ABSTRACT

In recognizing the potential for large, damaging impacts from climate change, California enacted Executive Order S-03-05, requiring a reduction in statewide greenhouse gas (GHG) emissions to 80% below 1990 levels by 2050. Given that the transportation light-duty vehicle (LDV) segment accounts for 28% of the state's GHG emissions today, it will be difficult to meet the 2050 goal unless a portfolio of near-zero carbon transportation solutions is pursued. Because it takes decades for a new propulsion system to capture a large fraction of the passenger vehicle market due to vehicle fleet turn-over rates, it is important to accelerate the introduction of these alternatives to ensure markets enter into early commercial volumes (10,000s) between 2015 and 2020.

This report summarizes the results and conclusions of a modeling exercise that simulated GHG emissions from the LDV sector to 2050 in California. Specifically, the analysis addressed two policy questions: (1) what fraction of the on-road fleet in 2050 needs to be zero-emission vehicles (ZEVs) in order for the LDV sector to achieve an 80% GHG reduction, and (2) what annual ZEV sales are necessary between 2015 and 2025 to initiate these fleet volumes?

Two scenarios were developed revealing how difficult it will be to achieve this goal. Scenario 1 achieves a 66% reduction in GHG emissions by 2050 using aggressive assumptions. This scenario assumes ZEV sales reach a quarter of a million units annually by 2025 and become 100% of new vehicle sales by 2050. Scenario 2 was developed to show what would be required to achieve the full 80% GHG goal. To achieve this, two key parameters were modified with more aggressive and less certain assumptions. A steeper ZEV sales projection was simulated that achieves half a million ZEVs annually by 2025 and becomes 100% of new vehicle sales by 2040. Additionally, the availability of biofuels was increased to 1.7 billion gallons gasoline equivalent (BGGE), where it was limited to 1 BGGE in Scenario 1.

INTRODUCTION

In developing the policy for Assembly Bill (AB) 32, the California Air Resources Board (ARB) and other State agencies carefully studied the specific impacts of climate change on the State of California. The AB 32 goal of reducing emissions to 1990 GHG levels by 2020 is the first step towards longer-term, deeper, reduction needed to stabilize the climate. The 2020 requirement is critical for two reasons. First, achieving deep GHG reductions in 2050 requires multiple decades of concerted effort, where interim actions are important. Secondly, climate change is a function of cumulative emissions in the atmosphere. Early reductions (2020) are therefore essential. In addition to the Governor's Executive Order and AB 32, the State Legislature and ARB have adopted a number of policies that address GHG emissions in the transportation sector specifically.

Scenarios represent a projection of what could be possible - a “what if” story that can help provide context for decision makers. In the case of GHG policy development, scenarios help illuminate the bounds of how large emissions could...
grow, and what kinds of solutions could be employed to reduce them. Scenarios can reveal how large specific solutions would have to be, and over what timescales they need to be implemented. Scenarios are not, however, predictions of what the future will be, nor are they roadmaps for specific policies to 2050.

The scenarios in this analysis assumed a 2050 target of 80% below the passenger vehicle portion of 1990's GHG inventory, or 20% of 108.5 million metric tons (MMT) of carbon dioxide equivalent (CO2e) emissions. This represents a “fair share” by the passenger vehicle sector. In reality, each sector will carry varying reduction levels to meet the statewide average of 80%. However, it is not likely that the target can be met unless passenger vehicles achieve large reductions in GHG emissions, given its 28% contribution to overall emissions today.

Figure 1 above shows California's actual GHG emissions through 2004 and projected emissions in 2020, along with the emissions reduction goals for all sectors. Meeting the 2020 goals will require over 170 MMT reductions of CO2e emissions from projected 2020 levels (30%). For 2050, an additional reduction of 341 MMT is required to meet the 80% reduction goal. Compounding this challenge is a growing population which increases pressure on limited resources. According to the California Department of Finance (DOF), the State's population is projected to reach 60 million people by 2050\(^5\), double what it was in 1990.

This modeling exercise was conducted to support the development of the ZEV Regulation which is being considered for revision by ARB in late 2010. It does not represent ARB positions or assumptions in the other GHG policies such as LCFS, Pavley, SB 375, AB 32, etc.

**METHODOLOGY**

To develop an analysis of California's transportation sector GHG emissions over the next several decades, an energy and vehicle stock turn-over model was employed to simulate the vehicle fleet and its changing emission profile. The tool used was the United States Department of Energy's (U.S. DOE) Vision model, developed by the Argonne National Laboratory.\(^6\) ARB made changes to the model to simulate a California passenger vehicle fleet and energy system. The Vision model allows the user to specify new vehicle fleet market shares, vehicle technology and performance assumptions, fuel carbon intensity, and VMT per vehicle trends. The model then determines the on-road fleet composition, fuel usage, GHG emissions and total VMT. The Vision model is used by Federal policymakers and analysts in evaluating transportation energy policy questions.

In developing the scenarios for this analysis, assumptions were identified based on extensive review of the literature and stakeholder discussion. Key assumptions were identified for vehicle technology and performance, fuel supply, sales projections, and vehicle usage patterns. The primary factors that vary between scenarios are vehicle sales projections, the

\(^5\)California Department of Finance (DOF). [http://www.dof.ca.gov/research/demographic/reports/projections/p-1/](http://www.dof.ca.gov/research/demographic/reports/projections/p-1/)

vehicle technology mix in the market, biofuel supply levels, and vehicle miles traveled (VMT) per vehicle reductions.

California vehicle annual sales projections are based on ARB's EMission FACtors 2007 (EMFAC 2007) dataset, which includes historical data through 2008 and projections to 2040. Trends were extrapolated to 2050 to complete the dataset for this analysis. The fleet turnover rates are based on the national trends in the U.S. DOE's Vision model. Fleet turn-over rates determine how many vehicles remain on the road in any given year, and account for vehicle age, scrapage rates, declining VMT per vehicle based on age, etc. The average lifetime of a passenger vehicle in the United States is roughly 15 years. Generally, the market diffusion is slow, resulting in several decades for a new technology to substantially replace older vehicles.

ASSUMPTIONS

This section outlines the primary input assumptions for the model along with how the varying advanced vehicle scenarios were chosen.

Achieving an 80% reduction in the transportation sector will require a broad mix of solutions. This includes reduced VMT per capita (partly through increased use of transit), increased vehicle fuel efficiency, reduced fuel carbon content, and implementation of advanced vehicle technologies. This analysis includes all of these solutions, but most carefully studies the vehicle technologies. Hydrogen fuel cell vehicles (FCV), battery-electric vehicles (BEV), and plug-in hybrid-electric vehicles (PHEV) with low carbon biofuels are the three most viable candidates for near-zero carbon transportation. This analysis shows all three vehicle technologies will be necessary in order to achieve an 80% reduction target, and to reduce the risk of technology or market failures.

The dataset assumes roughly 22 million vehicles are on the road in 2000, increasing to 40 million vehicles in 2050. Annual sales rates start from roughly 1.5 million vehicles sold per year in 2000 and grow to 2.7 million in 2050 (accounting for a sales decline in 2008-2009). Additionally, the analysis assumed a sales mix of cars and trucks shifted to a 70%/30% respectively by 2050.

Efficiency and VMT reductions

Fuel economy improvements are assumed and result from a number of factors, including vehicle down-sizing and vehicle weight reduction, in addition to powertrain efficiency improvements. Specifically, the analysis in MIT 2008 was heavily leveraged for conventional vehicle fuel economy and the ratio of fuel economy between technology alternatives (although the exact projection of fuel consumption for each technology may vary from the MIT study). The MIT analysis was based on a mid-sized vehicle platform. This analysis assumes that by 2050, the average vehicle size has been reduced to a compact vehicle platform. This is represented as a steeper increase in fuel economy than would be expected if the platform size remained constant. Figure 2 below shows the assumed fuel economy values in the analysis for autos, separate fuel economy assumptions were developed for light trucks.

All technology alternatives are based on vehicle platforms with the same improvements relative to today's vehicle (weight reduction, down-sizing, aerodynamics, etc). Note that the PHEV fuel economy is not shown. The model accounts for the fuel economy of PHEVs on both grid-electricity and liquid fuels separately. For simplicity, this analysis assumes that when a PHEV is operating on grid supplied electricity, the fuel economy is the same as a BEV; when the PHEV is operating on liquid fuels, the fuel economy is the same as an HEV. In reality, this will depend on the specific vehicle design, weight, and control algorithms.

VMT reduction goals will target regional development and transportation planning, and will include solutions such as mass transit, compact urban design, carsharing, and more. The VMT per vehicle reductions in the scenarios were assumed to be 20% below the projected “business as usual” (BAU) per vehicle VMT in 2050. These projections for the BAU assume VMT per vehicle will stagnate at approximately 12,000 miles/yr, therefore the VMT in the scenarios are 9,600 miles per year per vehicle. Figure 3 shows the scenario trends for VMT where total VMT increases as State population grows.

Electricity and fuels carbon intensity

Electricity, hydrogen, and bio-hydrocarbon fuel carbon intensities were modeled with large reductions through 2050. The carbon intensity values from the LCFS were used in this model for each type of fuel production and feedstock, and

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9 The vehicle population numbers are derived using both the vehicle sales projections from ARB's EMFAC model, and the national fleet turn-over rates used in the Vision model.
10 The scenarios all assume an increasing amount of all electric range for PHEVs over time.
11 As noted above, DOF estimates California's population will grow to nearly 60 million people by 2050.
were assumed to be relevant out to 2050. This is a change from the Vision model where the carbon intensity numbers were from Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model. Specifically, the carbon intensity of hydrogen, electricity, and biofuels is largely reduced by 2050 (80%, 65%, and 90% respectively below today's levels), relying on sustainable feedstocks and carbon capture solutions. These changes will be challenging to achieve, and will require expanded transmission lines, fuel distribution and large investments in sustainable power production facilities, along with technology innovation. Note that the scenarios ensured the 2020 policy goal was achieved for the LCFS, a 10% reduction in average carbon intensity by 2020. Additional details on the specific fuels and their feedstocks can be found in the Appendix.

Over time, an increasing amount of low-carbon biofuels was assumed. Through 2020, a maximum of 10% ethanol in

\[12\text{ Low Carbon Fuel Standard Initial Statement of Reasons (ISOR) report, March 5, 2009 [1].} \]
gasoline (E10) was modeled given the current national blend wall limit. To achieve the LCFS carbon reduction compliance in 2020, a large amount of E85 (85% ethanol fuel with 15% gasoline) fuel was assumed in addition to E10, but only for a limited timeframe between 2015 and 2025. After 2020, the model assumed a non-ethanol based bio-hydrocarbon fuel was commercialized. This is a long-term goal of the energy industry as it creates large flexibility in the levels of biofuel blends in gasoline and diesel, and allows them to transport biofuels blended with fossil fuels in pipelines.13

An important bounding parameter in the scenario was the projected biomass availability in 2050.14 If unlimited biomass supplies were available, theoretically conventional engines operating on very low-carbon biofuels could achieve the 2050 80% goal. In reviewing recent biomass assessments15, an upper limit of 1 BGGE was set for the passenger vehicle sector (including biomass for H2) for Scenario 1. This limitation considers that large quantities of biofuels will be needed in the aviation, heavy-duty vehicle, and marine sectors to reach their 2050 GHG reductions. Additionally, there will be increasing competition for sustainable biomass resources from other states and non-transport sectors. Although it was not modeled in this analysis, future commercialization of algae-based biofuels could significantly increase biofuel supplies. However, algae biofuel development is highly uncertain though is showing increasing potential. Refer to the Appendix for additional detail on the biofuel supply limitation.

Advanced vehicle sales projections

Several scenarios were developed to evaluate various advanced vehicle market and technology assumptions. The unique aspect of each scenario focuses on the different technology sales projections over time. Most of the sales projections are aggressive to achieve the deep GHG reductions. The projections were developed by studying external sources for long-term trajectories16 and using judgment of what is possible from the automotive industry for the near-term trajectories. Although this model does not simulate economic factors and consumer choice, the projections assume consumers will demand and purchase the advanced vehicles, either because of high gasoline and carbon prices or because the advanced vehicles offer new and attractive alternatives.

The following key trends are captured in Scenarios 1 and 2. Figure 4 shows the assumed sales projections for the major vehicle technologies in the automobile (car) segment for Scenario 2 (additional figures are provided in the Appendix).

- The vehicle technology sales curves relied on the historical rate of hybrid electric vehicle (HEV) growth as a benchmark for the first 10 years, and realistic technology sales growth projections by 2020 based on known technical and infrastructure challenges.
- Both scenarios assume PHEV sales take off faster and decline long-term when FCVs & BEVs reach high volumes. It also assumes BEV sales take off faster than FCVs initially, but reach a saturation limit (30% of sales market by 2050); FCVs take off last but become the dominant low-carbon alternative by 2050.
- A progression of battery technology improvements was assumed. For PHEVs, the amount of all-electric range (AER) that the batteries can support grows over time from 10 miles (2020) to 50 miles (2050). For BEVs, it is assumed range increases and infrastructure grows to justify market shares projected.
- Although trends are similar for light trucks (not shown below), there is less reliance on BEVs in trucks and more reliance on PHEVs and diesel HEVs all the way to 2050.

RESULTS

Figure 5 shows the GHG emissions between 1990 and 2050 for a “business as usual” (BAU) projection17 and two scenarios, both assuming all advanced vehicle technologies are fully commercialized. Scenario 1 in this analysis achieves a 66% reduction in GHG emissions by 2050 using aggressive but plausible assumptions. This scenario assumes ZEV sales reach a quarter of a million units annually by 2025 and become 100% of new vehicle sales by 2050. Scenario 2 was developed to show what would be required to achieve the full 80% GHG goal. A steeper ZEV sales projection was simulated where ZEV sales reach half a million units by 2025 and are 100% of new vehicle sales by 2040. Additionally, the availability of biofuels was increased to 1.7 billion gallons gasoline equivalent (BGGE), where it was limited to 1 BGGE in Scenario 1.18

The BAU projection assumes the Pavley 1 Regulation and LCFS are both fully implemented, followed by a straight-line projection that assumes the vehicle fuel economy and fuel
carbon intensity values from 2020 are fixed to 2050 as vehicle population grows. It is important to note that the exact BAU projection does not affect the scenario results given the 80% GHG goal is referenced to the 1990 emission level.

Figure 6 shows that by increasing the 2020 ZEV annual sales six-fold (25,000 vs. 150,000), 2050 GHG reductions improve from 66% to 73%. This is achieved by starting ZEV sales earlier but maintaining the same long-term sales slope as in Scenario 1. The scenario that achieves 75% assumes ZEV sales in later years are more rapid and reach the full new market share 10 years earlier (2040 rather than 2050). Using this “steeper” ZEV sales projection along with a larger amount of biofuels (1.7 BGGE vs. 1 BGGE), results in Scenario 2 in Figure 5.
The results from this scenario and others show that high-volume (100,000s) ZEV markets need to exist by 2020 in order for ZEV sales and fleet turn-over rates to result in enough ZEVs to achieve deep GHG levels. In other words, over three decades of strong ZEV sales are required to reach the policy goal. Figure 7 shows the cumulative on-road vehicle mix for Scenarios 2 that results from these aggressive sales rates.

Figure 7 below shows the total energy usage by fuel type over the course of the scenario timeframes. A similar trend is revealed compared to Figure 7, where electricity and hydrogen are a minor part of energy consumption up through 2020, but expand quickly over the next three decades. Additionally, Figure 8 shows that biofuel levels expand through 2030 and then somewhat decline by 2050. This trend is expected as the fuels industry aggressively moves to

\[19\] The truck segment relies less on ZEVs. The combined passenger vehicle sector has a resulting 79% ZEV on-road penetration in 2050. For reference, the 2000 California vehicle population is 22 million, and increases to 40 million in 2050.
biofuels to comply with the LCFS by 2020, but then shifts to ZEV technology fuels after that point. Additionally, limited biofuel supply will slowly shift to other sectors, such as aviation and heavy-duty vehicles in the later years. For reference, the quantity of liquid fuels (combined gasoline, diesel, and biofuels) is plotted on the right of Figure 8. This shows that in 2010, California is projected to consume approximately 20 BGGE, but that by 2050, this is dramatically reduced to 2.5 BGGE (Scenario 1). This scale is important when considering the biofuel limit of 1 BGGE (nearly 40% of the total liquid fuels in 2050).

SUMMARY/CONCLUSIONS

This 2050 GHG modeling analysis has addressed two policy questions as they relate to California's 2050 GHG goals in Executive Order S-03-05,20 revealing several key conclusions.

1. What fraction of the on-road fleet in 2050 needs to be ZEVs in order for the LDV sector to achieve an 80% GHG reduction, and
2. What annual ZEV sales are necessary between 2015 and 2025 to initiate these fleet volumes?

Market growth by 2020. Commercial markets for the advanced vehicles need to be established by 2020 to ensure sufficient time for vehicle fleet growth and turnover. This includes FCVs, BEVs, and PHEVs. Specifically, ZEV sales need to move from early commercial scale (10,000s) by 2020 to full commercial scale (100,000s) by 2025. In specifically addressing the policy questions above, the scenarios in this analysis show:

Cumulative on-road:
- Scenario 1: 900,000 ZEVs (FCVs + BEVs) in CA by 2025, growing to 61% of the on-road fleet by 2050
- Scenario 2: 1.4 million ZEVs by 2025, growing to 79% of the on-road fleet by 2050

Annual ZEV sales:
- Scenario 1: 25,000 in 2020, and 230,000 in 2025
- Scenario 2: 25,000 in 2020, and 425,000 in 2025

ZEV sales projections. If the ZEV sales curve to 2050 shown in Figure 6 is shifted 5 years earlier, a 73% GHG reduction results. This shows that increasing early ZEV sales can make a difference, though ZEV technological readiness may prevent this. If, instead, the slope were increased so that ZEV sales reach the 100% level in 2040 instead of 2050, a 75% GHG reduction is achieved. These concepts are shown in Figures 6 and 16 (Appendix).

PHEVs & Biofuels. In addition to the ZEV volumes, Scenario 2 includes over 1 million on-road PHEVs by 2025, showing that PHEVs will also have an important role in reducing transportation GHG. In addition to an increasing

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20% reduction in GHG emissions below 1990 levels by 2050.
amount of AER over time, an increasing amount of low-carbon biofuel is blended into gasoline and diesel.

Fuel carbon intensity. To achieve the large GHG reductions with plug-in vehicles and FCVs, the carbon intensity of hydrogen, electricity, and biofuels is largely reduced by 2050, relying on sustainable feedstocks and carbon capture solutions. The carbon intensity of electricity, hydrogen, and biofuels is reduced by 80%, 65%, and 90% respectively, from today's levels. Refer to Figures 9, 10, and 11 in the Appendix.

VMT & Efficiency. Large vehicle efficiency improvements (via powertrain efficiency, vehicle weight reduction, vehicle downsizing) and reductions in VMT per vehicle were assumed. Efficiency and VMT reduction solutions are especially important as they reduce primary energy usage. Refer to Figure 3.

Achieving the advanced vehicle sales projections in these scenarios will be extremely difficult, as they represent sales growth rates equal to or greater than the historical HEV growth in the US. For these sales trends to emerge, existing market forces may not be enough (fuel prices, vehicle incentives, etc). Additional “market pull” policies may be required to encourage the sales, and could include policies such as carbon pricing (tax or cap/trade), vehicle “feebate” incentives, or federal vehicle purchase incentives. An expanded discussion on this topic is at the end of the Appendix.

REFERENCES
**Additional sources reviewed**


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**ACKNOWLEDGMENTS**

The author would like to thank the many individuals within ARB who contributed and made this work possible, and to thank the automotive and environmental stakeholders who contributed to key assumptions in the model.

**DEFINITIONS/ABBREVIATIONS**

**AER**  
All electric range

**ARB**  
Air Resources Board

**BAU**  
Business as usual

**BEV**  
Battery electric vehicle

**BGGE**  
Billion gallons gasoline equivalent

**CO2e**  
Carbon dioxide equivalent emissions

**DOE**  
U.S. Department of Energy

**DOF**  
CA Department of Finance

**EMFAC**  
Emissions Factor (ARB model)

**E10**  
10% ethanol blend in gasoline

**E85**  
85% ethanol

**FCV**  
Fuel cell vehicle

**GHG**  
Greenhouse gas

**HEV**  
Hybrid electric vehicle

**H2**  
Hydrogen

**LCFS**  
Low Carbon Fuel Standard

**LDV**  
Light duty vehicle
**MMT**  
Million metric tonnes

**MPG-GE**  
Miles per gallon (gasoline equivalent)

**PHEV**  
Plug-in hybrid electric vehicle

**VMT**  
Vehicle miles traveled

**ZEV**  
Zero emission vehicle
APPENDIX

Details on electricity and fuels carbon intensity

The following three figures (Figures 9, 10, and 11) show two trends for each vehicle fuel. The bar chart for each figure (left hand Y-axis) shows the fraction of the fuel production from each type of input resource (feedstock) for three key decades in the analysis. The figures also show the resulting average carbon intensity for the fuel and how it changes with the varying feedstock sources (right hand Y-axis). Figure 9 shows the production feedstock and carbon intensity for the electricity sector in California.

California's electricity mix is already significantly lower in carbon emissions than the national mix, with over 40% of the production coming from natural gas, 20% from large hydroelectricity, and 10% from traditional renewables today. However, the carbon intensity of the State's electricity will have to be reduced significantly to achieve the 2050 goals. This analysis assumed the 2050 carbon intensity was roughly 29 gCO2e/MJ from the current 121 gCO2e/MJ. The scenario assumed the 2010 and 2020 renewable policy goals were achieved (20% in 2010, 33% in 2020). Traditional renewables continue to grow to 40% of the grid mix in 2050, with large hydro being maintained at 20% for a combined 60% “zero carbon” supply. A growth in nuclear energy is assumed as well as the commercialization of carbon capture and sequestration (CCS), where CO2 is captured from coal or natural gas power facilities and stored permanently underground. The commercialization and success of CCS is highly uncertain, and therefore represents a risky assumption.

Today, hydrogen is produced predominantly from natural gas, and is a widely used gas at industrial facilities, including oil refineries. As a hydrogen economy for transportation emerges, Figure 10 shows the hydrogen will initially be produced from natural gas to leverage existing industry experience and costs. However, over time, hydrogen will have to increasingly come from more sustainable sources.21 The resulting low carbon intensity assumes a mix of electrolysis with renewable electricity, high temperature direct water separation, and coal with CCS in 2050. Although biomass is a feasible feedstock for hydrogen, and may be the least expensive sustainable hydrogen source, it was not modeled here given the limitations on biomass for the passenger vehicle segment. This is an assumption that could be revisited.

Figure 11 shows the carbon intensity and production feedstocks for biofuels. This analysis assumes ethanol will continue to be blended into gasoline in blends up to 10% (E10) through 2020. However, soon after that time, the analysis assumes a new biofuel chemistry will be commercialized, a “bio hydrocarbon fuel” that is more similar chemically to gasoline and can be shipped in pipelines as a blend. As a result, after 2020, this analysis assumes biofuels can be blended in gasoline at any volume fraction. The carbon intensity trend in the figure shows a rapid decline through 2030, and a more gradual decline to 2050. This is a result of dramatic carbon reductions in biofuels to comply with the LCFS regulation by 2020.

21 California's Senate Bill 1505 (2006) requires that once a certain amount of hydrogen is produced for markets, one third of the fuel must come from sustainable feedstocks.
The LCFS will drive innovation through 2020 and is expected to incentivize significant quantities of low-carbon biofuels in the California market. This innovation will create development of new biorefinery technology and more sustainable feedstock choices. Hydrogen and electricity will be incentivized as well, though they will remain a small part of the transportation fuel mix by 2020.

**Biomass Resource Availability**

Figure 12 compares biomass resource assessments from three sources\(^2\). The bar chart, showing units of million dry tonnes of biomass per year (DT/yr), reveals how little of the biomass resource may be available for the passenger vehicle segment in California. The International Energy Agency (IEA) assessment starts with a national resource level for all energy consuming sectors, and then isolates the fraction of that available for passenger vehicles (approximately 7% of the total national resource). This analysis further reduced this to account for the fraction available in California.

A more recent National Research Council (NRC) study has more specific U.S. assumptions and shows the national resource at approximately 550 million DT/yr. Using the NRC total value, this analysis hypothesized a simple split between sectors: 50% consumed by the transportation sector, and then a further 50% by passenger vehicles specifically. After accounting for a 15% share used in California, the result is 1 BGGE for the passenger vehicle sector. The California Energy Commission (CEC) reference shows biomass

\(^2\)[3, 15, 17]
resources specifically in California, though does not isolate individual consuming sectors. But the total resources available in California from the IEA and NRC studies are similar in scale to the CEC study. Further study on this parameter is necessary given that the model is sensitive to the biomass value.

The resulting biofuel level from the NRC case in Figure 12 became the value used in the analysis for the biofuel availability. It is important to note that 1 BGGE of biofuels represents over 40% of all liquid fuels consumed in Scenario 1 in 2050 (approximately 2.5 BGGE). This is significantly less than today's California fuel consumption, and is largely because the 2050 on-road fleet are predominantly ZEVs. This is shown in Figure 8.

Advanced Vehicle Sales Projections & On-Road Fleet Results
The following two figures show additional new vehicle sales projections compared to Figure 4. Figures 13 and 14 show the passenger car and truck sales projections for Scenario 1. Figure 15 shows the on-road fleet.

Sensitivity analysis - Scenario Variations
The following scenario variations were all created starting from, and are referenced to, Scenario 1. The results from Scenario 1 can be summarized relative to the policy questions at the beginning of this report. Figure 16 below shows the resulting 2020 & 2025 ZEV annual sales, along with the 2050 GHG reduction levels, for each case.

(a). If the solid ZEV sales curve\textsuperscript{23} to 2050, shown in Figure 6 (Scenario 1) is shifted 5 years earlier, a 73% GHG reduction results. This shows that increasing early ZEV sales can make a difference; though ZEV technical readiness may prevent this (this represents a 110% increase in annual ZEV sales in 2025 compared to Scenario 1)

(b). If, instead, the slope were increased so that ZEV sales reach the 100% level in 2040 instead of 2050, a 75% GHG reduction is achieved.

(c). If this most aggressive ZEV sales trajectory is used along with additional biofuels (1.7 BGGE vs. 1 BGGE), the full 80% GHG reduction level is achieved - Scenario 2.

(d). The quantity of bio-hydrocarbon fuel for the passenger vehicle segment is doubled in this variation (2 BGGE vs. 1 BGGE). When this is added to the advanced vehicle sales assumptions in Scenario 1, the GHG reductions improve from 66% to 73%. Another variation on this is to maintain the same GHG levels by reducing the required ZEV volumes (35% reduction in 2025 ZEV sales compared to Scenario 1).

(e). A variation was created to see the sensitivity of the VMT per vehicle assumption. In this variation, the VMT per vehicle reductions were not as aggressive as Scenario 1 - 10% below 2050 rather than 20%. As a result, additional ZEVs are required to simply maintain the same 2050 GHG reduction.

\textsuperscript{23}The slope of the ZEV sales over multiple decades is highly uncertain. This analysis assumes an aggressive growth that is similar to assumptions in the NRC 2008c [9].
General Technology Tradeoffs

Battery Electric Vehicles (BEVs)
- (Pros) Efficient drivetrain, easier market launch compared to FCVs (less infrastructure challenges and lower early costs)
- (Cons) Potentially higher long-term vehicle costs, limited range, reliant on long charge times, limited vehicle sizes

Fuel Cell Vehicles (FCVs)
- (Pros) Long range, fast refueling, wide range of vehicle sizes
- (Cons) hydrogen storage, and fuel infrastructure - largest hurdle and possible show stopper

Plug-in Hybrid Electric Vehicles (PHEVs)
- (Pros) Long range, fuel flexibility and convenience, wide range of vehicle sizes, straightforward market transition (build on HEVs, battery size can grow over time as costs improve)
(Cons) reliant on low carbon biofuel supply for deep carbon reductions, fuel economy benefits depend on drive cycle and trip length

**Literature Review Highlights**

A large number of references were identified with direct relevance to this analysis. Although many of the references provided isolated information for specific assumptions, a few of the references listed were studied critically as they relate to broad 2050 GHG projections.24

Each of these studies had varying contexts and assumptions, but they all arrived at a few common conclusions. First, achieving large GHG reductions by 2050 will require dramatic changes in the way we use and produce energy. This includes the need for the majority of the on-road vehicle fleet to be near zero emission alternatives, along with an electricity and fuel supply that is largely de-carbonized. This will require aggressive policies to ensure GHG reductions occur in a timely and coordinated way. A combination of regulation and market incentive policies will be needed.

A second common conclusion is the need to act soon to ensure the passenger vehicle fleet changes over multiple decades for robust, widespread GHG reductions.25 Specifically, the next 10 years are important to experiment with low-volume, early commercialization before aggressive sales need to begin.

A few excerpted quotes from key references follow to emphasize these conclusions:

“A global revolution is needed in ways that energy is supplied and used. Far greater energy efficiency is a core requirement. Renewables, nuclear power, and CO2 capture and storage (CCS) must be deployed on a massive scale, and carbon-free transport developed. A dramatic shift is needed in government policies, notably creating a higher level of long-term policy certainty over future demand for low carbon technologies, upon which industry's decision makers can rely. Unprecedented levels of co-operation among all major economies will also be crucial, bearing in mind that less than one-third of “business-as-usual” global emissions in 2050 are expected to stem from OECD countries.” [International Energy Agency “Energy Technology Perspectives: Scenarios & Strategies to 2050”, pg 38.]

“A portfolio of technologies including hydrogen fuel cell vehicles, improved efficiency of conventional vehicles, hybrids, and use of biofuels-in conjunction with required new policy drivers-has the potential to nearly eliminate gasoline use in light-duty vehicles by the middle of this century, while reducing fleet greenhouse gas emissions to less than 20 percent of current levels. This portfolio approach provides a hedge against potential shortfalls in any one technological approach and improves the probability that the United States can meet its energy and environmental goals. Other technologies also may hold promise as part of a portfolio, but further study is required to assess their potential impacts…

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24 These included the California Energy Commission's AB 118 investment report, and 1, 3, 5, 6, 9

25 Passenger vehicle fleet turn-over rates are roughly 15 years.
Sustained, substantial, and aggressive energy security and environmental policy interventions will be needed to ensure marketplace success for oil-saving and greenhouse-gas-reducing technologies, including hydrogen fuel cell vehicles.” [National Research Council, “Transitions to Alternative Transportation Technologies: A Focus on Hydrogen,” pg 6.]

“While no individual “Silver Bullet” strategy exists that can achieve the goals, a portfolio approach that combines strategies could yield success.” [University of California, Davis, “Meeting an 80% reduction in GHG emissions from transportation by 2050: A case study in California,” pg 1.]

Critical Factors Necessary for Success

Given that these ZEV sales projections are aggressive, it is ARB’s conclusion that both market push policies, such as the ZEV Regulation, and market pull policies will be needed to ensure the sales materialize - if consumers don’t buy the vehicles, advanced vehicle markets will not grow. Market policies are especially important in the next 10 years as the advanced vehicles are first introduced to consumers and production costs still remain high. These ideas are explored further in a Complementary Policies report by ARB [19].

Several parameters in the modeling analysis are particularly sensitive and therefore require further review of the assumptions and data. Biomass supply is expected to be limited for the passenger vehicle sector in 2050 as other sectors compete for the resource. This analysis assumed 1 BGGE of biofuels as a limit for passenger vehicles in 2050. Changing the value by +/- 50% has a noticeable impact on the number of ZEVs required to reach the 80% goal. A second parameter that is particularly sensitive is VMT per vehicle. Opinions vary widely among experts as to how large reductions will be in this parameter. Continued evaluation is important.

A few other parameters may not be as sensitive, but their success is highly uncertain, either due to technical innovation required, market cost barriers, or large political will necessary to advance the solution. If any of these parameters are not as successful as assumed in this analysis, achieving the 80% GHG goal would require even more aggressive ZEV sales and success. This is part of the reason why pursuing multiple ZEV solutions are essential to hedge risks against non-vehicle assumptions. Uncertain parameters include:

1. Hydrogen infrastructure. This requires a substantial amount of stakeholder coordination at all levels of government and industry. Political will and private investment motivations need to be aligned for this to emerge.

2. Carbon capture & sequestration (CCS). This is critical for baseload power in addition to renewable electricity. Most scenario references reviewed recommend use of CCS to achieve deep GHG reductions, but challenges such as reliable storage and monitoring, and sufficient underground reservoirs must be overcome. Public support is also currently a

Figure 16. Sensitivity Study - impact on ZEV 2020 and 2025 sales

* Includes ZEV sales from (b) and an increase in biofuel usage (1.7 BGGE instead of 1 BGGE in Scenario 1)
challenge that will need to be addressed, and includes liability rules, and “not in my backyard (NIMBY)” concerns with pipelines and underground locations.

3. **Bio-hydrocarbon fuel.** As a replacement for ethanol to be blended into gasoline, this fuel would be very similar in chemistry to gasoline. This future fuel eliminates the need for vehicle and pump changes, reduces the upstream fuel infrastructure burden by allowing blended fuel in long distance pipelines, and provides flexibility to energy firms for varying blends over time depending on oil prices, cap/trade requirements, etc. However, this fuel has not been developed and commercialization is not expected before 2020.

4. **Renewable electricity expansion.** This will be very challenging given limits on transmission line development (costs and land rights) as well as local resistance in some cases (wind and solar farm locations). Growth in renewable electricity is expected, but achieving the 2010 and 2020 State targets will require large coordination and cooperation among all stakeholders.

**Closing Thoughts - Risk Management**

Each technology has a large set of challenges which makes market growth uncertain. All three (BEVs, FCVs, and PHEVs) offer energy security and fuel diversification over time. But it is too early to pick winners at this time. Doing so would dramatically increase the risk of missing the 2050 GHG goal because it would create no room for technology or market failures. Discussions between ARB and automotive firms confirm this - it is impossible for industry to know exactly what consumers will demand and accept in the future. BEVs will most likely play a role and obtain a sizable portion of the long-term market, focused on small vehicle platforms in urban areas.26

For long-range, larger applications, both FCVs and PHEVs with biofuels offer deep GHG reductions, but both have large market uncertainties. FCVs offer deep well-to-wheel (WTW) GHG reductions [20, 21] and fast refueling, but creating the fuel infrastructure is a substantial challenge. PHEVs offer less infrastructure challenges but would rely on biofuels in quantities that may exceed the 2050 limit of supply for passenger vehicles.

WTW energy and GHG comparisons between advanced vehicle and fuel pathways are useful but should be used in a future context and should not be used in isolation from other comparison factors. The WTW comparisons should use future electrical grid and fuel production assumptions to be appropriate. Further, only studying the WTW performance ignores the consumer preferences in vehicles (range, cost, features, fueling time, access to fuel). Without consumer demand, advanced vehicle sales will not emerge and grow.

Early markets take time and are very slow to grow initially. Because of large uncertainties initially in how consumers will react to various advanced vehicle technologies, features and costs, automotive firms develop one advanced vehicle product and wait to receive market feedback before expanding the technology to additional vehicles and platforms. Historically this can be seen in the successful, but slow, growth of the HEV market in the US. It took 10 years for hybrids to reach 4% of the new vehicle market in California and for industry to determine the best vehicle tradeoffs that will allow the market to grow. PHEVs, BEVs, and FCVs have even larger uncertainties in consumer expectations creating larger market uncertainties. Once commercial volumes are achieved, it may be appropriate to phase out a mandate and solely rely on a performance standard.

In managing the large risks of climate change impacts and achieving California's 2050 GHG goals, the recommended policy is to pursue all promising advanced vehicle solutions and aggressively encourage advanced vehicle markets through the ZEV Regulation as well as market pull mechanisms.

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26 The scenarios in this analysis assume BEVs saturate in the market at 30% of 2050 vehicle sales.