Battery Electric Vehicles (BEVs), Vehicle Market Growth and Carbon Dioxide Emissions Reduction Potential in California

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ABSTRACT

Battery Electric Vehicles (BEVs) have an important role to play in combating climate change by lowering personal vehicle transportation emissions. In recent years, California has been a national and global leader in BEV adoption and in implementing lower transportation emission policy. This study utilizes the Well-to-Wheel (WTW) Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model to estimate per vehicle emissions for BEVs and conventional ICEVs at five year increments starting in the year 2020. This study also projects California vehicle market trends and composition for the purposes of calculating the total carbon dioxide emissions reduction potential that is associated with BEV market growth at the same five year time increments. The results of this study show that at any simulated time period, BEVs emit 33 - 38% of the total WTW carbon dioxide emissions associated with conventional ICEVs and that BEVs projected market growth has the capacity to reduce statewide CO2 emissions by 54 million tonsCO2/year. This study encourages state policy makers to pass more aggressive policy and incentives focused on personal vehicle emissions regulations that will work to promote more rapid adoption of BEVs. I suggest that policy makers work with manufacturers and consumers to promote electric vehicle technology, as it is shown to be more emission efficient and has greater capacity to improve carbon dioxide emission levels over the next couple of decades.

KEYWORDS

Battery Electric Vehicles, California Vehicle Market, Well-to-Wheels Life Cycle Assessment, Carbon Dioxide Emissions, Sustainable Transportation

INTRODUCTION

The United States transportation sector is responsible for 28 percent of the nation's total greenhouse gas emissions while personal vehicles are responsible for approximately 80 percent of the transportation sector's emissions (EPA 2018). This is largely due to the societal reliance on fossil fuel powered production systems and personal internal combustion engine vehicles (ICEVs). The emissions from these conventional transportation systems accelerate the effects of climate change while also directly contributing to environmental conditions that negatively impact human health, specifically through human exposure to harmful air pollutants and particles. The total life cycle GHG reduction potential of BEVs will gradually improve as infrastructure and production processes improve. (Wu 2018) Emissions associated with vehicle production systems as well as direct tailpipe emissions contribute to the total amount of vehicle life cycle emissions, which is a measurement that is highly variable across different regions in the United States. (Tamayao 2015)

The societal reliance on personal vehicles and conventional fossil fuel energy systems is evident in California's densely populated urban and suburban areas. This dependence results in high levels of greenhouse gas emissions and concentrations. (McDonald 2013) The current personal vehicle transportation sector in California is responsible for emitting GHGs equivalent to approximately 174 million metric tons of carbon dioxide per year, meaning that the average emissions of one ICEV is about 4 metric tons of carbon dioxide per year (CARB 2020). The transitioning of California's transportation sector to a more sustainable, likely electric personal vehicle system is required in order to meet the state's net-zero carbon emissions goal by 2045. California state policy has been introduced to address this issue, most recently in the form of a mandate to only sell net-zero emission vehicles after 2035. Electric vehicle influence in the market has grown in the last decade, however, the commitment to a robust plan and growth strategy must be aggressive in order to accelerate the transition to lower GHG emissions statewide.

The projected growth of the electric vehicle market and the full electric vehicle transition timescale is uncertain in California due to the many political and social factors involved; while the total carbon emission reduction potential is largely unknown due to the lack of large scale data and models that are specific to California's vehicle market. Political commitment and environmentally focused "green" policy is fundamental in determining the market growth of BEVs. State sanctioned financial incentives and the development of net-zero emission goals are examples of how policy can promote a faster transition to a more sustainable vehicle transportation sector. In the United States, several automakers have stated their intentions to sell more than 15 million electric vehicles per year by 2025, up from 1.2 million in 2017 and 2 million in 2018. (Lutsey 2016) The social desire of BEVs is expected to grow over the near future, while production costs are likely to decrease with the declining costs of batteries. This predicted situation will further incentivize automakers to focus their production on BEVs as opposed to ICEVs due to profitability and long term sustainability. California's transition to a fully electric vehicle market is uncertain, and may result in largely different emission outcomes and timeframes based on specific scenarios decided by the level of commitment by the largest stakeholders, namely the state, the vehicle manufacturer and the individual.

This study examines the total carbon dioxide emissions reduction potential in California due to the growing influence and projected market growth rate of Battery Electric Vehicles (BEVs) in the current and projected personal vehicle transportation market. This requires short-term and long-term predictions of the projected market growth rate of BEVs in California as well as a comparison of total life cycle emissions between BEVs and Internal Combustion Engine Vehicles (ICEVs) through a carbon life cycle analysis that encompasses emissions from both production and operating usage.

I hypothesize that:

i) The market dominance of BEVs will grow exponentially as the environmental and market costs of fossil fuel powered vehicles rise.

ii) BEVs will emit less carbon emissions on average than their ICEVs counterparts over the complete lifespan on a per vehicle basis in California.

iii) A faster transition to a market dominated by BEVs will increase the total carbon reduction potential.

BEVs are widely accepted as emission sources responsible for less carbon dioxide when compared to ICEVs, however the emissions associated with their production are likely more due to the required production of their energy intensive batteries. It is the goal of this study to quantify and compare the life cycle GHG emissions of BEVs and ICEVs, while also quantifying the GHG reduction potential of California's projected vehicle market transition.

BACKGROUND

There is growing global concern about the long-term impacts of transportation system emissions in regards to climate change and air pollution levels. California has emerged as one of the main world leaders in setting vehicle carbon reduction goals while also implementing targeted emission reduction policies such as the mandates regarding Zero Emission Vehicles (ZEVs). A large part of these carbon emission reduction policies will involve the transition and replacement of conventional ICEVs to BEVs. California's population is responsible for one of the largest electric vehicle markets in the world, and thus, the state has a very important role in influencing world emission reduction policy surrounding the electric vehicles. State sanctioned financial incentives and the development of net-zero emission goals are examples of how policy can promote a faster transition to a more sustainable vehicle transportation sector. These actions combined with BEV market growth strategies focused on affordability and accessibility can work to increase the adoption rate of electric vehicles, however, the resulting speed of transitioning away from ICEVs will ultimately be decided by the individual consumer's capacity and willingness to purchase an electric vehicle as opposed to an ICEV (Clinton 2019). Policymakers will require significant scientific data regarding the benefits of the electric vehicle transition, as well as predicted carbon reduction scenarios in order to accurately implement useful "green" policy for the benefit of climate conditions in the short term and long term futures.

There has been research in the field of quantifying carbon emissions reduction potential of the transition to electric vehicles, however, there is little significant research regarding the California market specifically. The wheel-to-well life cycle assessment is the dominant analysis method for vehicle emissions, and is useful in achieving understandable data that has the power to influence regulatory emission policy. This method allows for assessment of greenhouse gas (GHG) emissions and energy use savings throughout the complete life cycle of a vehicle.

Research Framework

I used key literature focused on the carbon reduction potential in the transportation markets to guide and influence my market research and the creation of my own emissions LCA. While it is true and widely accepted that BEVs emit less direct greenhouse gas emissions than their fossil fuel reliant ICEV counterparts, the complete carbon reduction potential of BEVs over their full lifespan is more uncertain. The production of batteries required for BEVs is fossil fuel intensive and requires a large amount of raw materials (Wu 2018). Research papers also establish a complete "wheel-to-well" life cycle assessment (LCA) of carbon associated with BEV and conventional vehicle production in China, which I used to heavily influence my own LCA (Zheng 2020). This LCA relies on quantifying carbon emissions at different life cycle stages, mainly the production phase and vehicle operation phase. Important variables of the LCA include per vehicle energy consumption, emissions associated with vehicle fuel type, and average vehicle distance traveled.

The emissions environmental costs of BEVs and ICEVs are estimated and compared through this complete LCA, however, the paper relies on accessible national emissions standard data available in China. Wheel-to-well methodology can be seen as a quite simplified LCA, designed to assess only the energy consumption and the GHG emissions of road transport fuels without considering, for example, the impacts of manufacturing and decommissioning of the vehicles themselves (Qiao 2017). As a simplified dataset with understandable metrics and visualizations, the wheel-to-well LCA is useful for policy support when comparing vehicle regulations..

National Energy Resources Commission (NERC) data on the emissions associated with plug-in energy for electric vehicles is analyzed in NERC reports and research papers on regional variability and use of eGrid. This data shows that higher energy consumption, vehicle use and reliance on fossil fuels are concentrated around urban and suburban areas in California. In the United States, regional variability and infrastructure also heavily influence the readiness levels of communities in terms of BEV adoption and market penetration rate (Lutsey 2016). The most current and up to date data and market models from the International Council of Clean Transportation allows for projections of market share and total number of BEVs at different time intervals and under varying conditions and societal commitment to the transition of the vehicle market (ICCT 2018). Long term trends of BEVs in California's vehicle market are also used to project the growth and future use of BEVs (Clinton 2019).

Theories

BEVs have a high carbon reduction potential which will increase as the market dominance of BEVs grow, and charging infrastructure and political/social commitment increases. This is based on the idea that on a per vehicle basis, a BEV emits less greenhouse gases over its lifespan than a ICEV.

I hypothesize that:

i) The market dominance of BEVs will grow exponentially as the environmental and financial costs of fossil fuel powered vehicles rise.

ii) BEVs will emit less carbon emissions on average than their ICEVs counterparts over the complete lifespan on a per vehicle basis in California.

iii) A faster transition to a market dominated by BEVs will increase the total carbon reduction potential of the transition.

BEVs are widely accepted as emitters responsible for less carbon dioxide when compared to ICEVs, however the emissions associated with their production are likely more due to the required production of their energy intensive batteries. Ultimately, political and social commitment to the transition to BEVs in place of conventional vehicles will be the biggest factors in deciding the realized reduction of vehicle carbon emissions in California.

Key Concepts

The key concepts all relate to the main goal of the research which is to quantify the carbon emissions reduction potential of transitioning California's vehicle market to one dominated by BEVs. Carbon emissions reduction potential is the total amount of emissions that could potentially be reduced when comparing two different scenarios of energy use and associated emissions, typically current and future (Steinberg 2018).

- **BEVs**: Battery Electric Vehicles
- **ICEVs**: Internal Combustion Engine Vehicles

- **Wheel-to-Well (WTW)**: term used to describe the production process of a vehicle from the beginning instance of creation to completion.
- **gCO2/kwh**: metric for measuring the amount of carbon emissions associated with electric energy use.
- **gCO2/L (gasoline)**: metric for measuring the amount of carbon emissions associated with conventional ICEV fuel consumption.
- **LCA**: Life Cycle Assessment as a way to quantify carbon emissions associated with a vehicle's complete lifespan.

Battery Electric Vehicle Market Data and Projections

The electric vehicle market data in California shows that the state is home to nearly half of the national electric vehicles, while also demonstrating the highest market share growth rates and total sales for any state (ICCT 2018). From the most current BEV data available in California, models are projected under variable growth conditions to estimate the total market share of BEVs at different timescales. This is important in identifying the market share growth rate of BEVs, while also recording the total number of BEVs in use in California. Policy conditions and regulations will directly influence the amount of electric vehicles in the market as well as the vehicle sales rate at the specific timescale. To address this, I will use variable projection to project the market under different growth conditions, including constant and increasing growth. These will result in an estimated range of possible market numbers at different timescales.

Emissions Life Cycle Assessment

A "wheel-to-well" life cycle assessment model for factory and production emissions will be used along with collected data on average ICEV emissions per vehicle to quantify the total emissions associated with each type of vehicle. CARB and EPA data to determine the most reasonable estimate of emissions per conventional ICEV in California. Tentatively this is about 4.0 - 5.0 metric tons CO2/year) (EPA 2018). Many of the previously established LCA models that I rely on for my own research have been conducted in China and heavily rely on nationally available datasets that are specific to China. This poses challenges in my own data collection process as I have to look for many different sources, such as private market self-reports and governmental agency datasets, to synthesize metrics for use in my complete LCA.

Comparison of projected emissions based on the Market Model and LCA

By applying the average emissions per vehicle calculated with the LCA to the projected market model and total number of vehicles, it is possible to compare outcomes under different conditions as well as the total carbon reduction potential of BEVs in California. This comparison is completely reliant on the application of carbon emission data to the market models and projections from the first two methods subsections. This progression of methods will allow for a comparison and total carbon emissions reduction amount to be calculated and analyzed.

METHODS

California Personal Vehicle Market

Personal vehicle market projections in California are calculated through available data from the International Council on Clean Transportation (ICCT) and the California Energy Commission. The ICCT is an organization that provides technical and scientific analysis to environmental regulators, specifically in the field of sustainable transportation development. The electric vehicle market data in California shows that the state is home to nearly half of the nation’s electric vehicle fleet, while also demonstrating the highest market share growth rates and total sales for any state (ICCT 2019). Electric vehicle sales are concentrated in California’s urban coastal areas. This is due to these area’s high population, generally higher income and social norms regarding personal vehicle use. As of April 2020, there are 369,364 registered BEVs in California while there are 25,021,380 gasoline powered ICEVs in the state. The updated 2019 ICCT electric vehicle market projections are used to quantify the total number of BEVs and ICEVs on the road at 5 year increments between 2020 and 2040. The most recent available published ICCT report will be used to quantify the range of predicted vehicles on the road at the specified time. The upper and lower bound projections fluctuate based on predicted vehicle population growth rate limits, which are applied to a developed California specific logistic growth vehicle population model under different assumptions.

WTW Life Cycle Assessment System and Scope Boundary

I used the well-to-wheel (WTW) life cycle assessment method (Zheng 2020) to calculate the greenhouse gas emissions for battery electric vehicles (BEVs) and conventional internal combustion engine vehicles (ICEVs), starting in the model year 2020 and across a timescale of 5 year increments until 2040. Within this WTW life cycle, there are three key emission phases; vehicle production emissions, use or "on-road" emissions, and fuel production emissions. Emissions associated with each of three phases are quantified and projected under California specific assumptions through a developed Argonne National Lab model (GREET). An example of these assumptions are the use of the CAMX eGrid energy mix as well as modelling for lithium ion battery type vehicles as they are the most common type in California. Vehicle production emissions assume production similarities across global vehicle production factories and will consider all emissions associated with state registered vehicles, even if they are produced out of state.

The only air pollutant and emission greenhouse gas considered in the scope of the study is carbon dioxide CO2 gas emissions. The wheel-to-well life cycle assessment of carbon dioxide greenhouse gas emissions is given as a function of individual vehicle fuel consumption so that it can be applied to different vehicle types.

Equation (1)

$$EWTW = EWTP{,}fuel \times FC \div 100 + EWTP{,}vehicle + EPTW{,}tailpipe$$

where $EWTW$ is the GHG emission factor in gCO2/km. $EWTP,fuel$ is the fuel production phase GHG emission factor in gCO2/L gasoline or gCO2/kWH electricity. FC is the fuel consumption of a given vehicle in L/100km or kWH/100km. $EWTP,vehicle$ is the vehicle production phase GHG emission factor in gCO2/km this encompasses all the emissions associated with factory production on a generalized and uniform basis. $EPTW,tailpipe$ is the vehicle operation or "on road" phase GHG emission factor in gCO2/km, including direct tailpipe emissions for ICEVs.

The emissions associated with the collection of raw materials outside of the country and the emissions associated with energy used for material decomposition at the end of the vehicle life cycle are not included in this study due to the lack of available data. The total $EWTW$ emission factor is then applied to the average distance driven per year in California, approximately 22,000km/yr. (USDOT 2020) Resulting in the total average emissions associated with both ICEVs and BEVs in gCO2/yr. These average emissions will be tracked with the variables $EICEV$ and $EBEV$.

WTP (Production) Phase

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model (GREET) developed by the Argonne National Laboratory will be used to quantify the carbon emissions associated with both the fuel and vehicle production phases, $EWTP,fuel$ and $EWTP,vehicle$. This is the most widely used model for transportation sector life cycle assessments and allows for easy variable manipulation and defining of scope. The specific model used is the California GREET3.0 model which uses the most up to date state specific information regarding vehicle emission projections and allows for California-specific use through the Excel sheet application of the model. Statewide data for electricity generation, grid energy mixtures, air pollutant emission factors, gasoline usage/mixture, and energy efficiency are all variables that have been factored into the GREET model used in this study.

The $EWTP,fuel$ emission factor for BEVs relies on available data from the EPA and the U.S. Energy Information Administration (EIA) emission factors in g/kwh for electricity generation, while the study specifically looks at the data for the CAMX eGrid energy mix. The modelling of the $EWTP,fuel$ emission factor for ICEVs relies on published EIA projections for crude oil sources and petroleum refining efficiency over the timespan from 2020 - 2040. Specific gasoline and fuel composition are also taken into account in great detail through the base assumptions of the model. The results for WTW GHG emissions are calculated through the fuel consumption dependent equations 1. and 2. and operating under the assumption that WTW GHG carbon dioxide emissions are proportional to average fleet vehicle fuel consumption rate for both BEVs and ICEVs.

There are many built in key assumptions for the $EWTP,vehicle$ emission phase, including the metric that steam generation efficiency for steam co-generation in many vehicle production factories is assumed to be 80%. In addition to this metric, many other efficiencies for vehicle production factories are assumed and built into the base California GREET model, these include; GHG emissions recovery and processing efficiencies, natural gas conversion efficiencies, etc. The production emissions from both the vehicle and fuel production emission phases are combined to quantify the total $EWTP$ production emissions for both California BEVs and ICEVs in the results section.

PTW (Vehicle Use "On Road") Phase

In the United States, the average fuel consumption for conventional ICEV vehicles is about 10.2L/100km ~23mpg, while the average fuel consumption for BEVs is about 16kWh/100km in 2018 according to tests and data from the United States Bureau of Transportation Statistics. I applied these same estimates to my California model due to the lack of state specific data regarding these estimates. There is variability in these estimates due to the fact that test results of fuel consumption are often different than the actual on-road vehicle use fuel consumption metrics. These fuel consumption estimates for both ICEVs and BEVs are then applied to a on-road vehicle carbon dioxide CO_2 emissions calculation.

Equation (2)

$$EFCO2 = (Cratio \times 1000 \times \rho \times (FC / 100)) \div (12 /44)$$

Where *EFCO2* is the emission factor of CO2 during fuel combustion, g/L; *C*ratio is the average carbon ratio of gasoline, 82.8%wt; ρ is the average density of gasoline, 0.749 kg/L; *FC* is the vehicle fuel consumption of the vehicle; and 12/44 is the ratio of the atomic mass of carbon to the molecular weight of CO2 (Zheng 2020).

Carbon Dioxide Emission Reduction Potential

By assuming that the average vehicle distance traveled in California is constant at 13,500 miles per year (~22,000 km), I apply the emission factors from on a per vehicle basis from Tables

1. and 2 to the complete vehicle population across five year time intervals. Emission calculations are multiplied by the total number and types of vehicles at each specified time period which results in a complete estimate of the vehicle emissions associated with BEVs and ICEVs. The composition and split of these emissions for both BEVs and ICEVs are compared against each other to quantify the predicted carbon dioxide emission reduction potential.

These methods assume constants of market growth, vehicle miles driven, and production factor emissions. The scope of this study is limited by available California-specific data and the limited variables involved in the calculation. These results work to give estimates and insights into the future of California vehicle emissions under the current projections.

RESULTS

California Vehicle Fleet Average WTW Carbon Dioxide GHG Emissions

The average passenger fuel consumption rate in California is 7.8L/100km (~30mpg) for ICEVs and 15.1kwh/100km for BEVs. (EPA 2020) Figure 1. shows statewide vehicle fleet average WTW GHG emissions resulting from the initial equation estimates as well as the GREET model simulations at time intervals of five years starting in the year 2020. The complete WTW GHG carbon emissions are calculated through these two different processes and they are directly compared in Figure 1.

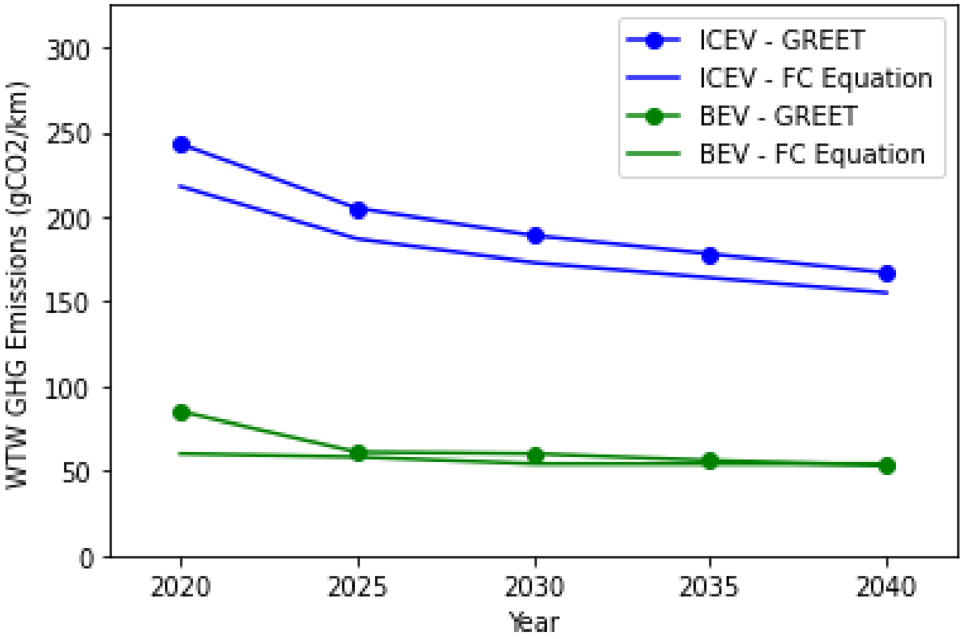

Fig 1. Emissions Graph Average per vehicle well-to-wheels GHG emissions for conventional internal combustion and battery electric passenger vehicles in California. Results from the California GREET Model developed by Argonne National Laboratory and estimates from equations 1. and 2. Measured in grams of CO2 per year and projected across 2020 - 2040 in 5 year increments.

ICEVs do have a higher emissions over their complete lifespan, as Figure 1 encompasses the total emissions resulting from both the production and vehicle operation phases of the LCA. I found that total WTW GHG emissions for BEVs are approximately 33 - 38% of the total WTW GHG emissions for ICEVs across any time period. I project that the emission levels for both BEVs and ICEVs will experience a downward trend on a per vehicle basis over time due to more improved and efficient fuel and vehicle technology. The emission results in Figure 1. are calculated based on fleet averaged medium sized passenger vehicles, the most popular vehicle type in California, and statewide average fuel/electricity grid mix.

Only the emission results from the GREET model simulations are used for further purposes of this research as they encompass a larger variety of factors and to a greater level of accuracy than equations results that rely on fuel consumption factors.

Table 1. ICEV Emission Stages shows the breakdown of the GREET emission results for both the EWTW and EWTP phases of the internal combustion engine vehicle (ICEV) life cycle projected across five year time intervals.

Year	EWTP Production/Fuel	EPTW Vehicle Use	EWTW (gCO2/km)
2020	39	204	243
2025	32	173	205
2030	30	159	189
2035	28	150	178
2040	26	141	167

Table 2. BEV Emission Stages shows zero emissions associated with direct electric vehicle use and that all of the total EWTW results come from production of the vehicle and generation of electricity over five-year time intervals.

Year	EWTP Production/Fuel	EPTW Vehicle Use	EWTW (gCO2/km)
2020	85	0	85
2025	61	0	61
2030	60	0	60
2035	56	0	56
2040	53	0	53

Tables 1. and 2. illustrate the amount of carbon emissions associated with both BEVs and ICEVs at either stage of the complete WTW life cycle. By breaking the LCA down into two components, the production/fuel phase, and the vehicle use phase, I compare the emissions produced at different stages. The tables show that all of the emissions throughout a BEVs lifespan are associated with the production/fuel phase, while the opposite trend is true for ICEVs. For ICEVs, most of the emissions come from the use phase or through "direct tailpipe emissions". We can also see that the use phase for ICEVs is by far the largest phase of emissions for either vehicle,

with emission results measuring at 204 gCO2/km as of 2020.

California Vehicle Market Projections

The number of vehicles from each type on the road at any given time is projected based on currently available statewide vehicle numbers and a logistic growth model. These values are important in order to apply the emissions data on a per-vehicle basis to the complete vehicle market based on vehicle type composition.

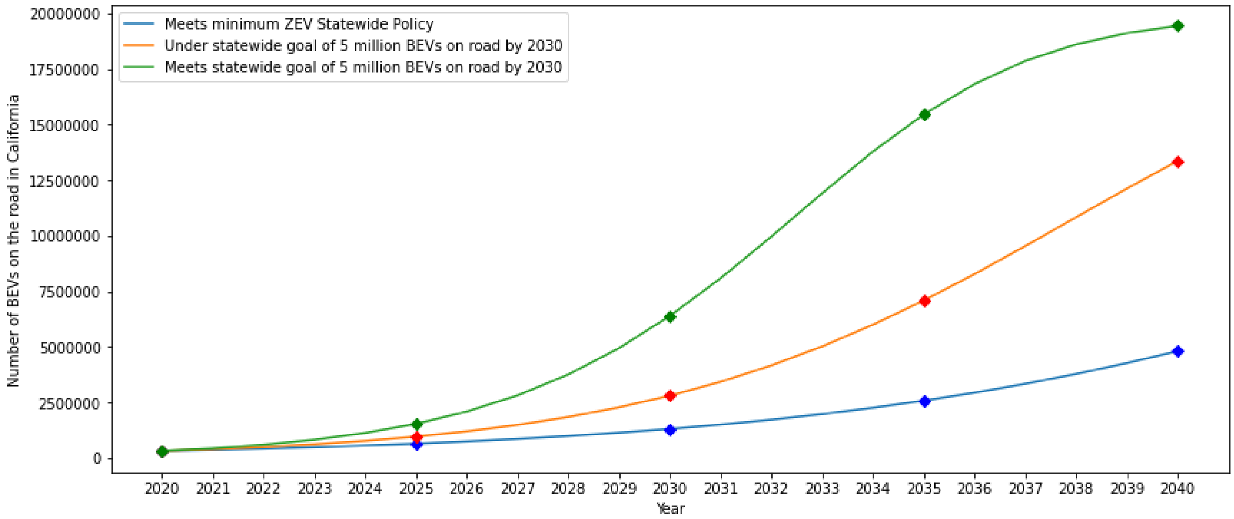

Fig 2. BEV Market the number of BEVs expected to be on the road in California under different vehicle adoption scenarios. Calculated through a logistic growth formula dependent on estimated growth rates under different vehicle adoption commitment levels (EPA 2020). The lower limit is calculated through the minimum commitment level, where the upper limit assumes that ambitious statewide policy goals are met.

Figure 2. shows the total number of BEVs predicted to be on the road at different time intervals of 5 years in California and under different scenarios of social and political commitment. The predictions are made through a logistic growth equation that relies on EPA and ICCT vehicle market sales rate data. For these estimates of the total number of BEVs on the road at one time, a carrying capacity at 20 million BEVs over 20 years was factored into the equation, as this accounts for California's population of eligible drivers. These estimates rely on current vehicle data numbers projected across constant BEV sales growth rates. Figure 2. compares lower and upper bounds of total vehicle estimates across 20 years in 5 year intervals.

The different scenarios in Figure 2. are reliant on the level of statewide social and political commitment to the vehicle market transition of one that is ICEV dominated to one that is BEV dominated. Recent legislation regarding zero emission vehicles and BEV production/sales goals work to increase the number of on road BEVs, but the exact number of vehicles on the road at any given time is highly variable. For the purpose of calculating carbon reduction potential, I used the conservative logistic growth model estimate with a growth rate of 26%.

Table 3. Projected Vehicles and Types The number of each vehicle type estimated to be on the road in California at time intervals of 5 years. BEVs calculated through logistic equations based on vehicle sales and predicted market trends, while ICEVs are assumed to have a constant decline of approx. 5% per year until 2035.

Year	Number of BEVs in California	Number of ICEVs in California
2020	308,477	25,526,368
2025	763,160	24,250,049
2030	2,468,968	23,037,547
2035	5,990,969	21,885,669
2040	12,120,702	19,697,103

Table 3. shows the trends of each type of vehicle on the road at time increments of 5 years. In 2020, BEVs only make up around 1.2% of the total market share, while all sources agree that BEVs market share is expected to grow exponentially as state policy and corporate incentives are passed. The BEV market growth rate is estimated to be 26% in this table, as this is a conservative estimate relating to the statewide goal of 5 million BEVs on the road by 2030. A steady decline of ICEVs on the road, -5% per year is assumed and will accompany BEVs exponential growth over this timeframe. Recent California policy bans the sale of the new ICEVs after 2035, meaning that total ICEV numbers will decrease at an increased rate after this year. I predict a slow decline of -5% of ICEVs per year based on EPA and California Energy Commission estimates, and the increasing social pressure to transition to zero emission vehicles.

Carbon reduction potential in California based on emissions per vehicle and number of vehicles on the road

Table 4. shows the annual emissions associated with each individual vehicle while also projecting this per vehicle calculation across the total market composition at the time. The per vehicle emission calculations are multiplied by the values in Table 3. to achieve a complete estimate of the vehicle emissions associated with BEVs and ICEVs at the specified time. Table 4. and Figure 3. illustrate the results of these calculations by showing the calculated emissions as well as the proportion of emissions to the combined emissions.

Table 4. Annual emissions on a per vehicle basis for BEVs and ICEVs measured in tons CO2/year. This value is also applied to the projected market data regarding on road vehicle numbers to calculate the total emissions associated with each type of vehicle per year.

Year	Annual emissions per BEV (tons CO2/year)	Annual emissions per ICEV (tons CO2/year)	Total Life Cycle BEV Emissions (tons CO2/year)	Total Life Cycle ICEV Emissions (tons CO2/year)
2020	2.061322	5.892956	635,870	150,425,763
2025	1.479302	4.971424	1,128,944	120,557,276
2030	1.455051	4.58341	3,592,474	105,590,523
2035	1.358048	4.316651	8,136,023	94,472,795
2040	1.285295	4.049892	15,578,677	79,771,140

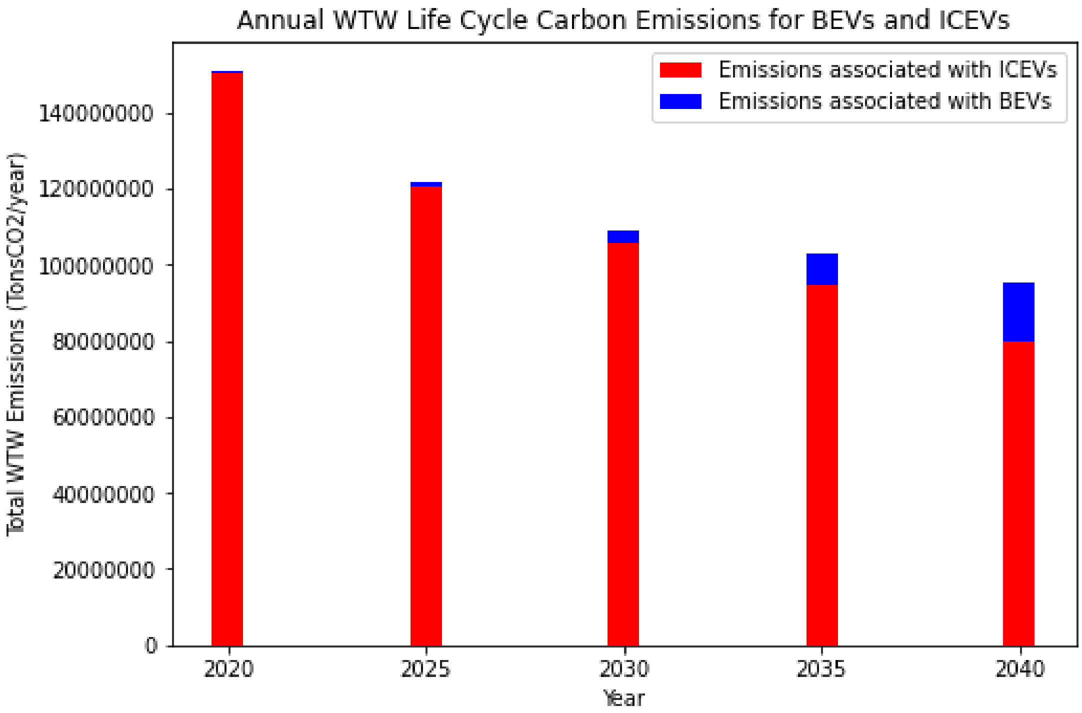

Figure 3. Emissions Reduction Potential shows the proportion of emissions that are associated with ICEVs and BEVs at the different time intervals. Measured in tonsCO2/year.

Table 4. and Figure 3. show that BEVs total share of statewide vehicle emissions is expected to grow as they increase in usage and market dominance. The total combined emissions from ICEVs and BEVs is decreasing as the number of emission intensive ICEVs goes down in favor of BEVs that emit less carbon dioxide on average. In 2020, BEVs emissions make up less than half a percent of the total vehicle emissions, while in 2040, this is expected to rise to about 16% of the total vehicle emissions. The total emissions from the California vehicle fleet will decrease with the increased use of BEVs and decreased use of ICEVs. The total combined vehicle emissions from ICEVs and BEVs are expected to fall from 150 million tonsCO2/year to 96 million tonsCO2/year over the course of the specified time period. The projected transition from ICEVs and BEVs in California over the next 20 years is expected to result in a carbon dioxide/year reduction of 54 million tonsCO2.

DISCUSSION

This study establishes California vehicle market projections and the resulting carbon dioxide emissions reduction potential. From the results, we can reasonably project what the statewide future of vehicle emissions will look like over the next couple of decades. The results also prove my hypotheses that BEVs will grow in market dominance, they emit less total WTW life cycle carbon dioxide emissions than their ICEV counterparts on a per vehicle basis, and the rate of vehicle market replacement will determine the realized carbon dioxide emission reduction potential in the state. A more rapid transition to BEVs will result in greater realized emissions reductions in the near future. The total WTW emission results support the predicted outcome that the total emissions associated with California's vehicle market will decrease over the next 20 years, while the share of emissions associated with BEVs is expected to rise. Individual BEVs are responsible for less WTW GHG emissions meaning that as they grow in dominance to replace higher emitting ICEVs, the total WTW GHG emissions are expected to decrease if the number of vehicles remains relatively constant. Although there is a measurable decrease in emissions associated with the transition to BEVs, the production and use of BEVs are not zero emission processes. The direct road emissions from BEV use is zero, however, further action and commitment to decreasing vehicle emissions are needed to ensure a net-zero emission future.

Reducing Vehicle Emissions

The transition from ICEVs to BEVs works to lower statewide vehicle emissions and will be crucial in defining California's active response to climate change over the next few decades. Total WTW GHG emissions for BEVs are approximately 33 - 38% of the total WTW GHG emissions for ICEVs at any time in the model simulation. Given the projected growth of BEVs and decline of ICEVs, the total amount of emissions is expected to decrease as BEVs emit less CO2 on a per vehicle basis. BEVs have the capacity to reduce the rate of statewide vehicle carbon emissions by approximately 54 million tons CO2/year by the year 2040. These results are corroborated by other research papers that find BEVs emit less WTW CO2 greenhouse gas emissions than their ICEV counterparts. A similar study in China found that "BEVs are able to reduce GHG emissions by 29 - 38% when compared with gasoline (ICEVs)" and cited "that the higher energy efficiency of BEVs exceeds the fuel saving from lower weight gasoline vehicles" (Zheng 2020). The modelled emission results of my California specific study are very similar to the results from other WTW life cycle emission studies in other countries, which shows that the potential for BEVs to reduce carbon emissions by a significant amount is a global trend.

Vehicle Market and Policy

California state policy and emission targets regarding the statewide vehicle market are the main factors that will determine the realized carbon dioxide emissions reduction potential over the next couple of decades. The main carbon reduction emission results rely on a conservative estimate of market growth in accordance with stated policy goals of 5 million BEVs on the road by 2030. The variation surrounding the total number of BEVs and ICEVs on the road is important in the realized vehicle emissions per year. There is significant vehicle emission policy in place already such as the zero emission vehicle (ZEV) mandate and the passed legislation to ban the sale of non-ZEVs after the year 2035. More aggressive policy that promotes faster adoption of BEVs in place of ICEVs will increase the rate of greenhouse gas emissions reduction in California. In comparison to other states and countries, California is the one of the leaders in aggressive and impactful policy (Lutsey 2016). Vehicle affordability, personal vehicle purchasing capabilities and charging infrastructure growth will all contribute to the realized rate of BEV adoption. Societal and political commitment to the rapid transition from ICEVs to BEVs is crucial in lowering personal vehicle transportation emissions in the near future. In addition to state policy and stated emission goals as specified by state legislature, the vehicle manufacturers and social desire and power to purchase new BEVs will affect the realized market growth.

Commitment to Sustainable Transportation

A full commitment to an emission efficient personal vehicle transportation system by California's policy makers, manufacturing companies, and citizen drivers is needed to better mitigate the state's emissions and climate change contribution. There are many stakeholders when it comes to California's vehicle market, and decisions made by each sector will affect the rate at which BEVs are adopted as well as the actual greenhouse gas emission levels associated with personal vehicles per year. Vehicles both BEVs and ICEVs are a public-interest good, meaning that social and economic factors largely influence the consumers motivation and power to buy while also determining production rates by manufacturers (Demirci 2017). The greatest factors that will motivate a rapid transition to BEVs are public interest and power to purchase as well as political pressure on manufacturers. Incentives for individuals and manufacturers are crucial in determining the societal commitment to lowering vehicle emissions. Ultimately these incentives work with the main goal of lowering emissions while other effects and consequences of these incentives and policy restrictions must be taken into consideration before they are implemented (Lutsey 2016). The individual power to buy and transition from ICEVs to BEVs is pivotal for determining the real world emissions reduction outcome. The variability and uncertainty surrounding these political, social, and economic factors could greatly affect the number of each vehicle type on the road at any given time period, resulting in changes to the emission reduction potential calculations.

Conclusion

The scope of my study looks at California specific factors meaning that the results cannot be directly applied to other states or countries, however, it can work to inform reasonable estimates of vehicle emission projections elsewhere. A limitation to this study is the fact that generalization and uniformity across certain variables such as vehicle size, weight and distance travelled was needed to reach a reasonable conclusion. A more advanced model that relies on the availability of previous data and machine learning could model emissions better, however, this option was out of my current scope and capabilities. The vehicle market projections are conservative estimates and assume reasonable and steady growth, which can be greatly influenced by unforeseen future economic factors or events. Built in the GREET model used to quantify WTW life cycle emissions, it is assumed that production and fuel technology will steadily improve at five year increments, however, these assumptions may lead to inaccuracy at longer timescales. The same research process of calculating per vehicle emissions and market composition can be applied to other states and countries based on their individual regional characteristics of energy mix and dominant fuel type. A future direction of this research could be to model and compare the carbon dioxide emission reduction potential of various states, which would be helpful in assessing areas and states of need as we collectively work towards the shared goal of lowering emissions.

This study shows that a rapid transition to BEVs should be prioritized in California state policy and by individual vehicle buyers. BEVs have a massive capacity to reduce emissions from the California personal vehicle transportation sector as they replace higher emitting ICEVs. Their emission reduction potential will only increase as fuel and production technology improve, and the WTW life cycle for BEVs may theoretically reach near carbon dioxide emission neutrality as the electricity generation systems in use include more renewable energy technology. The market and WTW life cycle assessment results in this study work to motivate decision makers to work towards transitioning to a BEV dominated personal vehicle fleet. The possibility of reducing vehicle fleet emissions in California by transitioning to BEVs is promising for the future statewide emissions outlook, and can work to motivate further emissions reductions in other sectors. Overall, California's personal vehicle transportation sector is trending downward in total emissions and that trend is expected to continue as commitment levels, technological capabilities, policy and incentives increase.

ACKNOWLEDGMENTS

Thank you to Patina Mendez, Kyle Leathers, and my mentor, Julia Szinai who all provided continued support and helpful insight throughout my research process. The feedback I received from all of you has been crucial to my learning process, and working on this project with you has been a fantastic experience that I will never forget. I am also very grateful for the continued support and feedback from my ESPM 175 groupmates Emily Yen, Ella Naylor, and Elizabeth Shehter. I appreciate all of the knowledge and academic support offered by the whole ESPM department and the College of Natural Resources. Lastly, I would like to thank my family and friends that have helped me throughout the last four years of my academic journey.

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