eq/mile for the CV are manufacturing of vehicle parts, engine manufacturing, transportation of vehicle parts, the fuel cycle, and disposal. The tornado graphs further below demonstrate that the stages with the largest bars are the most influential.

Figure 6. BEV Energy Sensitivity

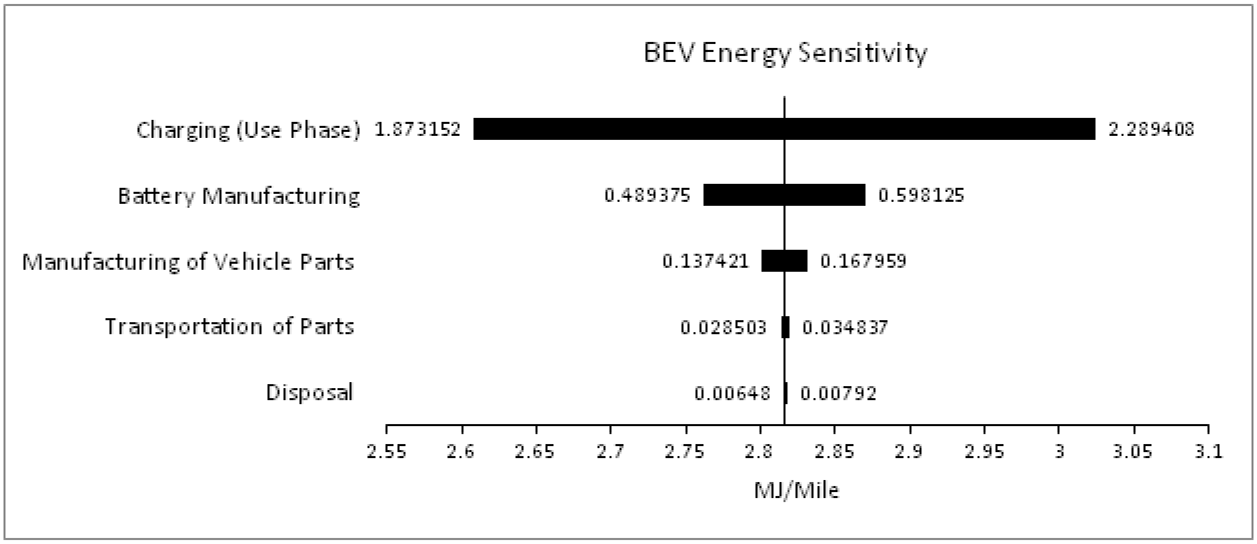


Figure 6 demonstrates that a change in energy intensity (MJ/mile) during the electrical charging process will be the most influential in the overall lifecycle energy intensity for the BEV. A change in MJ/mile during battery manufacturing will also greatly impact the overall energy intensity of the BEV. This proves that charging and battery manufacturing are crucial contributors to BEV energy intensity.

Figure 7. BEV Emissions Sensitivity

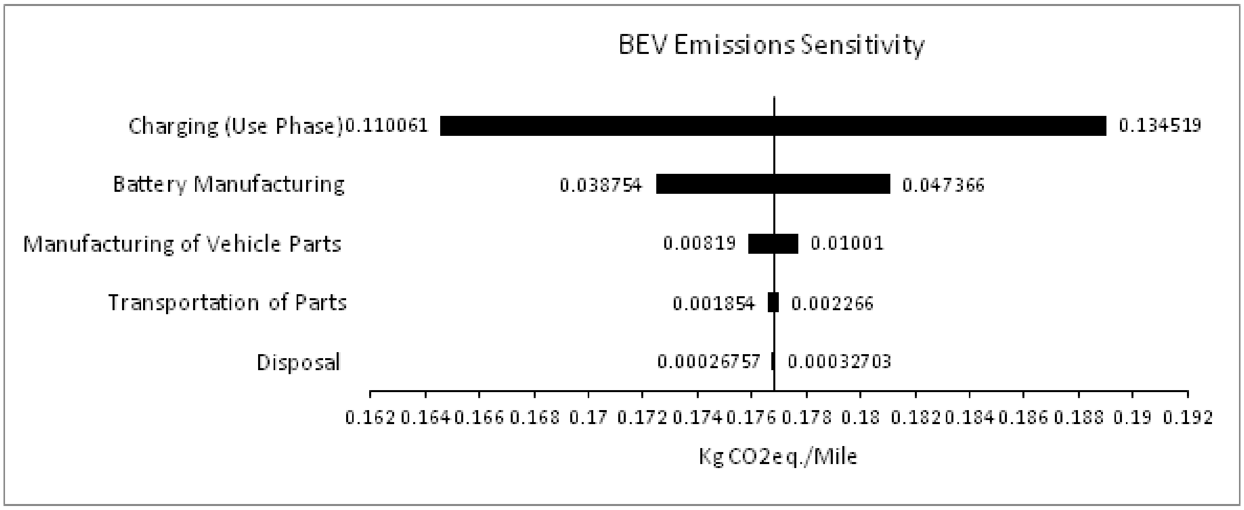


Figure 7 demonstrates that a change in emissions intensity during the electrical charging process (or use phase) will be the most influential in the overall lifecycle emissions intensity for the BEV. A change in kg CO2eq/mile during battery manufacturing will also greatly impact the overall emissions intensity of the BEV. This proves that charging and battery manufacturing are crucial contributors to BEV emissions intensity.

Figure 8. CV Energy Sensitivity

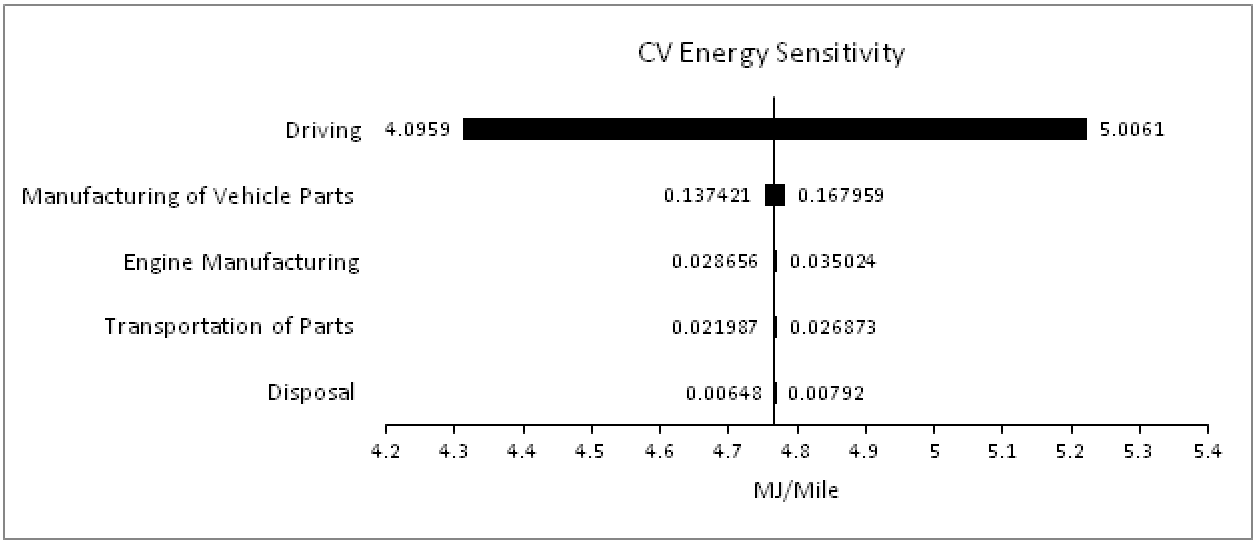


Figure 8 demonstrates that a change in energy intensity during the driving stage will be by far the most significant contribution to the overall lifecycle energy intensity for the CV. A change in MJ/mile during the manufacturing of vehicle parts is also influential but not as critically as the actual driving of the CV.

Figure 9. CV Emissions Sensitivity

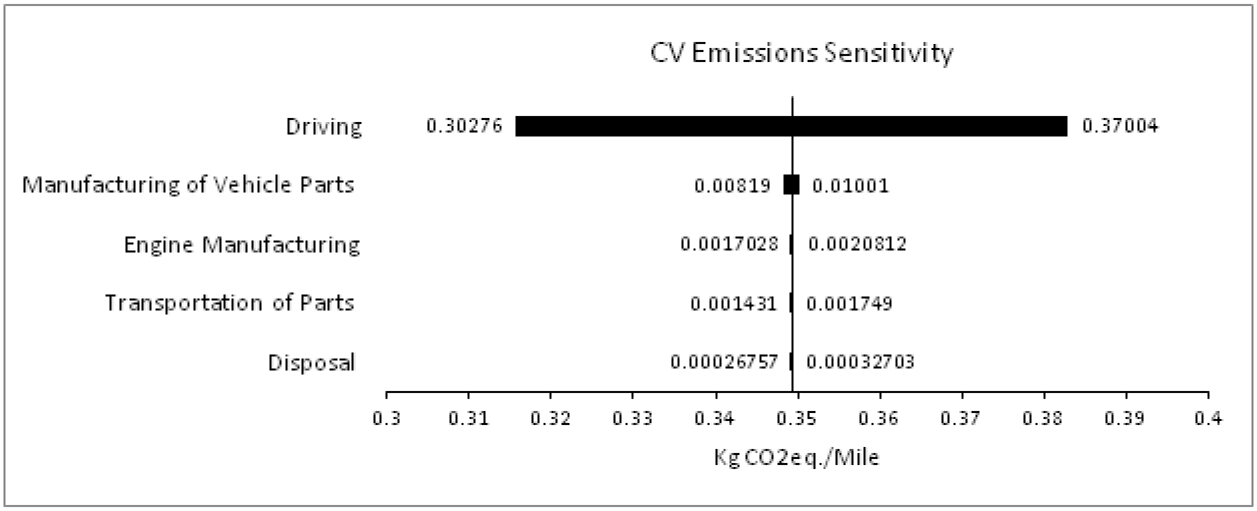


Figure 9 demonstrates that a change in emissions intensity during the driving stage will be by far the most significant contribution to the overall lifecycle emissions intensity for the CV. A change in kg CO2eq/mile during the manufacturing of vehicle parts is also influential but not as critically as the actual driving of the CV.

ii. Future Projections of Carbon Intensity for Gasoline and Electricity Mix

While a lifecycle analysis of current data is useful, it is important to extrapolate data into the future when deciding on a vehicle that will last for 180,000 miles. Assuming that gasoline is progressively getting dirtier as we explore tar sand technology, CVs will become more polluting with time. Because hybrids also consume gasoline during the use phase, the hybrid model also becomes more polluting with time. BEVs however will become more efficient and less polluting as the electricity mix is shifted towards renewable energy sources such as solar and wind.

Figure 10. CO2 Equivalents Lifecycle Comparison

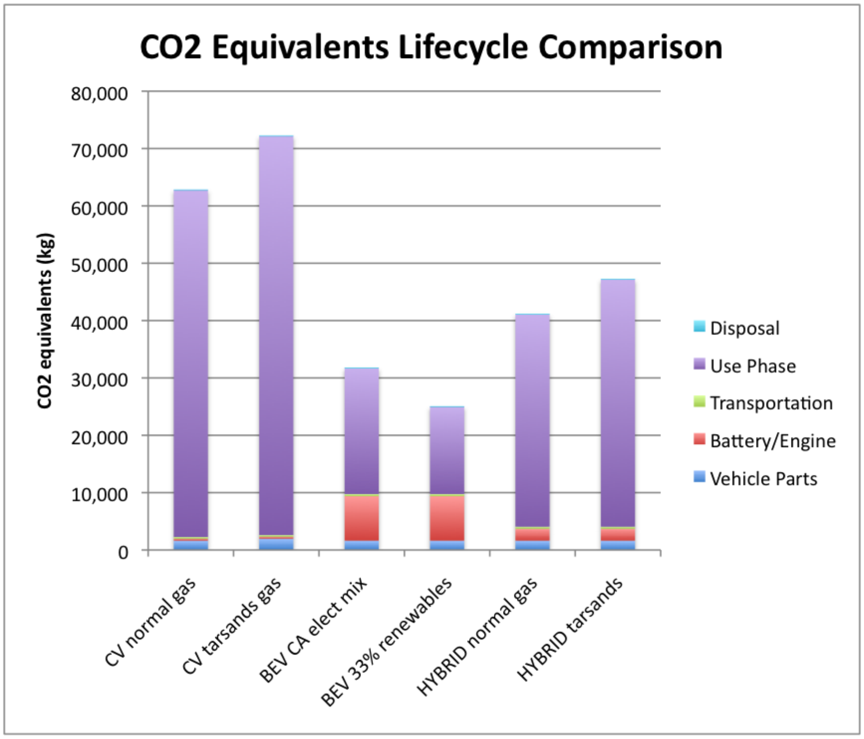
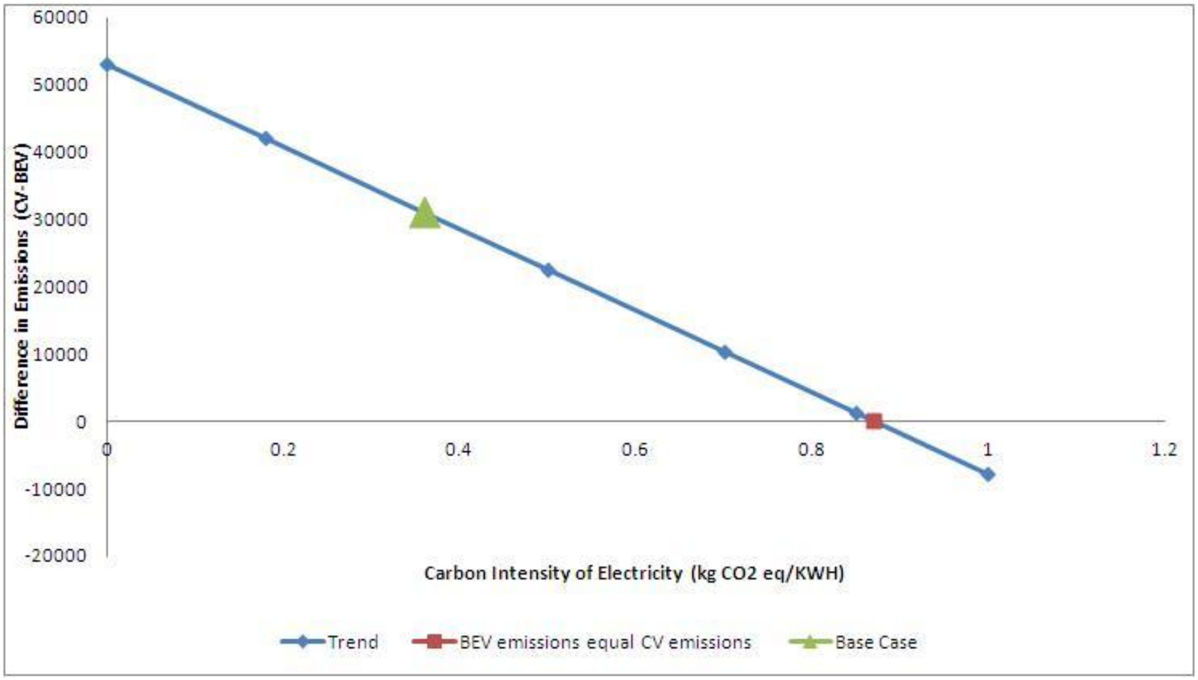


Figure 10 is a compilation of our base case results and our projected results for the year 2020 based on gasoline getting 15% dirtier with increased extraction from tar sands and California's electricity mix getting cleaner with increased power coming from renewable energy sources. If gasoline becomes 15% dirtier because of increased extraction from tar sands then CV and hybrid CO2 equivalents emissions will be 15% higher than the base case values. Based off of California's goal to have 33% of its electricity coming from renewable sources by 2020, we calculated the lifecycle energy inputs and emissions of a BEV charged with 33% renewables and found that the use phase emissions fell from 22,012 kg CO2 equivalents to 15,283 kg CO2 equivalents, a 31% decrease.

Figure 11 below shows the carbon intensity of electricity. From the graph we hoped to determine the requisite kg of carbon dioxide equivalents produced per KWH in order to make the difference in CV and BEV equal to zero. Effectively this would make the CO2 emissions equal for both cars. If electricity had a higher intensity, this would make the BEV worse than a CV from an emissions standpoint. The break even point in terms of carbon intensity is 0.87 kg CO2eq/KWH. We can see from the figure that the base case is current at approximately 0.34 kg CO2eq/KWH. This means that carbon intensity would have to more than double in order for the break even point to occur. At the break even point, however, there are still benefits to driving a BEV; electricity production occurs at a point source. CO2 emissions from electricity production come from a stationary location and thus have the potential to be confined. CV emissions are a mobile source and thus are harder to capture.

Figure 11. Carbon Intensity of Electricity



We did a similar analysis and graph for increasing carbon intensity of gasoline which can be found in the Appendix D. As expected, the graph demonstrates that as carbon intensity of gasoline increased, the difference in emissions between the CV and BEV also increases and never approaches zero.

iii. Variations in Electricity Mix

By substituting the electricity mix for different regions of BEV operation, we were able to see how energy intensity and emission intensity varies during the lifecycle. The different electricity mixes considered, besides the California mix used in the base case, were the AB32 projected mix with 33% renewables, the U.S. mix, and the Chinese mix.

Table 2. BEV Energy and Emissions Intensity for Different Electricity Mixes

Life Time	Energy (MJ/mile)	Emissions (kg CO2eq/mile)
California AB32 2020 Projected 33% Renewables	2.32	0.14
CA Electricity Mix (Base Case)	2.82	0.18
U.S. Electricity Mix	3.63	0.29
China Electricity Mix	4.04	0.40

In comparison to the California base case mix, the AB32 2020 projected 33% renewables mix demonstrates a decrease of 18% in emissions intensity and a decrease of 22% in emissions intensity. The U.S. electricity mix entails an increase of 29% in energy intensity and an increase of 61% in emissions intensity, when compared to California. China's electricity mix yields an increase of 43% in energy intensity and an increase of 122% in emissions intensity. Figure 11 and Figure 12 further display the energy and emissions intensity percentage differences among electricity variations. Our sensitivity analysis of electricity mix dependency shows that California's electricity mix with 33% renewables, is the most energy efficient and the least polluting, followed by the base case California mix, then by the U.S. average national mix, and finally by China's average electricity mix. California not only has the highest percentage of renewables, but also the lowest percentage of electricity coming from coal-fired power plants, which lowers emissions considerably. Thus, it is more energy and emissions efficient to charge a BEV in California than it is to charge it elsewhere in the United States or in China.

Figure 12. Electricity Mix Comparison-Energy

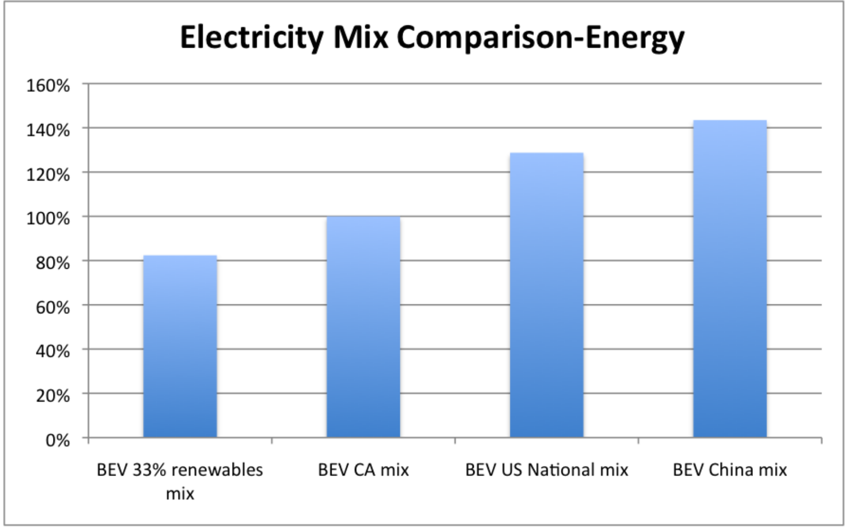


Figure 12 shows how the electricity mix impacts the lifecycle energy inputs requirements of a BEV by comparing the California base case to a future projection of 33% renewables in California, of the U.S. national average mix, and of China's average mix. The graph is normalized and the changes are seen as percentages rather than in MJs.

Figure 13. Electricity Mix Comparison-Emissions

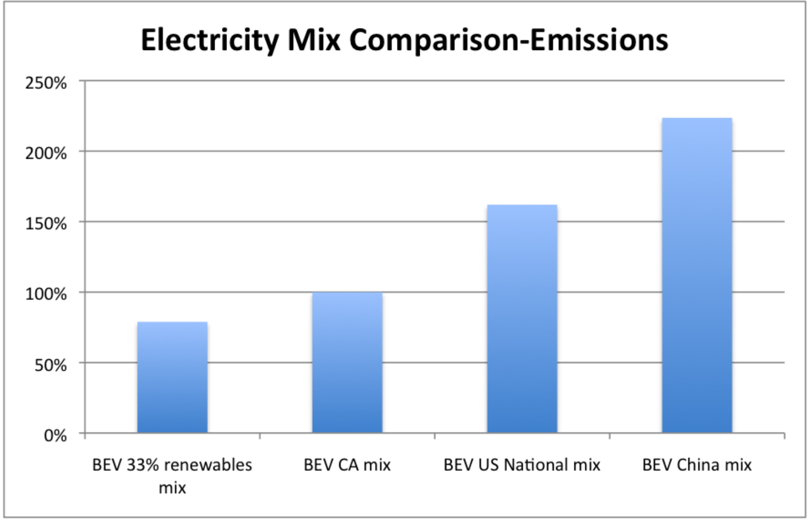


Figure 13 shows how the electricity mix impacts the lifecycle emissions of a BEV by comparing the California base case to a future projection of 33% renewables in California, of the U.S. national average mix, and of China's average mix. The graph is normalized and the changes are seen as percentages rather than in CO2 equivalents.

iv. Battery Lifetime Analysis

In the BEV base case, it was assumed that half of the battery modules would have to be replaced once during the lifetime of the vehicle. To test the sensitivity of this partial replacement, calculations for the energy intensity and emissions intensity were done assuming different circumstances where either one complete battery would have to be replaced or the battery would not have to be replaced at all.

Table 3.

	Energy (MJ/mile)	Emissions (kg CO2eq/mile)
BEV, battery replaced once during lifetime	3.001	0.191
BEV, battery partially replaced(50%) (base case)	2.817	0.177
BEV, no battery replacement	2.632	0.162

The battery technology used in BEVs is constantly evolving and becoming more efficient. While we assumed that 50% of the battery would need to be replaced once over the lifetime of the BEV in our base case, we feel that this will not hold true for BEVs in the future and that less replacement will be necessary. To analyze this decreasing scale of battery energy requirements and emissions, we tested our data by decreasing the number of batteries from 1.5 to 1 to determine how fewer battery resource needs would impact the overall lifecycle impacts, and also tested our results if the full battery needed to be replaced and changed the number of batteries to 2. Running sensitivity analysis on the life of the lithium ion battery found in the BEV shows that if the battery lifetime range were to increase so that only 1 battery was needed instead of 1.5, making replacement unnecessary, the BEV would become 6.57% more energy efficient and produce 8.47% fewer emissions. If all of the battery modules required replacement during the life of the BEV (or one whole extra battery), the energy per mile would be 3.001 MJ/mile and the emissions per mile would be 0.191 kg CO2eq/mile. Requiring two batteries over the BEV lifetime rather than a single battery increases the CO2 equivalents emissions by 17.9%. While battery efficiency does carry some weight in the overall lifecycle emissions; it is the still the use phase and charging of the battery that impacts lifecycle emissions the most.

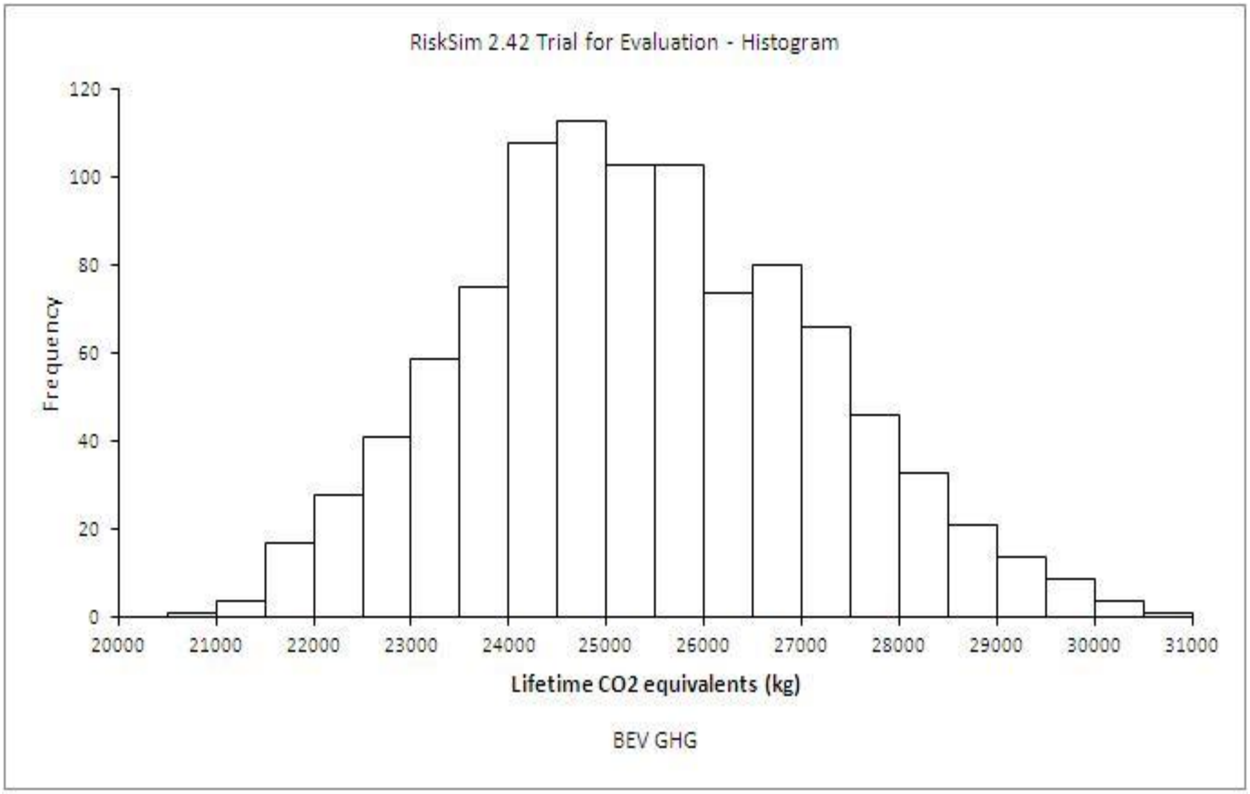
v. Fuel Economy Analysis

Because the drivetrains of BEVs and CVs differ so extensively, it is important to be able to compare their efficiencies against each other; using conversion factors found in GREET, we were able to use the metric of miles per gallon equivalents to compare the CV and BEV base cases. In our base case we assumed that a CV had a fuel economy of 31 miles per gallon of gasoline, which is comparable to the fuel economy of a Nissan Versa. The BEV was assumed to have an efficiency of 100 miles per gallon of gasoline equivalents, which is comparable to the fuel economy of a Nissan Leaf. In terms of lifecycle energy input requirements, for a CV to equal a BEV in energy usage, a CV must achieve an improved fuel economy of 54 miles per gallon of gasoline. Similarly, the CV would have to increase its fuel economy from 31 mpg to 63 mpg to meet the lifecycle emissions of a BEV. While CV technology is likely to improve with time, the gasoline will also become more polluting, potentially negating the efficiency increases in conventional engine technology.The fuel efficiency for the BEV in terms of km/KWH was also manipulated to see how a 10% battery efficiency change would affect lifecycle energy and emissions. These battery efficiency results are visible in Appendix D.

c. Monte Carlo Uncertainty Analysis

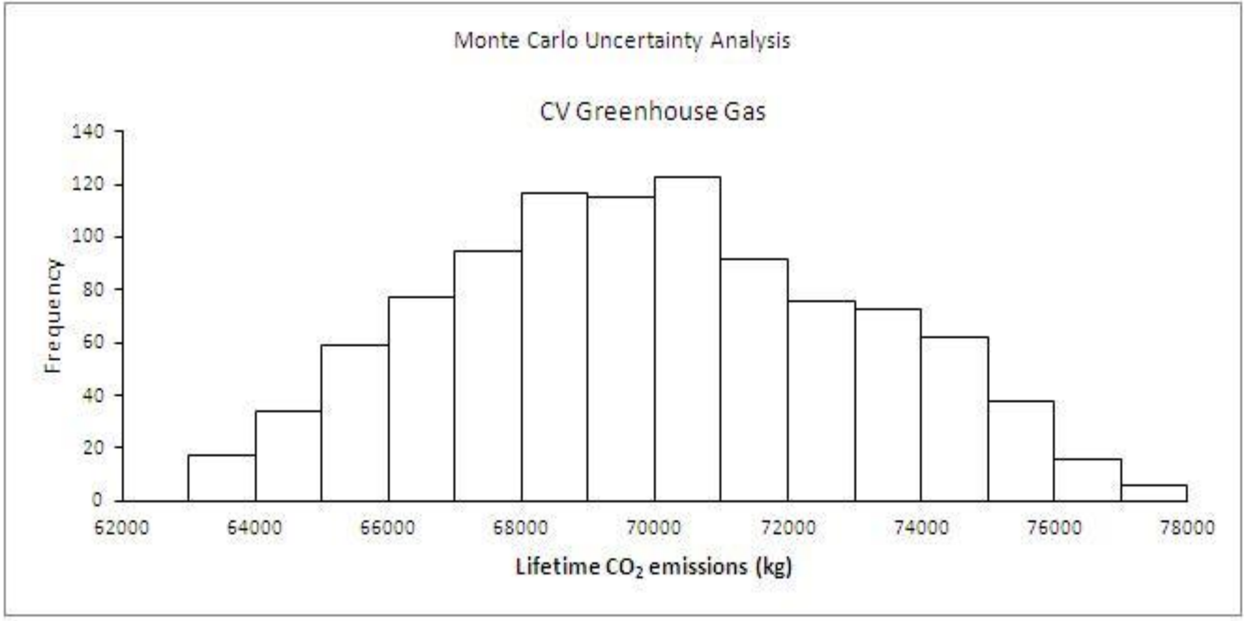
When performing a Monte Carlo Analysis on BEV Greenhouse Gas emissions, we ran an Excel plug in that ran 1000 iterations. For the analysis, we held a number of variables as constant because they played little role in affecting the overall value for emissions. For BEV, we assigned variable parameters to battery manufacturing and charging because we were uncertain about how they would change over time. Our results from this analysis shows that at our current base case standards, the emissions are at 31,820.56 kg CO2 for lifetime carbon emissions. When looking at Figure 14, we can see that this number is an outlier. From Figure 14, we interpret this statistical result to mean that as electricity sources become less carbon intensive and more focused on renewables, the lifetime CO2 equivalents will decrease. The mean from this standard bell curve shows the most frequent occurrence will be between 24000 and 25000 kg CO2 over the whole lifetime. This is a stark contrast and dramatically reduced from the base case values. The implications of this is that cleaner energy inputs and less battery replacement trends the BEV towards a more favorable vehicle.

Figure 14. Monte Carlo Uncertainty Analysis for BEV GHG emissions



For a CV, our base case analysis equates CO2 equivalents to 62,866.2 kg over the lifetime. When conducting the Monte Carlo uncertainty analysis on the CV GHG emissions, we kept vehicle parts manufacturing, engine manufacturing, transportation of parts, and disposal as constants because these had little effect on the overall outcome and emissions level. Instead we performed a uncertainty test on the GHG emissions from the use phase. When looking at Figure 15, we see that our base case emissions value is at the low end of the frequency. As gasoline mix becomes dirtier because fuel sources are moving towards the marginal and more energy intensive extraction, then it will shift the mean emissions higher. According to the 1000 trials ran in the assessment, there will be more likely occurrences of 70,000 kg CO2 being emitted over a lifetime of a CV.

Figure 15. Monte Carlo Uncertainty Analysis for CV GHG emissions

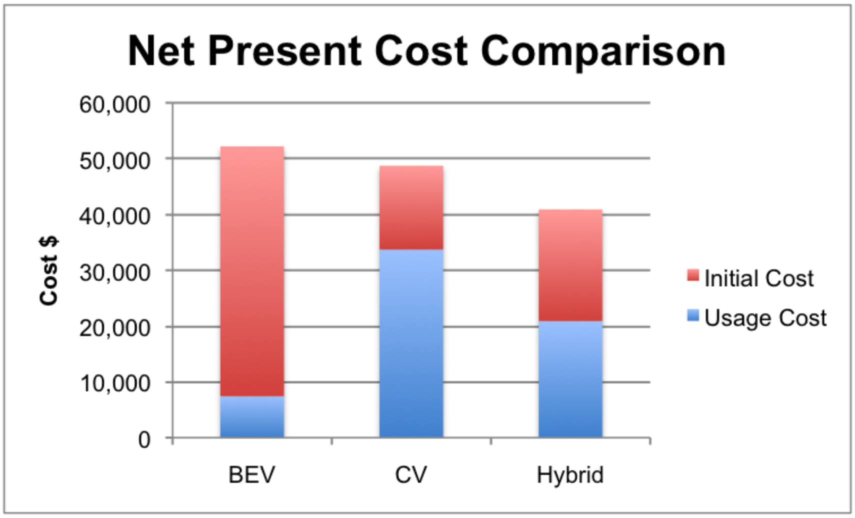


d. Cost Analyses

i. Total Lifecycle Cost and Payback Period

The BEV will cost the consumer an estimated $52,203.95 over its 15 year, 180,000 mile lifetime. This lifecycle cost includes a mandatory charger for the electric vehicle, which must be installed at the owner's home for $3,000, as well as a $10,000 partial replacement battery after 8 years or 100,000 miles. This figure does not include government tax credits which would lower the cost by $7,500. Although the sticker price of the BEV is only $35,000, the net present cost including the charger and replacement battery is $45,435.56. The electricity usage adds $7,435.56 over its lifetime. The Hybrid vehicle is the cheapest over its whole lifetime at $40,906.50. The upfront cost is $20,000 and the lifetime cost of gasoline adds up to $20,906.50. The Conventional Vehicle is $48,720.17 over it's lifetime. The upfront cost for the CV is only $15,000.00, but the gasoline costs add up to $33,720.17.

Figure 16. Net Present Cost Comparison



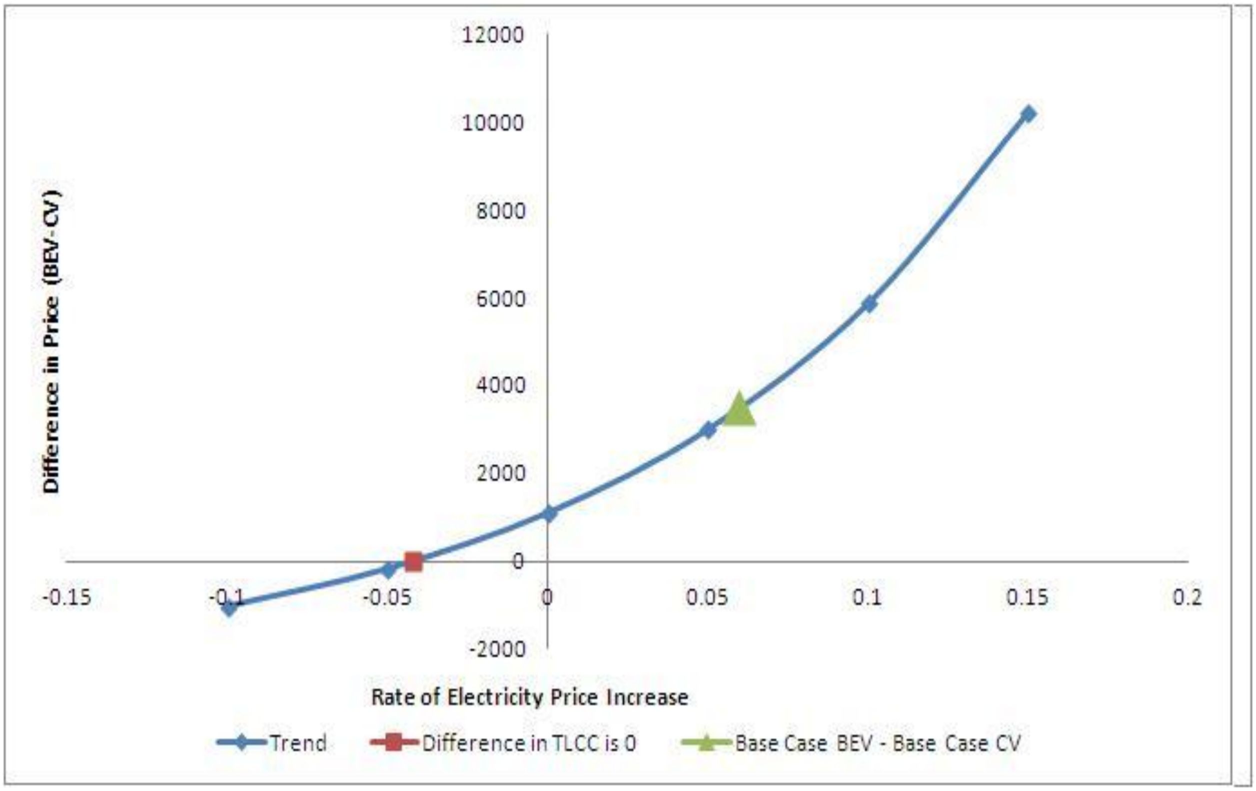
The hybrid vehicle is the cheapest over its lifetime, followed by the CV. The BEV is the most expensive. The time it takes to recover the initial difference varies depending on how much gasoline will cost in the future and what the interest rate is. These rates will change the usage costs at each year.

Based on our calculated differences in usage costs, a consumer should be willing to spend an extra $26,284.61 on a BEV compared to a CV or an extra $13,470.95 compared to a hybrid for the vehicles to have the same lifetime costs. This means that the BEV does not pay itself off over its lifetime since the BEV costs $30,435.56 more than a CV. If one takes into account government subsidies, the BEV is effectively $7,500 cheaper. After 13 years, the consumer would have spent $30,374.78 on gasoline for a CV or $6,906.29 on electricity for a BEV. At this point the savings would be $23,468.49 which is greater than the initial subsidized vehicle price difference, meaning the extra initial cost for a BEV will have been paid off after 13 years.

Using the same calculation to compare a hybrid to a CV, the Hybrid’s extra initial cost of $5,000 will be paid off after 8 years. The gasoline costs will be $8,754.08 for a hybrid and $14,119.49 for a CV.

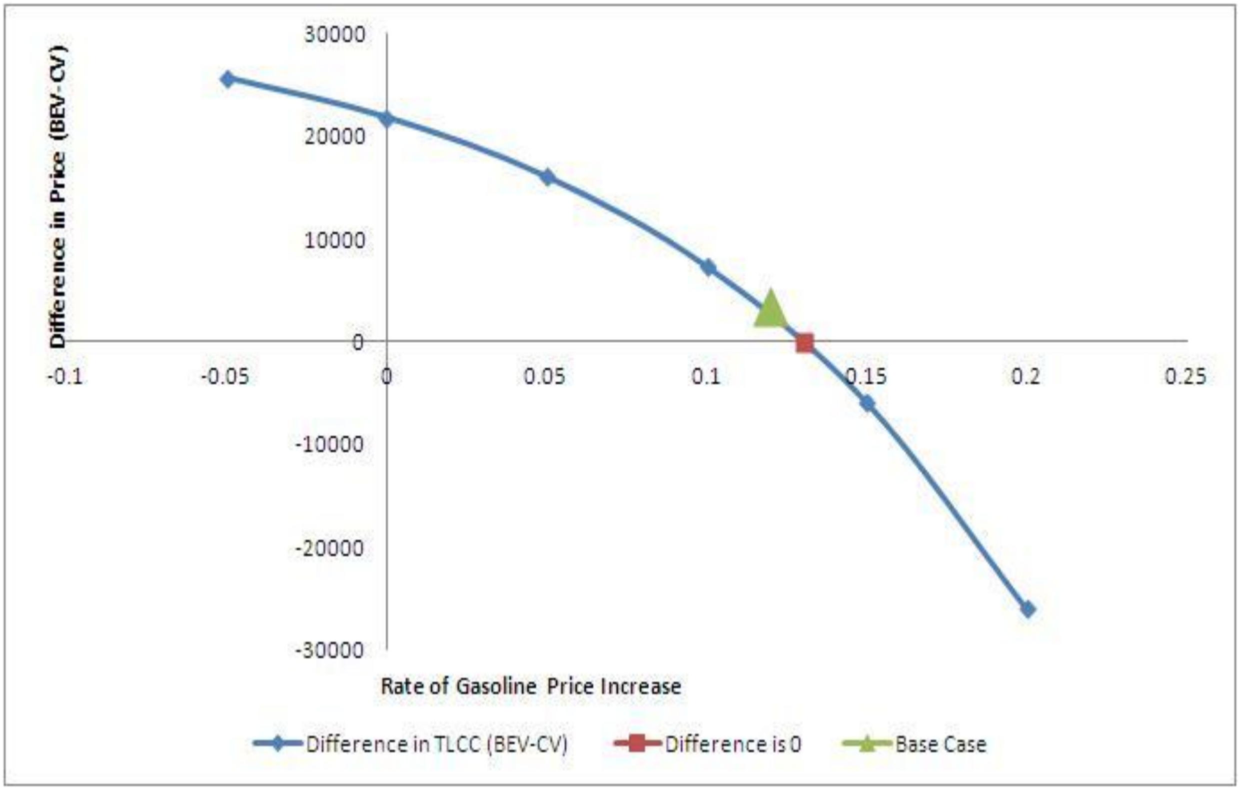
In Figure 17 below, we determined the rate of electricity price increase needed in order to equate the cost of the BEV and the CV. In doing so we held all other prices constant, which is a limitation. What we determined however is that in order for the costs to be equivalent, electricity prices must increase by a negative percentage, effectively decrease by approximately 5% to make the costs the same. The graph also shows that as electricity prices continue to increase, the cost differential between a BEV and CV will increase at a faster rate, effectively making the BEV a worse economic choice.

Figure 17. Breakeven Point for Cost of BEV and CV When Altering Rate of Electricity Price Increase



Alternatively this Figure 18 shows the difference in price between a BEV and CV when comparing them to rising gasoline prices. We wanted to analyze how gasoline prices had to increase, again holding all other prices constant, in order to break even and make the CV costlier than the BEV. Our findings indicated that the base case costs were very close to the break even point and that gasoline prices need to rise at a rate of approximately 13% per year, a much more reasonable expectation. From the graph, we determine that as the gasoline rate continues on an upward trend, the CV overtakes the BEV in terms of lifetime costs and quickly outpaces it.

Figure 18. Breakeven Point for Cost of BEV and CV when altering Rate of Gasoline Price Increase



ii. Cost Effectiveness

To calculate the cost effectiveness of the BEV and the hybrid, the incremental total lifecycle costs were divided by the lifecycle emissions avoided. Thus, an incremental cost of \$3,483.78 was calculated based on the difference of CV total lifecycle cost of \$48,720.17 and of BEV total lifecycle cost \$52,203.95. The difference in emissions between the CV and the BEV was 31,045.64 kg CO2eq. This shows that for every additional dollar spent on the BEV compared to the CV, 8.91 kg CO2eq. are avoided or that it costs approximately \$0.11 to avoid emitting 1 kg CO2eq. Similar approaches were taken to calculate the cost effectiveness for the hybrid compared to the CV and for the BEV compared to the hybrid. The cost effectiveness for the hybrid compared to the CV is -2.77 kg CO2eq/\$ or -0.36 \$/kg CO2eq. There is a negative cost for the hybrid here because the total lifecycle cost is lower than that for the CV, so there is no incremental cost for the emissions avoided. Although one saves money while also saving emissions with the hybrid, there is still a positive payback period because the consumer must wait 8 years to recuperate the additional upfront cost. Nonetheless, the hybrid is the more cost effective option for reducing emissions because even if the efficiency in terms of km/KWH increases for the BEV, there is still an incremental cost for the avoided emissions, whereas with the hybrid there is actually cost savings.

5. Limitations

Despite our attention to detail when conducting our study, there are certain factors that are difficult to account for in our project. As such, it is expected that the project has certain limitations. For example, most of our assumptions are based on current events and technology.

The future is very uncertain so these assumptions likely will change. The energy mix is one such inevitable change. Our base case employs current California and U.S. energy mixes but these will likely shift towards a higher percentage of renewables as the world shifts away from fossil fuels. This shift will result in widespread use of BEV's being even more appealing. Battery electric vehicles are a newly emerging technology. As these vehicles get more popular, more firms will develop BEV's to compete in the market. With increased popularity comes increased research and technological upgrades. BEV's likely will become increasingly efficient in the future in terms of both their manufacture and fuel economy. With an increasing number of BEV's on the road, the demand on electricity will also increase causing electricity rates to rise. Simultaneously, the cost of gasoline will fall as the need for it decreases. These two opposing trends will likely lead to a price equilibrium, which will determine the quantity of each vehicle type on the road. Therefore, our cost analysis has its limits.

Another factor limiting our project is national security. World events and conflicts are volatile events that influence energy prices. Unfortunately, it is very difficult to predict the effects of these events for our project so we did not incorporate national security in our study. In many ways, we implicitly considered the current state of world affairs by choosing our base energy prices for our study. The prices we chose are a function of the current state of the economy and international relations. By doing so, we automatically kept this factor constant when we made our projections but in reality, it is unpredictable. For example, most of our imported oil is from the Middle East, which is quite unstable, but this may not be the case in the future. Again our study is limited due to be being based on current information. Lifecycle analyses by definition describe the state of system at a specific point in time, and hence is limited.

6. Conclusions

After our base case, sensitivity analysis, and uncertainty analysis, all of our results point to one main finding: a BEV is more energy efficient, and less polluting than a CV.

Although it takes 13 years to pay off the extra initial cost of a BEV over the lifetime of the vehicle, a BEV can ultimately save the consumer money. With improving technology, batteries and their production will become more efficient and BEV costs will likely decrease, making an electric car more attractive in the future from the consumer's standpoint.

The majority of CV lifecycle air pollutants are emitted on the road. This type of emission is a mobile source - pollution that is very difficult to confine. Air pollution from BEVs however are emitted during the production of electricity and thus are a point source. Pollution from point sources has the potential to be easier to mitigate. With future advances in capturing and storing or chemically removing air pollution, BEV's will have an even lower impact on the environment. Reduced air pollution leads to improved visibility and public health benefits.

With AB 32, California has committed to increasing its renewable energy sources through climate action policy. AB32 mandates that California's electricity mix contain at least 33% renewables by 2020. The production of clean, virtually emissions-free energy makes BEVs more appealing, especially as the charging of BEVs will increase electricity consumption. This increase in renewables is also likely to drive improvements in energy technology and efficiency.

Future research can project our analysis even further. We recommend continued analysis in battery production and recycling. Clearly the BEV is preferred in terms of environmental concerns. However, further research needs to be conducted on how to better meet consumers' need with longer battery range and faster charging ability.

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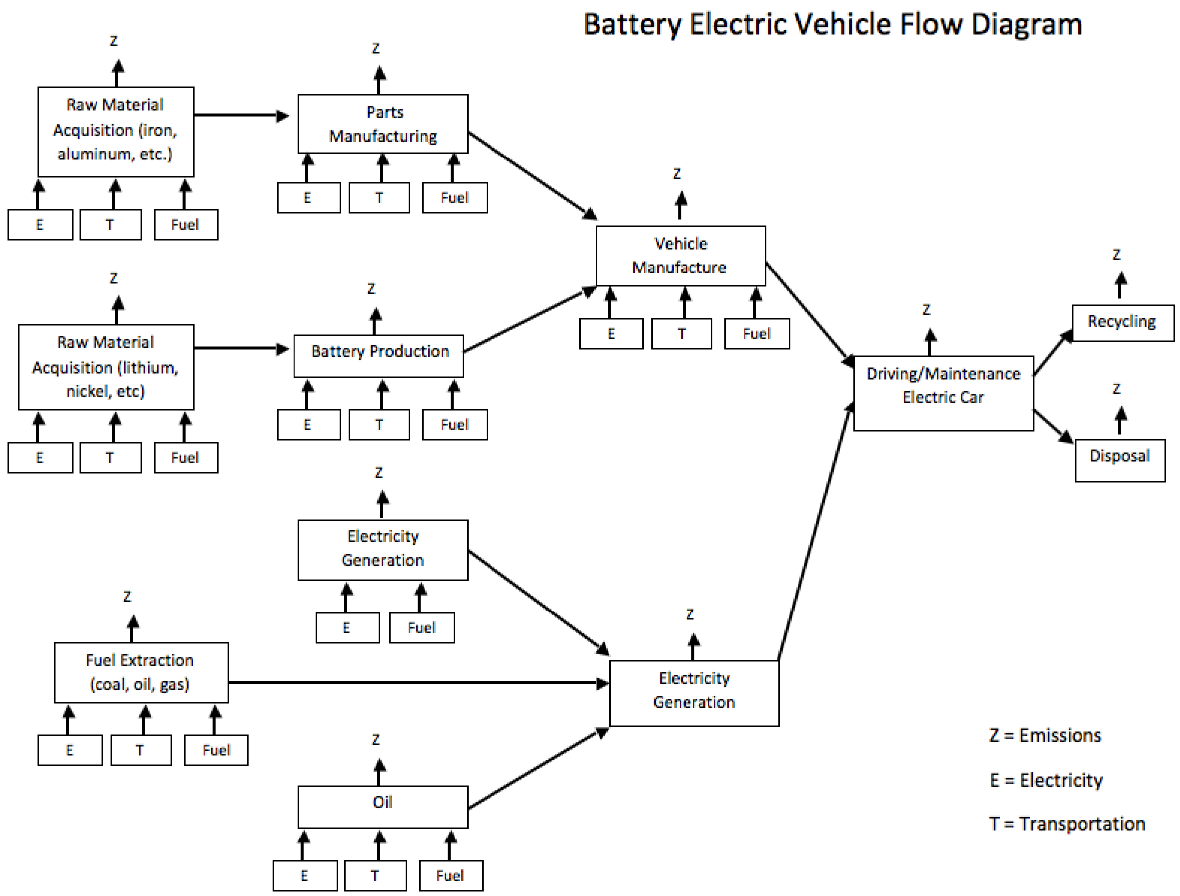
8. Appendices

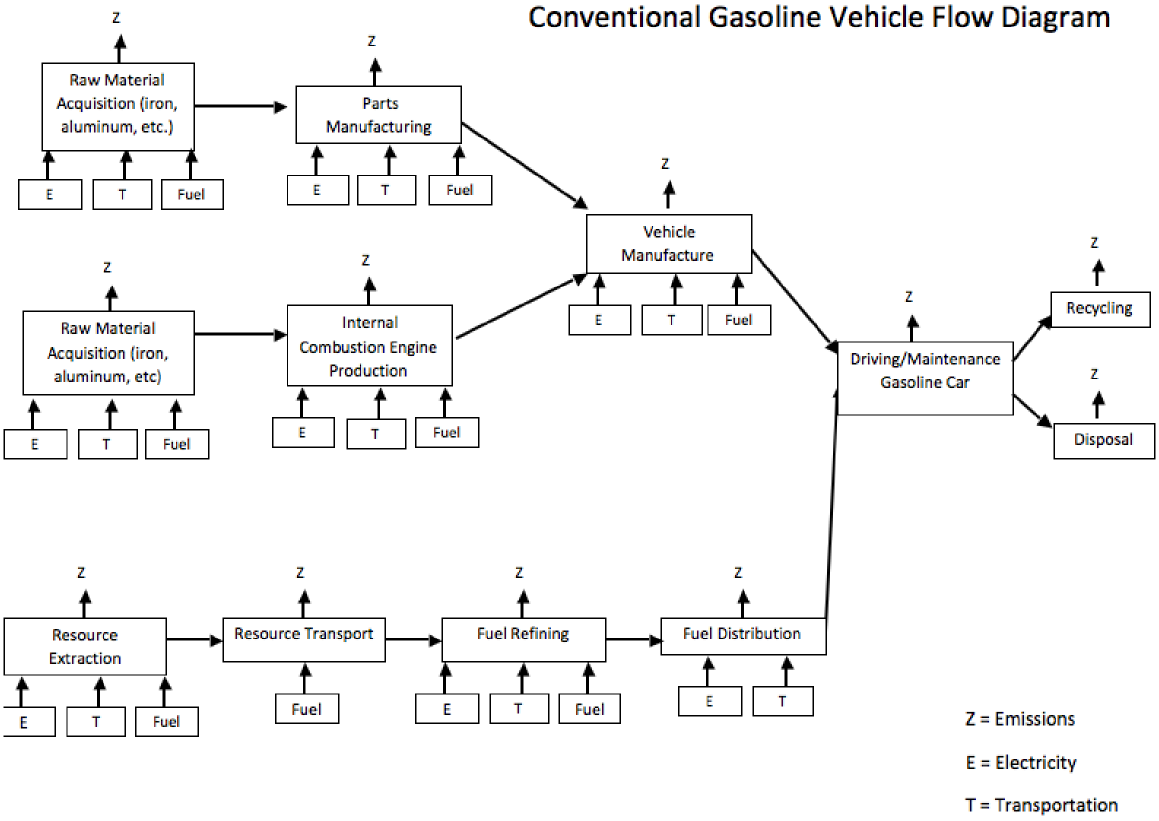
Appendix A. Flow Diagram of BEV

Figure 19. Flow Diagram of BEV



Appendix B. Flow Diagram of CV

Figure 20. Flow Diagram of CV



Appendix C. Unit Processes and Corresponding Sources

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Appendix D. Supplementary Data Tables and Graphs

i. Figure 21. Energy Inputs Lifecycle Comparison

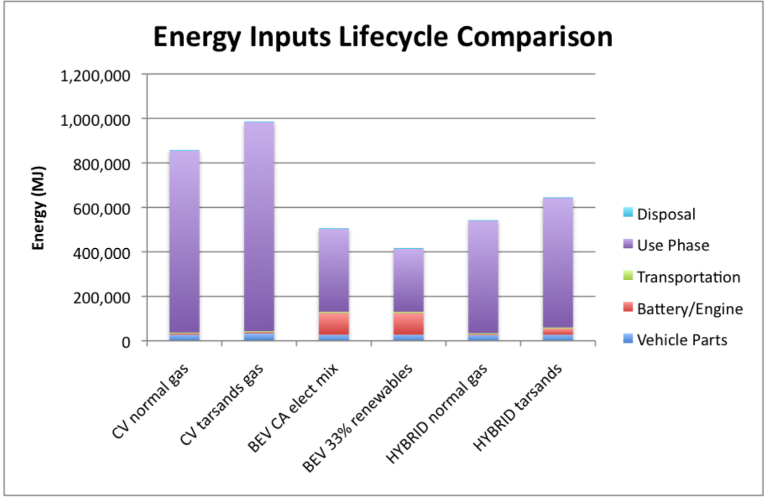

Figure 21 is a compilation of our base case results and our projected results for the year 2020 based on gasoline getting dirtier with increased extraction from tar sands and California's electricity mix getting cleaner with increased power coming from renewable energy sources.

ii. Figure 22. Energy Inputs Future Projections (2020)

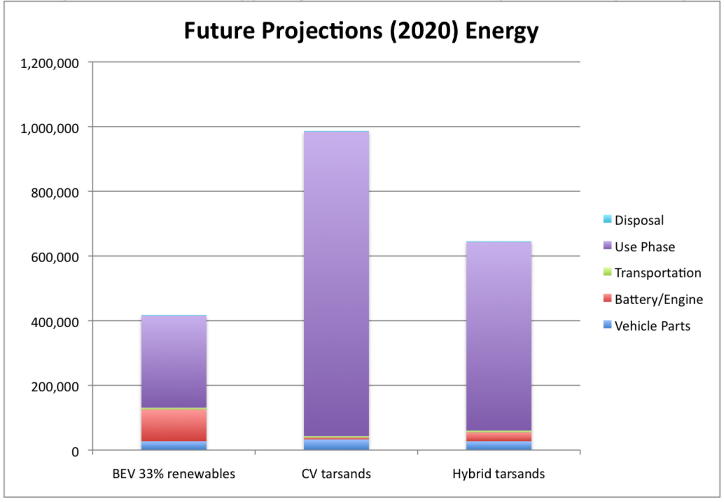

Figure 22 shows our energy inputs requirements for each vehicle based on projections for the year 2020. Our future projections are based off of our findings in the literature that gasoline will become dirtier as tar sands become exploited and that California's electricity mix will include 33% renewables.

iii. Figure 23. CO2 Equivalents Emissions Future Projections (2020)

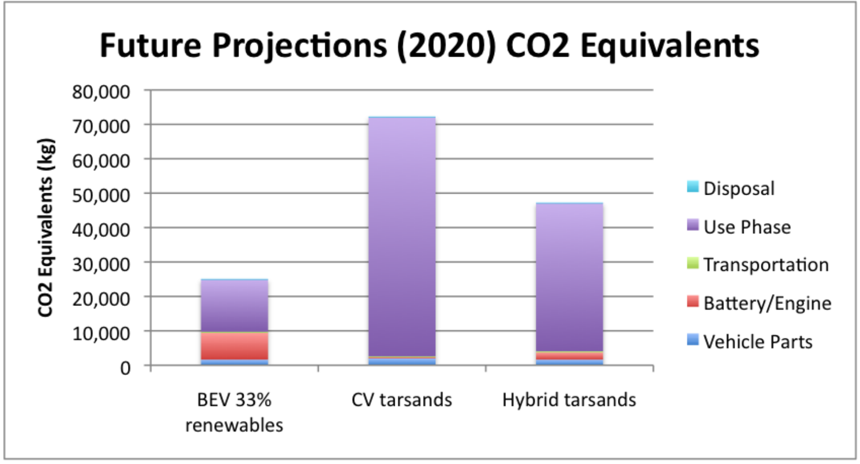

Figure 23 shows our emissions for each vehicle will be based on projections for the year 2020. Our future projections are based off of our findings in the literature that gasoline will become dirtier as tar sands become exploited and that California's electricity mix will include 33% renewables.

iv. BEV Battery Efficiency Analysis

Table 4. Lithium Ion Battery Efficiency Sensitivity Analysis

Lifetime	Energy (MJ/mile)	Emissions (kg CO2eq/mile)
BEV Base Case battery efficiency	2.82	0.18
10% more battery efficiency	2.61	0.17
10% less battery efficiency	3.03	0.19

By altering the lithium ion battery efficiency from the original 0.21 KWH/km, we can note the effects of battery efficiency on the energy intensity and emission intensity during the lifecycle. A 10% increase in battery efficiency means a 7.45% decrease in MJ/mile and a 5.56% decrease in kg CO2eq/mile. Conversely, a 10% decrease in battery efficiency means a 7.45% increase in MJ/mile and a 5.56% increase in kg CO2eq/mile.

v. Figure 24. CV Lifecycle Emissions with Changing Gasoline Carbon Intensity

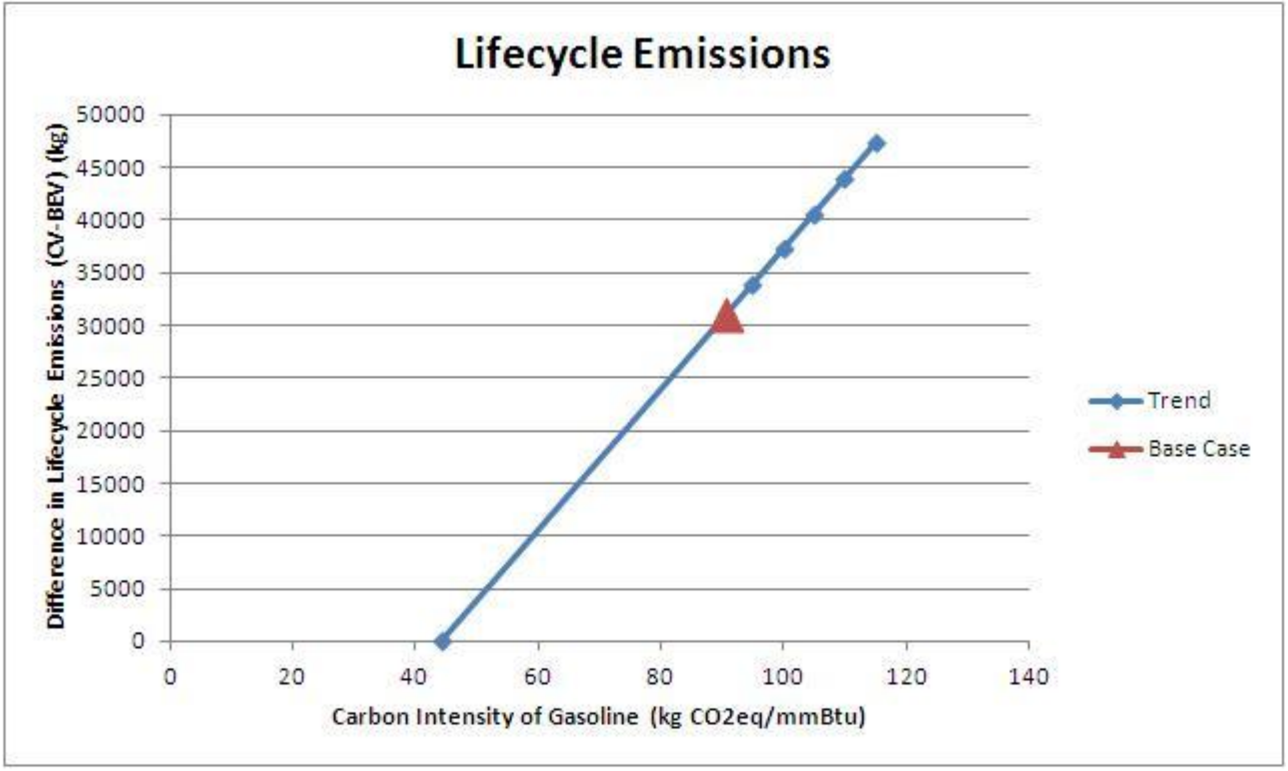

Figure 24 shows CV lifecycle emissions as we increased the carbon intensity of gasoline. Based on our understanding, gasoline sources are moving towards the margin and becoming dirtier. As expected, when carbon intensity increases, the difference in CO2 emissions between a CV and BEV increases. This makes the CV a continually worse option by emissions standards.