

ATTACHMENT B

2050 Greenhouse Gas Emissions Analysis: Staff Modeling in Support of the Zero Emission Vehicle Regulation

Disclaimer.

This modeling exercise was conducted to support the development of the Zero Emission Vehicle Regulation and does not represent ARB positions or assumptions in other greenhouse gas regulations or policies.

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1. Introduction & Results Summary

In recognizing the potential for large, damaging impacts from climate change, California Governor Arnold Schwarzenegger enacted Executive Order S-03-05, requiring a reduction in statewide greenhouse gas (GHG) emissions to 80-percent below 1990 levels by 2050.¹ In addition to the Governor's Executive Order, the State Legislature and the California Air Resources Board (ARB or the Board) have adopted a number of policies that address GHG emissions in the transportation sector.²

In developing the policy for Assembly Bill (AB) 32, ARB and other State agencies carefully studied the specific impacts of climate change on the State of California.³ The AB 32 goal of reducing emissions to 1990 GHG levels by 2020 is the first step towards longer-term, deeper, reductions 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. Secondly, climate change is a function of cumulative emissions in the atmosphere. Early reductions (2020) are therefore essential.

Given that the transportation passenger vehicle sub-sector 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 in the very near future.⁴ 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 accelerate⁵ the introduction of low-carbon vehicle alternatives to ensure markets enter into pre-commercial volumes (10,000s) between 2015 and 2020.

In March 2008, the Board directed staff in Resolution 08-24 to enhance the focus on GHG emissions within the Zero Emission Vehicle (ZEV) Regulation, in addition to its historical criteria pollutant focus, in order to meet California's long term climate change reduction goals.⁶ This report summarizes the results and conclusions of a modeling exercise that simulated GHG emissions from the passenger vehicle sector to 2050.

The goal of this analysis was to identify how large of a role ZEVs⁷ have in meeting California's 2050 GHG goals. Specifically, the analysis addresses two policy questions: (1) what are the cumulative ZEVs necessary by 2050 to help the passenger vehicle sector achieve an 80% GHG reduction, and (2) what annual ZEV

¹ California's 2020 and 2050 GHG emission reduction goals are consistent with where the international scientific community believes developed nations need to be in order for world-wide GHG concentrations to peak at 450 parts per million (ppm) by mid-century, a level thought necessary to avoid catastrophic climate impacts [UN]

² These include the vehicle GHG regulation (Assembly Bill 1493, 2004), the Low Carbon Fuel Standard (ARB, 2008), and the regional GHG targets (Senate Bill 375, 2008). Most importantly, the state adopted Assembly Bill 32, the California Global Warming Solutions Act of 2006, which caps GHG emissions at 1990 levels by 2020.

³ This work is summarized in the Scoping Plan [<http://www.arb.ca.gov/cc/scopingplan/scopingplan.htm>]

⁴ A number of studies have shown that multiple solutions will be required to achieve the GHG reductions [UC Davis 2009, U.S. EPA, IEA 2008a, MIT 2007b, MIT 2008, McKinsey, Pew, Princeton, NRC 2008c]

⁵ Accelerate advanced technology relative to how the automotive industry would introduce it if only complying with the vehicle GHG regulation (AB 1493).

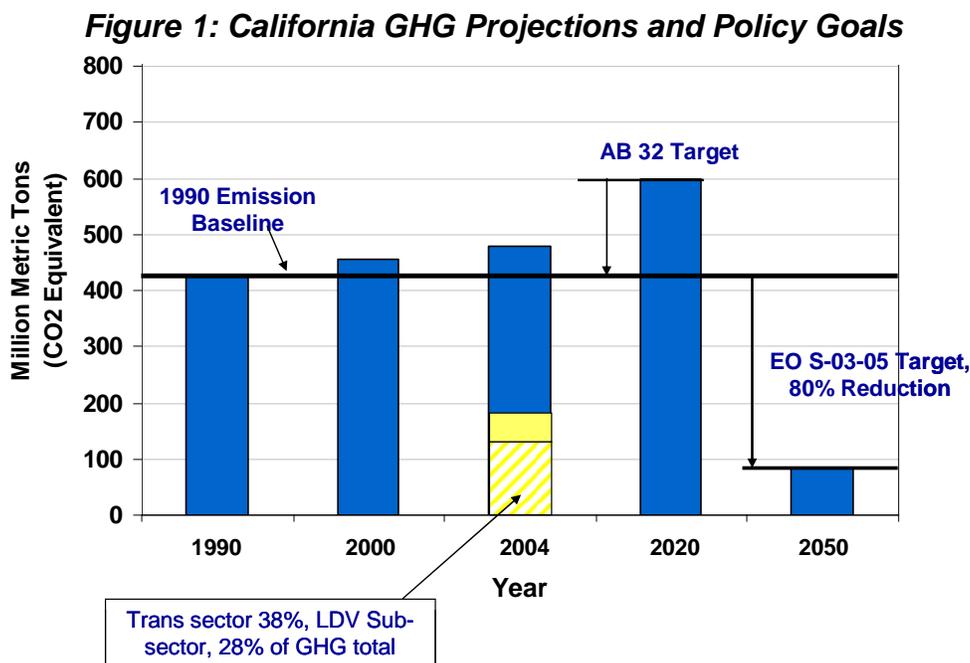
⁶ ARB Resolution 08-24

⁷ In this analysis, ZEVs include fuel cell vehicles (FCVs) and battery electric vehicles (BEVs), not plug-in hybrids.

sales are necessary between 2015 and 2025 to initiate these fleet volumes? The modeling exercise was conducted to support the development of the ZEV Regulation and does not represent ARB positions or assumptions in other GHG policies, such as LCFS, Pavley, SB 375, AB 32, etc.

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" for 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.

Figure 1 below 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.



According to the California Department of Finance (DOF), the State's population is projected to reach 60 million people by 2050⁸, double what it was in 1990, increasing pressure on limited resources. Energy demand will increase substantially, though not at the rate of population growth given the need for dramatic efficiency and conservation efforts. None the less, new biorefineries, electricity production, and hydrogen facilities will be needed along with distribution infrastructure to meet increasing fuel demand, adding to local and regional development requirements. Traffic congestion will increase and public infrastructure in urban areas will be stressed. Potentially the most dramatic change will be the integration of technology

⁸ California Department of Finance (DOF), <http://www.dof.ca.gov/research/demographic/reports/projections/p-1/>

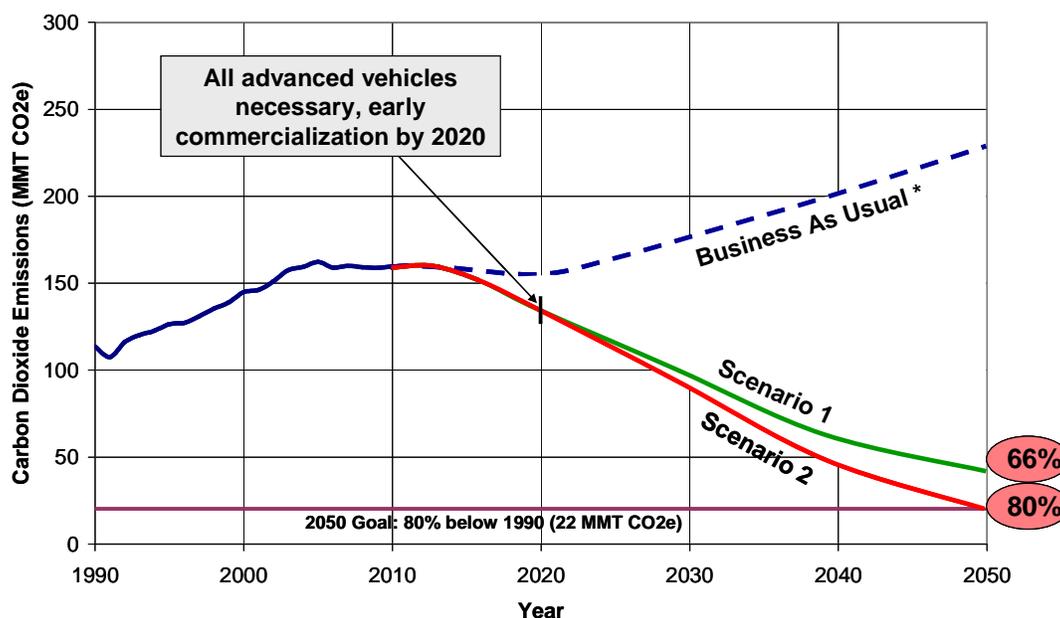
in personal transportation and residential buildings through home charging/fueling and smart communications.

Summary of Results

Figure 2 shows the GHG emissions between 1990 and 2050 for a “business as usual” (BAU) projection⁹ 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. To achieve this, two key parameters were modified with more aggressive and uncertain assumptions. 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 1.¹⁰

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.¹¹ It is important to note that the exact business as usual projection does not affect the scenario results given the 80% GHG goal is referenced to the 1990 emission level, they are shown purely for context.

Figure 2: Passenger Vehicle GHG Emissions – Historical and BAU



⁹ The BAU projection does not reflect official ARB GHG inventory projections; it was developed solely for this modeling exercise and is purely hypothetical. Population data from CA Dept of Finance (34 million people in 2000, 59 million in 2050). Total vehicle population grows from 20 million (2000) to 40 million vehicles (2050).

¹⁰ Both cases have reductions in VMT per vehicle (20% below the VMT/veh projections for 2050)

¹¹ 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; they are shown purely for context.

The following are the key conclusions from this GHG analysis.

- **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 turn-over. This includes fuel cell vehicles (FCVs), battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). Specifically, ZEV sales need to move from pre-commercial scale (10,000s) by 2020 to full commercial scale (100,000s) by 2025. This is evident in Graph 3 of the White Paper and Figure 9 below. In specifically addressing the policy questions above, the scenarios in this analysis show:
 - **Cumulative on-road:**
 - Scenario 1:* 100,000 ZEVs (FCVs + BEVs) in CA by 2020, accelerating to 900,000 ZEVs by 2025.¹²
 - Scenario 2:* 120,000 ZEVs by 2020, 1.4 million ZEVs by 2025
 - **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 curve¹³ to 2050 shown in Figure 9 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 13 and 17.
- **PHEVs & Biofuels.** In addition to the ZEV volumes, Scenario 2 includes over 1 million PHEVs cumulative by 2025, showing that PHEVs will also have an important role in reducing transportation GHG.¹⁴ Additionally, 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. Refer to Figures 5, 6, and 7 in Section II. The carbon intensity of electricity, hydrogen, and biofuels is reduced by 80%, 65%, and 90% respectively, from today's levels.
- **VMT & Efficiency.** Large vehicle efficiency improvements (via powertrain efficiency, vehicle weight reduction, vehicle downsizing) and reductions in vehicle miles traveled (VMT) per vehicle were assumed. Efficiency and VMT reduction solutions are especially important as they reduce energy usage. Refer to Figure 4 in Section II.

¹² The analysis assumes aggressive sales trajectories between 2010 and 2050. This analysis relied on external studies of how rapid advanced vehicle sales rates could become.

¹³ The slope of the ZEV sales over multiple decades is highly uncertain. This analysis assumes an aggressive growth that is similar to assumptions in NRC 2008c

¹⁴ An increasing amount of PHEV all-electric range (AER) over time was assumed as batteries improve: 10 miles in 2020; 50 miles in 2050

Literature Review

A large number of references were identified with direct relevance to this analysis.¹⁵ 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.¹⁶

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.¹⁷ 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.

¹⁵ The appendix includes a full list of the references reviewed for the analysis

¹⁶ These included the California Energy Commission's AB 118 investment report [CEC 2009], MIT 2008, McKinsey, IEA 2008a, UC Davis 2009, and NRC 2008c.

¹⁷ 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.

This report and modeling exercise

The content of the report is organized to provide a relatively high-level perspective on the analysis and the conclusions. The following sections will provide additional details on how major assumptions were developed, why scenario concepts were chosen as they were, and expanded results of the analysis. The final section revisits the key conclusions and highlights which assumptions carry the most risk, due to either technical, market, or stakeholder coordination challenges. An appendix is included that provides a list of references used for the analysis.

This analysis is the first phase of the scenario modeling for the ZEV Regulation.¹⁸ A second phase of modeling will continue through the spring of 2010 taking into account stakeholder input and refined modeling techniques and assumptions. This will support the ZEV Regulation proposal in a staff report in late 2010.

¹⁸ By conducting this analysis within ARB, a better understanding was gained of the tradeoffs and limitations of specific assumptions. Collaboration and/or detailed discussions have been established with other organizations conducting similar analysis, including the CEC, the U.S. DOE, U.S. EPA and UC Davis.

2. Scenario Development

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.¹⁹ Staff made changes to the model to simulate a California passenger vehicle fleet and energy system. This section outlines the primary input assumptions for the model along with how the varying advanced vehicle scenarios were chosen.

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.

In developing the scenarios for this analysis, assumptions were identified based on extensive review of the literature and stakeholder discussion. The majority of assumptions in this analysis are fixed for all the scenarios for consistency. The factors that vary between scenarios are vehicle sales projections, the vehicle technology mix in the market, biofuel supply levels, and VMT per vehicle reductions.

Achieving an 80% reduction in the transportation sector will require a broad mix of solutions. This includes reduced vehicle miles traveled (VMT) per capita, 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 lessen the risk of technology or market failures.

Vehicle sales and fleet turn-over

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 2040.²⁰ Trends were extrapolated to 2050 to complete the dataset for this model. The fleet turnover rates are based on the national trends in the U.S. DOE's Vision model, the tool used for this analysis.¹⁹ Fleet turn-over rates determine how many vehicles remain on the road in any given year, and account for vehicle

¹⁹ U.S. DOE Vision Model 2008, http://www.transportation.anl.gov/modeling_simulation/VISION/. Refer to Appendix A for background information.

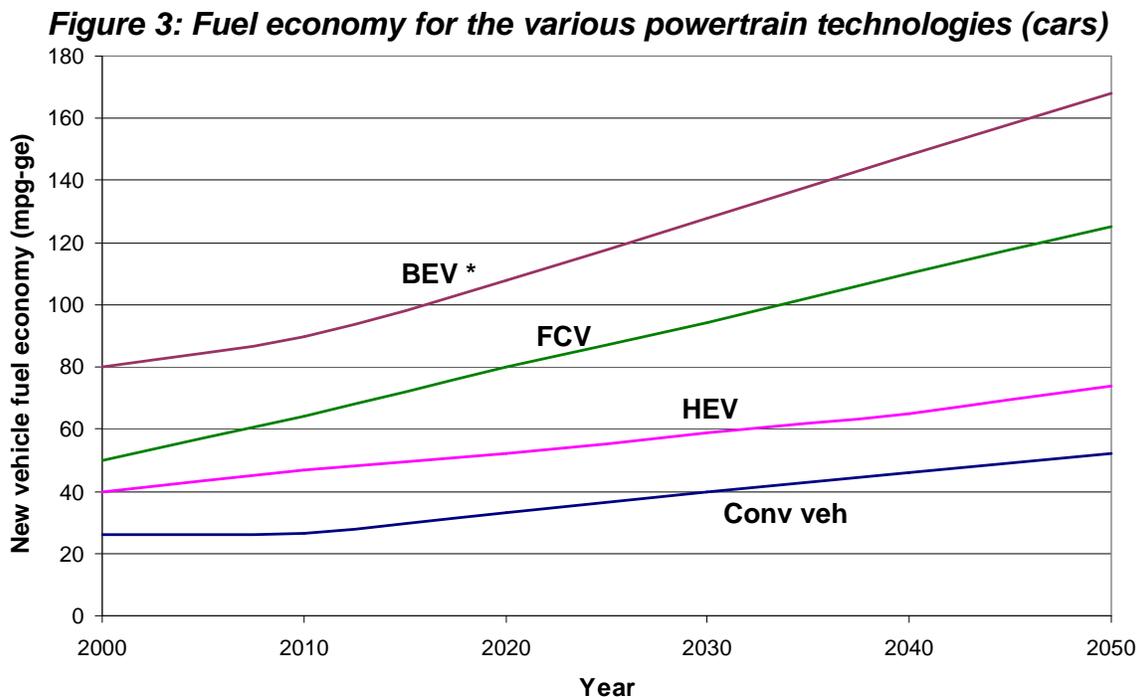
²⁰ ARB EMFAC 2007, http://www.arb.ca.gov/msei/onroad/latest_version.htm

age, scrapage rates, declining VMT per vehicle based on age, etc. The dataset assumes roughly 22 million vehicles are on the road in 2000, increasing to 40 million vehicles in 2050.²¹ Annual sales rates start from roughly 1.5 million vehicles sold per year in 2000 and grow to 2.7 million in 2050. Additionally, the analysis assumed a sales mix of cars and trucks shifted to a 70%/30% respectively by 2050.

These assumptions will be carefully reviewed in the next phase of the modeling analysis, including a review of whether California’s fleet turnover rates are different than the national average. 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 vehicles²².

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.



* Includes AC to DC energy loss from grid battery charging

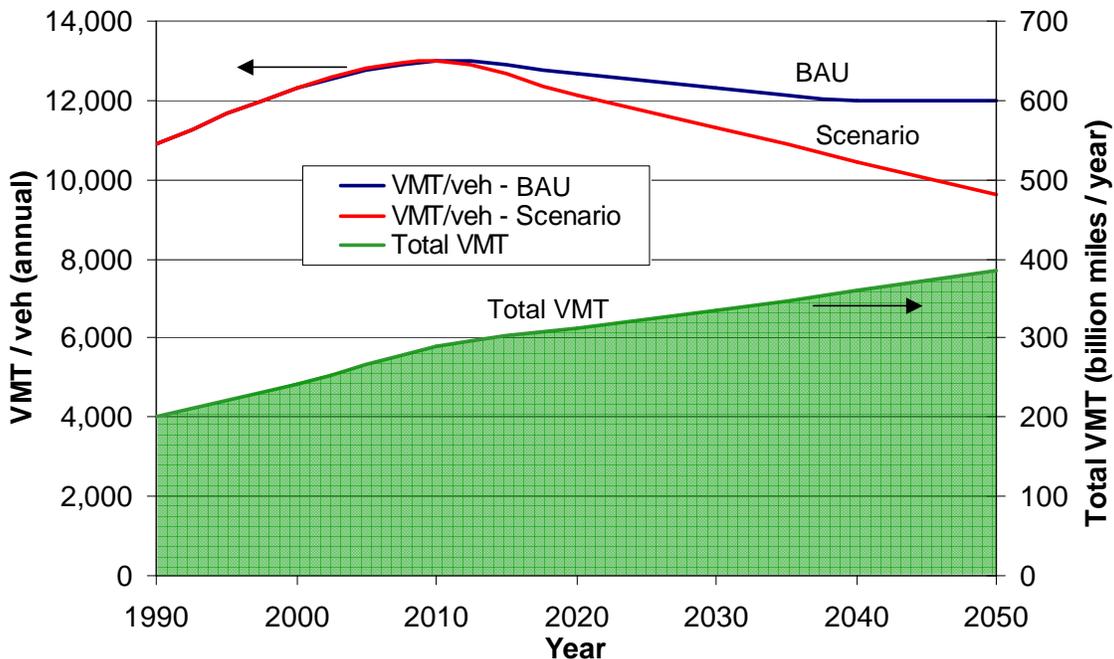
²¹ The vehicle population numbers are derived using both the vehicle sales projections from ARB’s EMFAC model, and the national fleet turn-over rates used in the Vision model.

²² IEA 2008a, MIT 2008, Pew, NRC 2008c.

Figure 3 above 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 BEV fuel economy assumes an energy loss associated with the AC-DC battery charging. Also 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.²³ 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 (20% reduction). Figure 4 shows the scenario trends for VMT. Total VMT increases as State population grows.²⁴

Figure 4: VMT Trends in Scenarios 1 & 2



²³ The scenarios all assume an increasing amount of all electric range for PHEVs over time.

²⁴ As noted above, DOF estimates California's population will grow to nearly 60 million people by 2050.

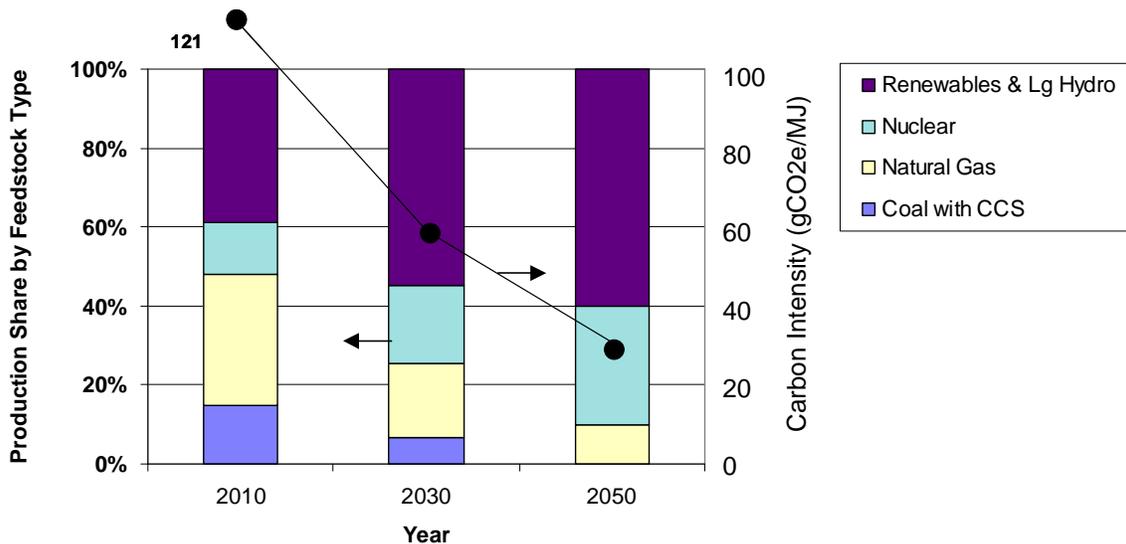
Electricity and fuels carbon intensity

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 were assumed to be relevant out to 2050.²⁵ 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. All of the fuels assume an extremely aggressive change over time that results in significant reductions in average fuel carbon intensity. 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.

In deriving the carbon intensity, the fuel production assumptions, which included changing feedstock mix over time, were developed by reviewing external sources and engaging stakeholders. However, the choice of fuel feedstocks was limited to the existing set of options in U.S. DOE's Vision model. This is an area of improvement in a later modeling effort, and will more fully incorporate California specific feedstocks expected from the energy industry.

The following three figures (Figures 5, 6, and 7) 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 5 shows the production feedstock and carbon intensity for the electricity sector in California.

Figure 5: Electricity Production Share and Carbon Intensity



²⁵ Low Carbon Fuel Standard Initial Statement of Reasons (ISOR) report, March 5, 2009 [ARB].

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 hydro-electricity, 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 6 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.²⁶ 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 6: Hydrogen Production Share and Carbon Intensity

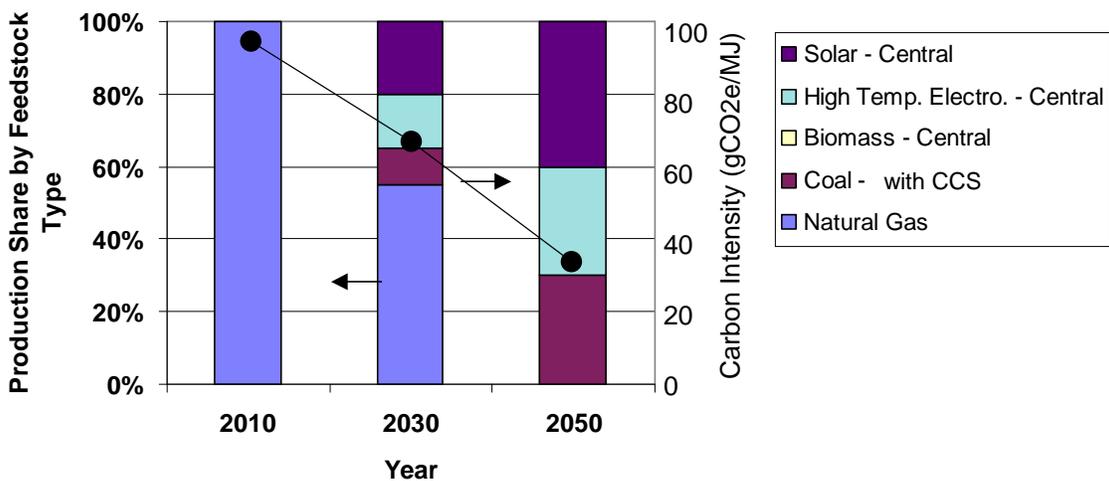
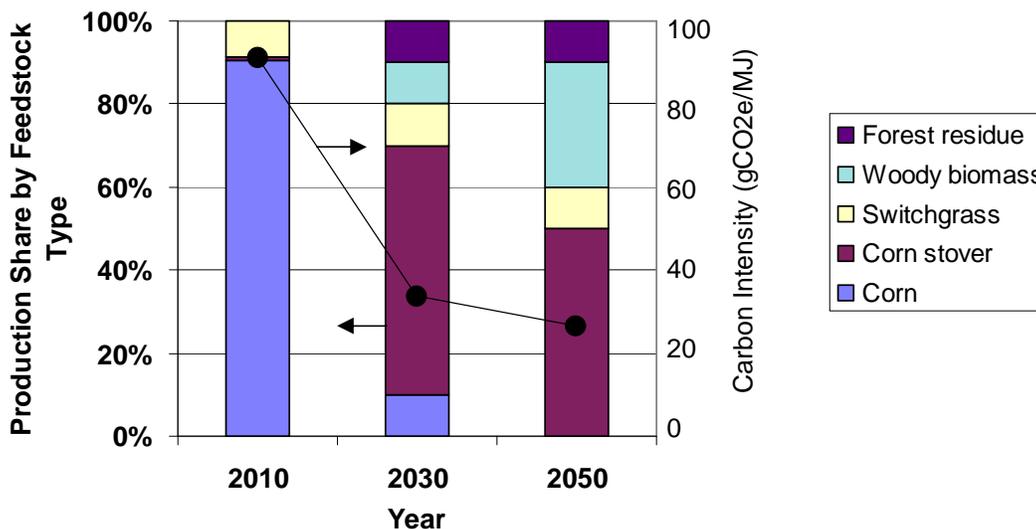


Figure 7 shows the carbon intensity and production feedstocks for biofuels. This analysis assumes ethanol will continue to be blended into gasoline in blends up to 10% (E10) through 2020. However, soon after that time, the analysis assumes a new biofuel chemistry will be commercialized, a "bio hydrocarbon fuel" that is more

²⁶ 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.

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.

Figure 7: Bio-hydrocarbon Fuel Production Share and Carbon Intensity



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.

An important bounding parameter in the scenario was the projected biomass availability in 2050.²⁷ 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 assessments²⁸, as shown in Figure 8, an upper limit of 1 billion gallons of gasoline equivalent (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.

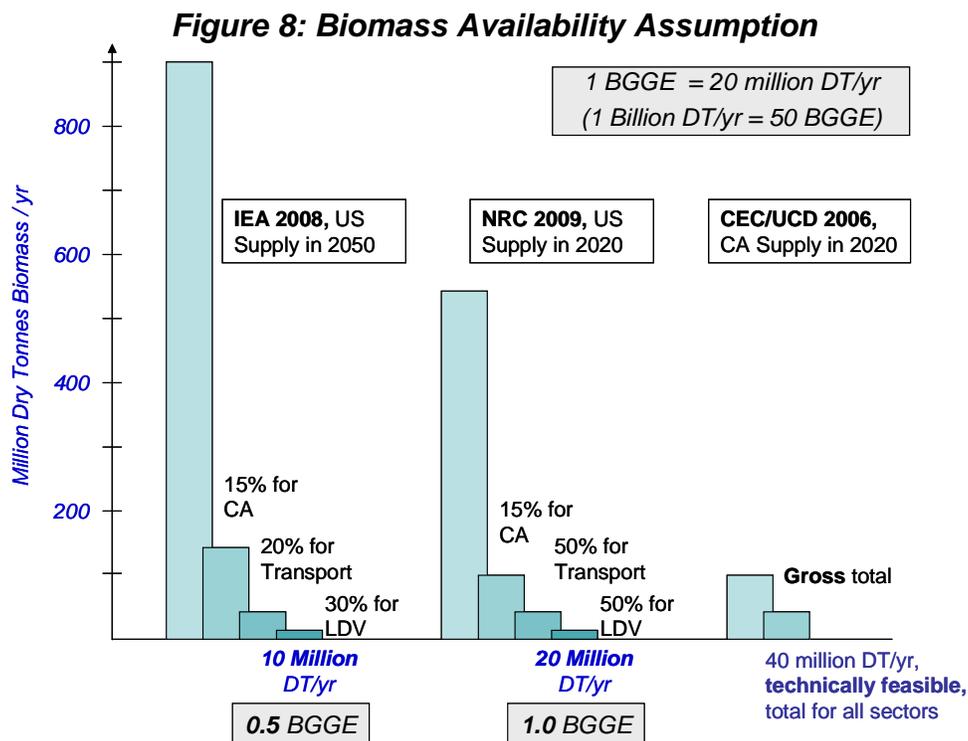
²⁷ This biofuel limitation does not reflect any assumption from other ARB policies, such as the LCFS, it is simply a hypothetical value used for this analysis

²⁸ IEA 2008a, UC Davis 2008b, U.S. DOE 2005, IEA 2005, CEC 2006, CEC 2008, NRC 2009.

Specifically, Figure 8 compares biomass resource assessments from three sources²⁹. The bar chart, showing units of million dry tonnes of biomass per year, 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 CEC reference shows biomass 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 8 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 16 later in the report.



²⁹ IEA 2008a, NRC 2009, and CEC 2006.

Advanced vehicle scenarios

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 trajectories³⁰ 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.

In addition to the vehicle sales projections, the use of biofuels was varied between scenarios. This was done by changing the fraction of biofuels blended into gasoline and diesel. Through 2020, a maximum of 10% ethanol in gasoline (E10) was assumed 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 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 pipelines³¹.

Among the various scenarios developed for this analysis, two will be featured in this report. Scenario 1 achieves a 66% GHG reduction, and represents a case where all major assumptions are aggressive compared to the business as usual. Scenario 2 achieves the full 80% GHG goal by pushing two key assumptions even further: ZEV sales projections, and the amount of biofuels used. Scenario 2 was developed to show it may be possible to achieve the 80% target, but will be extremely difficult. Both scenarios include all advanced vehicle technologies: FCVs, BEVs, and PHEVs, each with aggressive market growth assumptions.

The following key trends are captured in Scenarios 1 and 2. Figures 9 and 10 show the assumed sales projections for the major vehicle technologies in the automobile (car) segment, and Figure 11 shows the sales projections for the light-truck segment for Scenario 1.

- 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.
- Scenario 1 assumes PHEV sales take off faster and decline long-term when FCVs + BEVs (ZEVs) reach high volumes. It also assumes BEV sales take off faster than FCVs initially, but reach a saturation limit (30% of sales market by

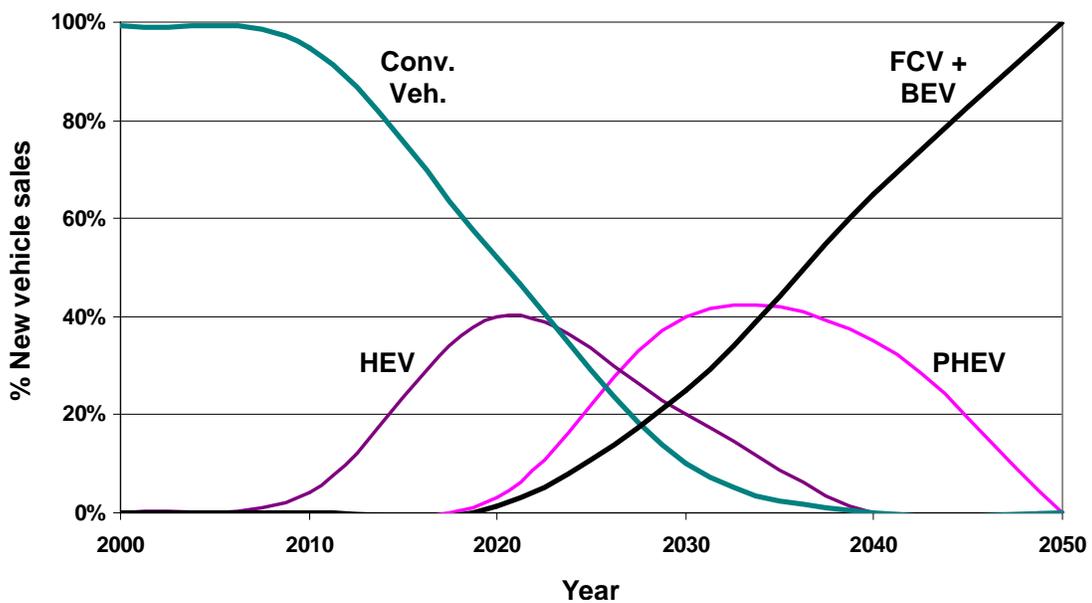
³⁰ IEA 2008, McKinsey, MIT 2008, NRC 2008c

³¹ Ethanol is currently shipped separately by rail car and blended in gasoline close to regional markets. This creates additional infrastructure requirements and higher transport costs.

2050); FCVs take off last but become the dominant low-carbon alternative by 2050 in Scenario 1. The shape of the sales projections was partially derived by reviewing the literature²⁹.

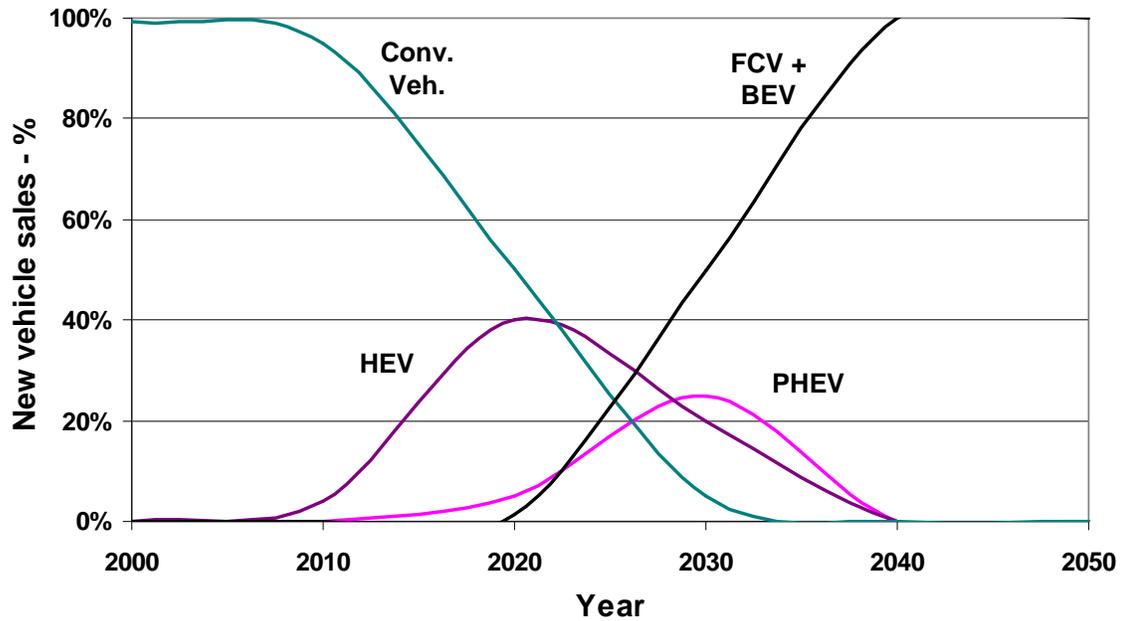
- A progression of battery technology improvements was assumed. For PHEVs, the amount of all-electric range (AER) that the batteries can support grows over time from 10 miles (2020) to 50 miles (2050). For BEVs, it is assumed range increases and infrastructure grows to justify market shares projected.
- Figure 11 shows sales trends for the truck segment. Although trends are similar, there is less reliance on BEVs in trucks and more reliance on PHEVs and diesel HEVs all the way to 2050.

Figure 9: New vehicle sales, Passenger Vehicle (cars) segment * - Scenario 1



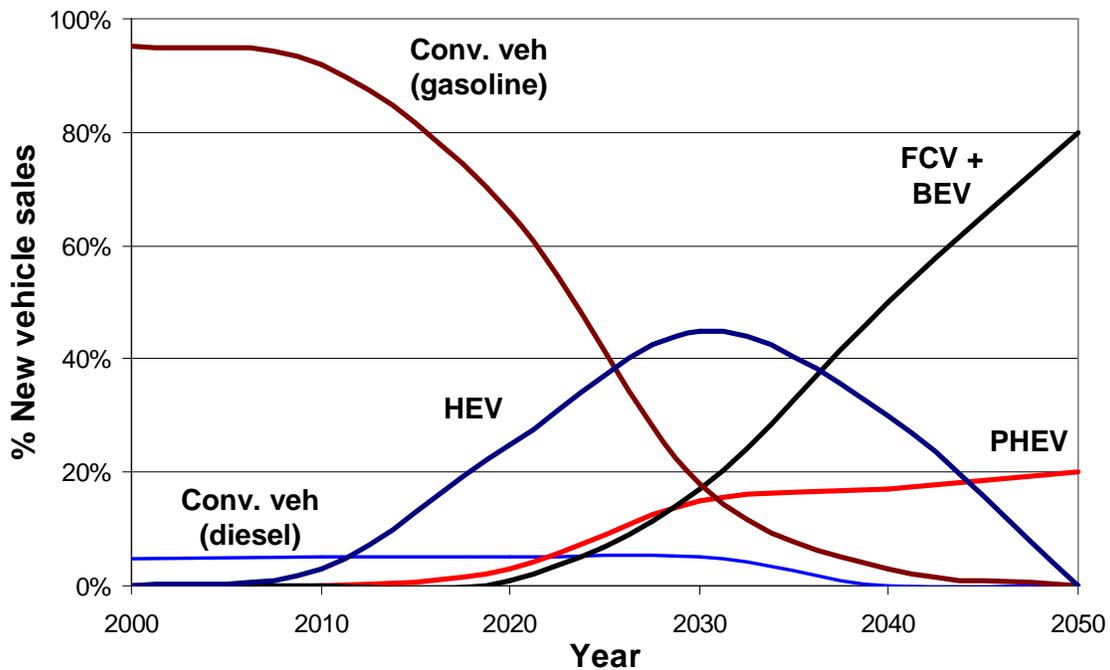
* Note: BEV = 30% of "FCV+BEV" in 2050

Figure 10: New vehicle sales, Passenger Vehicle (cars) segment * - Scenario 2



* Note: BEV = 30% of "FCV+BEV" in 2040

Figure 11: New vehicle sales, Passenger Vehicle (truck) segment * - Scenario 1



* Note: BEV = 10% of "FCV+BEV" in 2050; HEV includes both gasoline and diesel hybrids.

Sidebar: General Technology Tradeoffs

(Discussed further in the Technical Support Document)

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

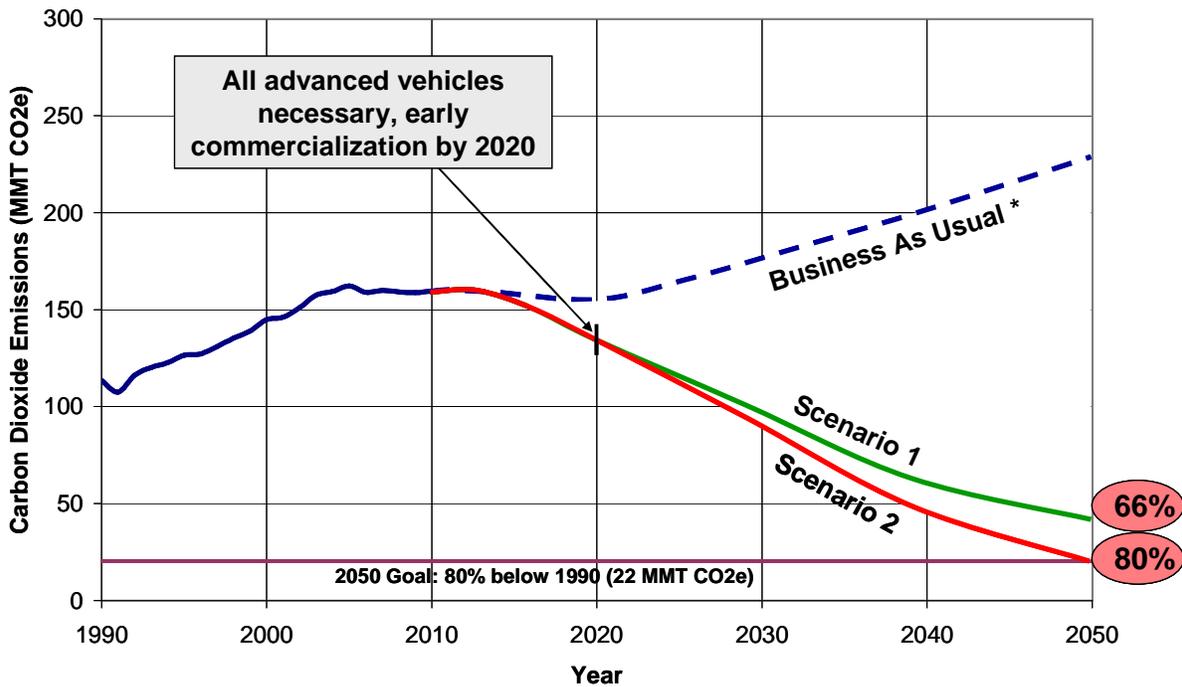
Plug-in Hybrid Electric Vehicles (PHEVs)

- (Pros) Long range, fuel flexibility and convenience, wide range of vehicle sizes, straight forward 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

3. Results

This section provides a more detailed summary of the analysis results. Figures 12 and 13 show the difference in total GHG reductions between Scenario 1 and two variations on ZEV sales projections. Although these secondary ZEV sales scenarios achieve higher GHG reductions, their success is more uncertain. Two of the ZEV projections in Figure 13 correspond to the GHG scenarios in Figure 12. Refer to Figure 2 for a description of the “business as usual” emission projections shown in Figure 12.

Figure 12: GHG Emissions for Three ZEV Sales Scenarios

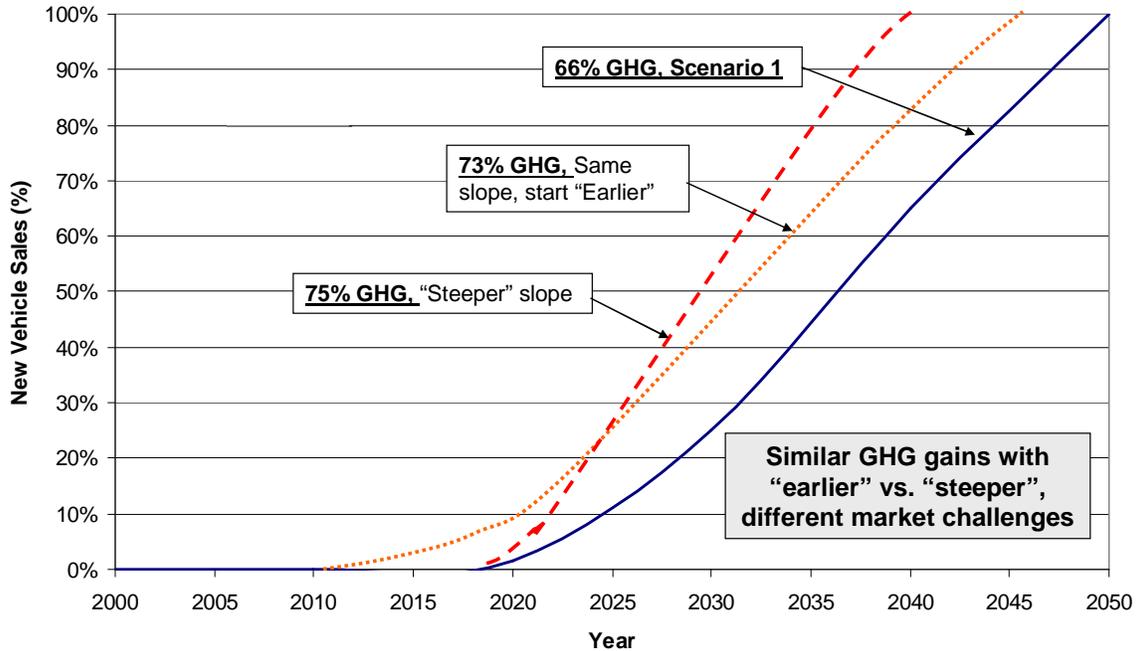


Scenario 1: 100% ZEV sales by 2050, 1 billion gallons gasoline equiv (BGGE) biofuels
 Scenario 2: 100% ZEV sales by 2040, and more biofuels (1.7 BGGE)

* Hypothetical BAU for this analysis only, does not represent ARB projections. Assumes Pavley 1 and LCFS are implemented.

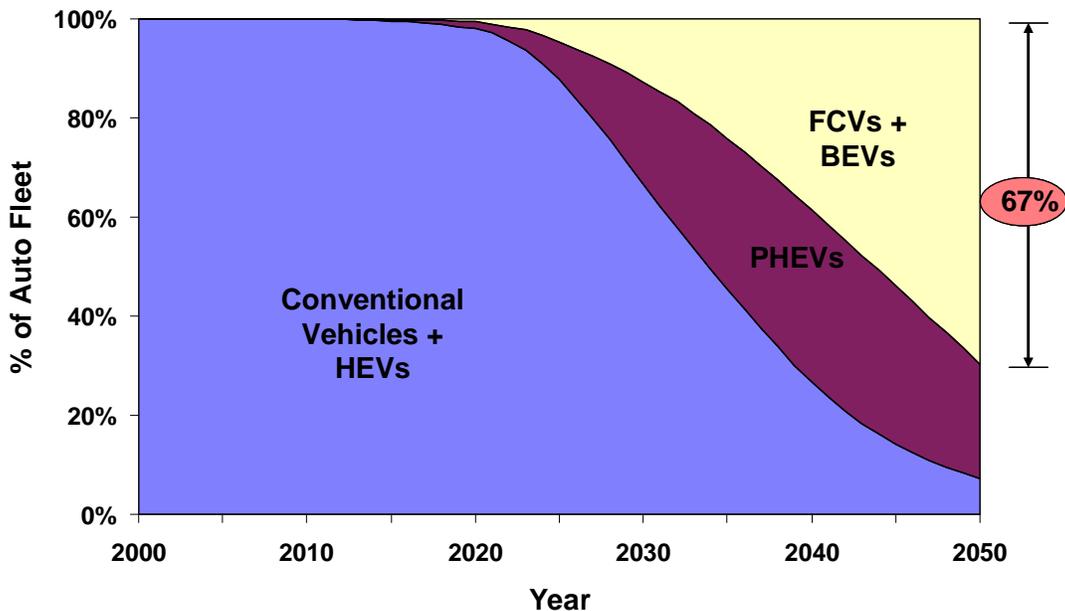
Figures 12 and 13 show that by increasing the 2020 ZEV annual sales six-fold (25,000 vs. 150,000), 2050 GHG reductions improve from 66% to 73%. This is achieved by starting ZEV sales earlier but maintaining the same long-term sales slope as in Scenario 1. The scenario that achieves 75% assumes ZEV sales 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 projections along with a larger amount of biofuels (1.7 BGGE vs. 1 BGGE), results in Scenario 2 in Figure 12.

Figure 13: ZEV Sales Scenarios



As shown in Figure 12 above, Scenario 1 achieves a 66% reduction in GHG emissions from the 1990 level, missing the 2050 policy goal of 80%. 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. Figures 14 and 15 show the cumulative on-road vehicle mix for Scenarios 1 & 2.

Figure 14: On-Road Fleet, Passenger Vehicle (cars) Segment – Scenario 1 ³²



³² The truck segment relies less on ZEVs. The combined passenger vehicle sector has a resulting 61% ZEV on-road penetration in 2050. For reference, the 2000 California vehicle population is 22 million, and increases to 40 million in 2050.

Figure 15: On-Road Fleet, Passenger Vehicle (cars) Segment – Scenario 2 ³³

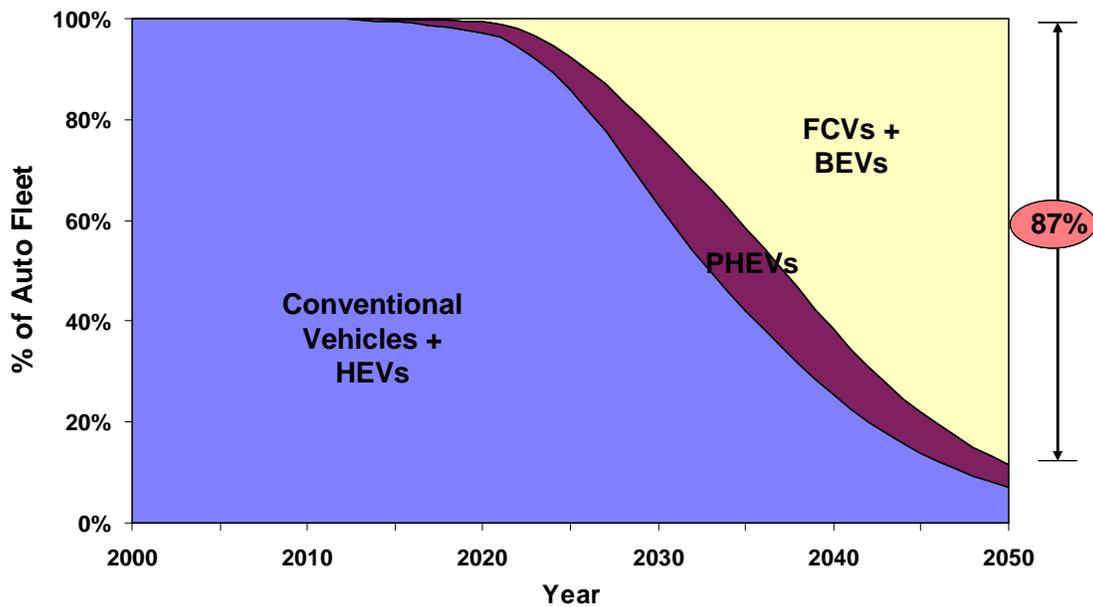
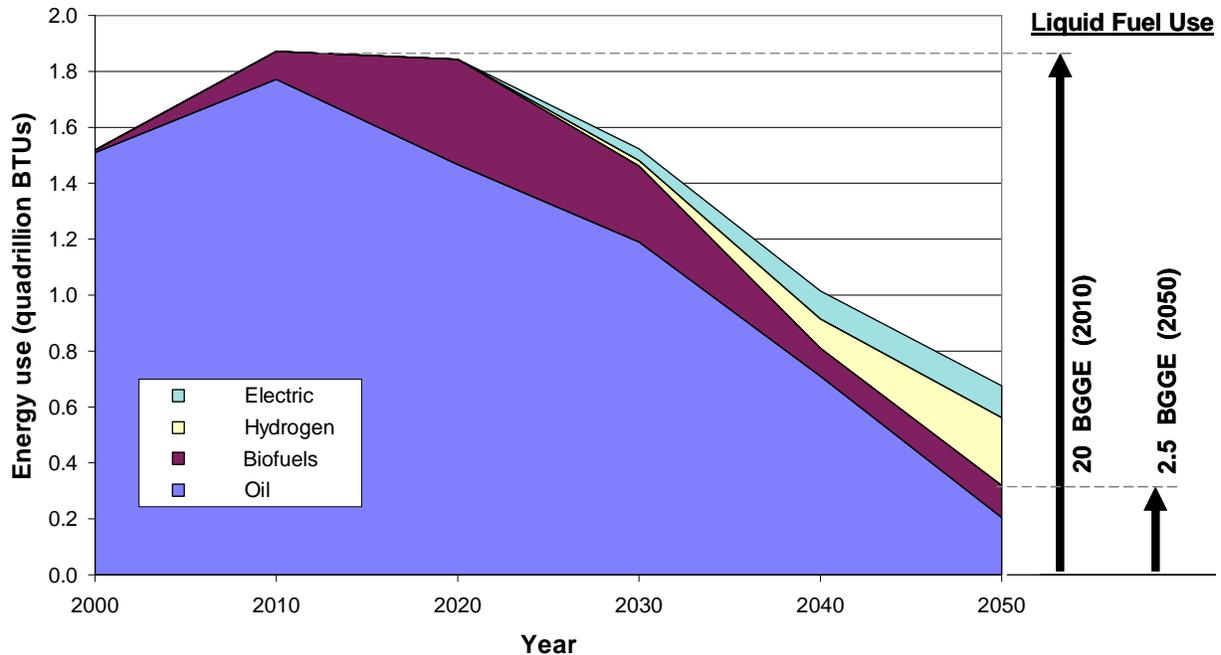


Figure 16 below shows the total energy usage by fuel type over the course of the scenario timeframes. A similar trend is revealed compared to Figure 14, where electricity and hydrogen are a minor part of energy consumption up through 2020, but expand quickly over the next three decades. A further trend to note is that of biofuels. Figure 16 shows that biofuel levels expand through 2030 and then somewhat decline by 2050. This trend is expected as the fuels industry aggressively moves to 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 16. 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).

Figure 16: Total energy usage of various scenarios



Sensitivity analysis – Scenario Variations

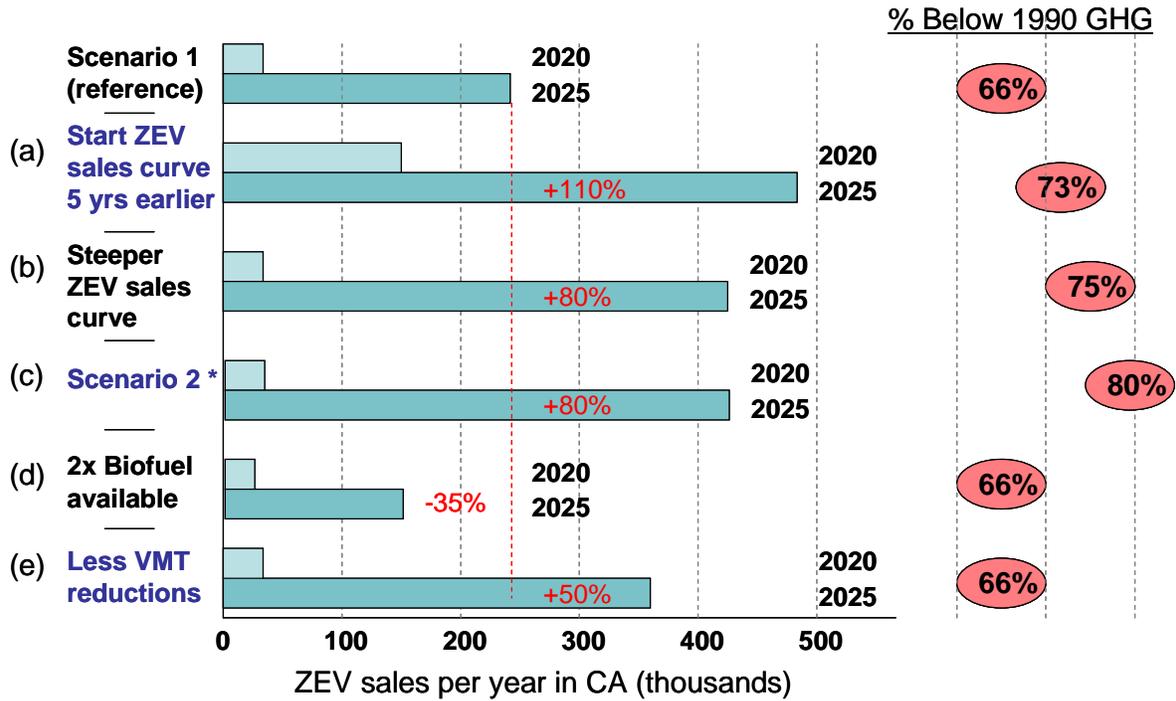
The following scenario variations were all created starting from, and are referenced to, Scenario 1. The results from Scenario 1 can be summarized relative to the policy questions at the beginning of this report. Figure 17 below shows the resulting 2020 & 2025 ZEV annual sales, along with the 2050 GHG reduction levels, for each case.

- (a) If the solid ZEV sales curve³³ to 2050, shown in Figure 13 (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

³³ 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.

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 level as Scenario 1 (50% increase in ZEV sales in 2025 compared to Scenario 1).

Figure 17: 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)

4. Conclusions - Critical Factors Necessary for Success

This 2050 GHG modeling analysis has addressed two policy questions as they relate to California's 2050 GHG goals in Executive Order S-03-05.³⁴

- (1) What are the cumulative ZEVs necessary by 2050 to help the passenger vehicle sector achieve an 80% GHG reduction, and
- (2) What annual ZEV sales are necessary between 2015 and 2025 to initiate these fleet volumes?

Several scenarios were developed to evaluate the passenger vehicle sector GHG emissions to 2050, and included detailed assumptions of vehicle sales of various technologies, fuel and electrical grid carbon intensity reductions, large VMT per vehicle reductions, and vehicle fuel economy improvements through vehicle platform, vehicle downsizing, and powertrain developments. Scenario 1 in this analysis achieved a 66% reduction in GHG emissions by 2050 using aggressive but plausible assumptions. Additional scenarios were developed with more aggressive, but more uncertain, ZEV sales projections to achieve the full 80% GHG goal. In specifically addressing the policy questions above, the scenarios in this analysis show:

- **Cumulative on-road:**
 - Scenario 1:* 100,000 ZEVs (FCVs + BEVs) in CA by 2020, accelerating to 900,000 ZEVs by 2025.³⁵
 - Scenario 2:* 120,000 ZEVs by 2020, 1.4 million ZEVs by 2025
- **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

Given that these ZEV sales projections are aggressive, it is the staff 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 the Complimentary Policies report included in the full White Paper.

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.

³⁴ 80% reduction in GHG emissions below 1990 levels by 2050.

³⁵ The analysis assumes aggressive sales trajectories between 2010 and 2050. This analysis relied on external studies of how rapid advanced vehicle sales rates could become.

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:

- 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.
- 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 challenge that will need to be addressed, and includes liability rules, and “not in my backyard (NIMBY)” concerns with pipelines and underground locations.
- 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.
- 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.³⁶

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 and fast refueling, but creating the fuel infrastructure is a substantial challenge. PHEVs offer less infrastructure challenges

³⁶ The scenarios in this analysis assume BEVs saturate in the market at 30% of 2050 vehicle sales

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.

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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