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California's Energy Future - Transportation Energy Use in California

California Council on Science and Technology

December 2011

California's Energy Future: Transportation Energy Use in California

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and Roland Hwang

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Message From CCST

CCST is pleased to present the results of an analysis of the potential for reducing fossil energy use in transportation in California. This study is part of the California's Energy Future (CEF) project, a study designed to help inform the decisions California state and local governments must make in order to achieve our state's ambitious goals of significantly reducing total greenhouse gas emissions over the next four decades.

California's Global Warming Solutions Act of 2006 (AB32) and Executive Order S-3-05 set strict standards for the state to meet. In order to comply, California needs to reduce its greenhouse gas emissions to 80% below 1990 levels by 2050 while accommodating projected growth in its economy and population. This will require that we use as little fossil fuel in transportation as possible. This study shows how a combination of electrification and increase in vehicle efficiency could significantly lower emissions from this sector.

We find that total transportation energy demand could be reduced 30% relative to 2005 levels in 2050 through improving overall vehicle efficiency and the use of advanced electric- drivetrains such as plug-in electric vehicles and fuel cell vehicles. Achieving high fleet penetration of efficient and alternatively fueled light-duty vehicles by 2050 will require rapid market adoption in the next decades and an expansion of efficiency policies to cover the entire range of transportation sectors, including aviation and marine.

We believe that the CEF transportation energy report represents valuable insights into the possibilities and realities of meeting California's transportation energy needs and emissions standards over the decades to come, and hope that you will find it useful.



Jane C.S. Long
California's Energy Future Committee
Co-chair



Miriam John
California's Energy Future Committee
Co-chair

I. Introduction and Executive Summary

The focus of this report is on the transportation technologies that can be used to reduce fuel usage. Even though reducing greenhouse gas emissions is the ultimate goal, the structure of the California Energy Futures project was to separate the demand for energy from the supply. Vehicle efficiency is a demand side option while developing low carbon electricity and fuels is a supply side option and each of these is considered separately (there are reports of the availability of biofuels and low-carbon electricity).

This report is a supplement to the Summary Report for the California Energy Futures (CCST 2011) and examines the contribution of the transportation sector to California's total energy demand along with the potential for technologies in different transportation sectors to reduce fuel demand in the year 2050.

If greenhouse gas (GHG) emissions are to be reduced substantially, by as much as 80% by 2050, transportation must play a large role, given that it makes up approximately 40% of greenhouse gas emissions in California. The transportation sector includes light-duty vehicles (passenger cars and light duty trucks), heavy duty trucks, buses, aviation, rail, marine, agriculture and off-road vehicles. The three primary means of reducing transportation emissions are reducing travel demand, reducing energy intensity and reducing carbon intensity. The equations below describes four primary parameters to reduce emissions, although controlling population is not a policy mechanism that is considered in this analysis (Yang 2009).

$$CO_{2,Transport} \equiv (Population)\left(\frac{Transport}{Person}\left[\frac{miles}{person}\right]\right)\left(\frac{Energy}{Transport}\left[\frac{MJ}{mile}\right]\right)\left(\frac{Carbon}{Energy}\left[\frac{gCO_2}{MJ}\right]\right)$$

$$CO_{2,Transport} \equiv (Population)\left(\frac{Transport}{Intensity}\right)\left(\frac{Energy}{Intensity}\right)\left(\frac{Carbon}{Intensity}\right)$$

In order to achieve the very deep reductions in emissions necessary to meet the target, advanced technologies will need to be employed both for making vehicles more efficient and for producing low-carbon fuels. The benefit of using of these advanced technologies is, of course, dependent upon the level of adoption of these technologies and the associated reduction in energy use and carbon intensity.

We forecast that total transportation travel demand will continue to grow through 2050 because of population growth and increasing demand per capita, which follows historical trends. This growth will need to be counteracted by significant increases in efficiency, electrification (including hydrogen) of vehicles and use of low-carbon fuels and electricity. The business-as-usual (BAU) scenario in this analysis projects that transportation fuel demand for 2050 will be approximately 43 billion gallons of gasoline equivalent (gge), compared with 2005 values of around 27 billion gge. Both the BAU and the median cases discussed in the summary report assume that the population increases 50% between 2005 and 2050 and per capita light-duty VMT increases by 33% (based upon Caltrans 2008). Implementation of technologies to significantly improve efficiency and deploy electrified transport could lead to transportation fuel demands in 2050 of approximately 17 billion gge, much of which is electricity, hydrogen and biofuels. Reductions in travel demand that occur because of changing development and demographic patterns as well as via policies such as SB 375 could

result in even further reductions in fuel use and make the GHG reduction targets easier to achieve. (Travel demand reductions are not included in the two technical scenarios, but are discussed in the behavior change scenario.)

Key Finding of the California's Energy Future Summary Report for Transportation

One of the key findings in the California's Energy Future Summary Report is that California will likely have limited availability of low-carbon biofuels for use in the transportation sector, because of biomass availability and competing uses for biomass for heat and power (CCST 2011). Given the median biofuels forecast of 13 billion gallons of gasoline equivalent (GGE) in 2050, it is necessary to place a high priority on electrification of the transportation sector, if large reductions are to be attained by 2050. In our scenarios, transportation subsectors were shifted to electrified (plug-in electric vehicles (PEVs) and fuel cell vehicles (FCVs)) vehicles as much as deemed realistic. And the remaining non-electrified transport was made as efficient as possible to reduce the amount of liquid fuels needed. This leads to scenarios where light duty vehicles are largely electrified, while aviation, marine and heavy duty continue to rely on liquids fuels.

Unlike biofuels, there do not appear to be the same supply constraints for low-carbon electricity and hydrogen. Without enough biofuels to meet all liquid fuel demand, petroleum fuels must be used in sectors that have not electrified. Thus, petroleum fuel is the "marginal" liquid fuel in this analysis and any option that reduces liquid fuel usage (i.e. efficiency, travel demand reduction or electrification) would reduce the usage of petroleum fuels.

The main conclusions from this analysis are as follows:

- Without policy intervention, total travel demand in every transportation subsector is expected to increase between 50 and 100% from 2005 to 2050 due to population growth and increasing travel demand per capita, with the most growth occurring in light-duty, heavy-duty and aviation sectors (Caltrans 2008, AEO 2011).
- Total transportation energy demand could be reduced 30% relative to 2005 levels in 2050 through improving overall vehicle efficiency (which includes the use of advanced electric-drivetrains such as plug-in electric vehicles (PEVs) and hydrogen fuel cell vehicles (FCVs). Additional reductions in energy use would accrue if options to control travel demand were also included.
- Improving efficiency with conventional combustion and hybrid technologies is the easiest and most cost-effective method for reducing fuel usage from the transportation sector, but this approach is not enough by itself to achieve 80% reductions in GHG emissions if petroleum fuels continue to be used.
- Electrification of vehicles using Plug-in Electric Vehicles (PEVs) or Hydrogen Fuel Cell Vehicles (FCVs) can further improve efficiency of light-duty vehicles (LDVs) while also lessening the reliance on liquid fuels and allowing for use of very low carbon sources for electricity or hydrogen.
- From a technology standpoint, PEVs and FCVs are commercially available (Bin 1) or demonstration phase (Bin 2) technologies[1] though key component costs (batteries, fuel cells and H_2 storage) are currently high and would need to be reduced by a factor of 2 or more for widespread adoption.

1 See main report (CCST 2011) for more detailed description of technology readiness bins.

- Achieving high fleet penetration of efficient and alternatively fueled light-duty vehicles by 2050 will require rapid market adoption in the next few decades.
- High initial costs, consumer unfamiliarity with advanced technologies, and limited availability of those technologies across vehicle makes and models will slow the market expansion of advanced light-duty vehicles. The relatively slow penetration of hybrid vehicles into the market since 2000 is suggestive of the challenges facing PEV and FCV adoption; arguably electric drive vehicles could face even more difficult barriers.
- Because less than 50% of car owners have access to dedicated, off-street parking at home (for charging), and because battery costs will be high for larger vehicle sizes, universal PEVs adoption appears unlikely.
- Hydrogen fuel cell vehicles (FCVs) will offer a range of approximately 300 miles and a 5 minute refueling time, potentially avoiding the PEV limitations. This should make them potentially attractive for larger vehicles (light trucks and SUVs) and those without access to dedicated, off-street parking. FCVs are a useful complement to battery electric vehicles (BEVs), which have a more limited range and long refueling times.
- Even with substantial conversion of light-duty and some other sectors to electricity and hydrogen, liquid fuel demand will remain strong, likely exceeding the availability of sustainable, low-carbon biofuel supplies and thereby necessitating some continued use of petroleum-based fuels.
- Aviation, marine and heavy-duty trucks, are likely to continue to use liquid hydrocarbon fuels (from petroleum or biofuels) because of fuel energy density requirements.
- A policy framework targeting efficiency and low-carbon fuels exists to bring about GHG reductions in the light-duty and heavy-duty sectors, but may need to be expanded to other transportation subsectors as well, such as aviation and marine.

The light-duty sector is the largest contributor to transportation fuel use (~50%) and emissions. Consequently, much of the report will focus on this subsector.

The purpose of this report is to understand the extent to which each transportation technology could be used to help meet the 80% emissions reduction target. This report focuses on end-use demands in the transportation sector (i.e. which vehicle technologies will be used to meet demand for mobility), rather than transportation fuel supply (how those fuels are produced). The report will attempt to answer a primary question as to whether various types of higher efficiency technologies could meet an 80% reduction in fuel use in and of themselves (stress test), and then if not, an important secondary follow up is to determine the potential reduction in fuel demand that could be achieved with the technology (realistic case). The supply of low carbon fuels and electricity, which are needed to meet the demand for transportation fuel, are discussed in the summary report and supplemental reports (CCST 2011a, CCST 2011b, others).

The report first discusses growth in travel demand and the challenges for widespread adoption of advanced vehicle technologies in the light-duty sector. It then discusses specific light-duty vehicle technologies, including conventional and hybrid vehicles, plug-in electric vehicles and fuel cell vehicles in the light-duty sector, their potential for reducing fuel demand and any challenges they may face in widespread deployment. Two realistic scenarios are also developed based upon PEVs and FCVs. Finally, an assessment is provided of two other important transportation subsectors, heavy-duty trucks and aviation, and the potential for reductions in fuel use is provided.

II. Travel and Service Demand

Travel Demand Projections

Table 1 shows the assumptions for travel demand that are used in the transportation scenarios described here and referenced in the main summary report. The assumptions are that the largest growth in travel demand will occur in the light-duty, heavy-duty truck, and aviation sectors. The scenarios assume travel demand growth equivalent to population growth demand (i.e. constant miles per capita) for bus, rail and marine travel. Since this analysis is primarily a technical analysis of the potential for efficiency and electrification within the transportation sector, options and measures that could reduce travel demand are not included in the primary scenarios (including business as usual and the median scenarios). These measures are discussed in the next section and are included in the behavior change option, which is discussed in the Summary Report.

Total travel demand in the light-duty sector is a continuation of historical trends and derived from an extrapolation of the latest California Department of Transportation statewide VMT forecast (Caltrans 2009). It projects total statewide light-duty VMT growth of nearly 64% from 2005 to 2030 and 92% from 1990 to 2030. These growth rates are consistent (on a per-capita basis) with the latest U.S. Department of Energy (DOE) projections (AEO 2011).

Category	*2005*	*2050*	*% change*
Population (millions)	36.6	54.8	50%
Light-duty Miles per capita Total miles (billion)	 8,160 298	 10,832 593	 33% 99%
Heavy-duty truck Total miles (billion)	 24	 47	 97%
Passenger Aircraft Miles per capita Total passenger miles (billion)	 5,533 202	 6,444 353	 16% 75%
Bus Total miles (billion)	 19	 29	 50%
Passenger Rail Total passenger miles (billion)	 3.6	 5.4	 50%
Marine Total miles (billion)	 1.6	 2.4	 50%

Table 1. Travel demand assumptions in the business as usual (BAU) and median scenarios (Based upon Caltrans 2008, AEO 2011 but extended to 2050)

Travel Demand Reductions

Decreasing transport intensity, defined as the amount of transport activity per person, is one of the primary ways to reduce GHG emissions. While the BAU VMT scenario described above is a continuation of long-term historical trends, recent data indicates that statewide VMT may be relatively flat (USDOT 2009). It is unclear which trend will continue to 2050. Reductions in VMT from this BAU projection do not require the use of advanced technologies and may not require the application of policies; reductions in vehicle usage and VMT could come about due to changes in land use, demographics, community development patterns and transportation needs.

Reducing aviation and freight miles are also important means of reducing transportation GHG emissions. Each of these options requires behavioral and structural changes in both society and the economy, unlike fuel decarbonization or vehicle efficiency improvements, which rely primarily on technological fixes.

Specific actions to induce reductions in demand for passenger travel include pricing policies such as congestion charges or fuel prices, but since California is highly car dependent, this approach can lead to loss of accessibility and mobility if not managed well. Application of land-use planning and development policies that take this into account could help to mitigate the negative effects by requiring or encouraging mixed land-use developments that strike a balance between jobs, housing, and other services lessen reliance on cars while at the same time maintaining, or improving, access to their desired destinations. The strengthening of pricing and land use policies, and enhancements of efficient, innovative forms of public transportation, (including greater use of information technologies, such as encouraged by SB 375) could have a significant effect on vehicle use. These options also take into account mode-shifting and vehicle pooling, which help reduce VMT demand. Land-use planning is critical to the success of mode-shifting as higher population densities increase the quality (timeliness and convenience) of service. Targets adopted under SB 375 call for reductions in GHGs related to passenger travel (excluding fuel and vehicle technology effects) of 6-8% per capita from 2005 levels by 2020 in major metropolitan areas, and about 15% by 2035. Numerous studies estimate the potential for strong transportation policies affecting growth, development and land use, transit and pricing policies (congestion, parking, fuel taxes, etc) to reduce per capita automobile VMT by 20-50% relative to business as usual forecasts (Ewing 2007, Rodier 2009 and Cowart 2008). The projected increase in population (50%) between 2005 and 2050 and the business as usual growth in VMT per capita (33%) lead to a doubling of light-duty VMT. The aggressive adoption of measures to reduce per capita VMT by 30% relative to BAU (approximately constant VMT per capita from 2005-2050) could still lead to a moderate increase in total light-duty VMT of 40% from 2005 levels. If significant shifts in demographics (i.e. older) and development/settlement patterns (i.e. towards urban centers) that could lower VMT are coupled with these travel reduction policies, it is plausible that total light-duty VMT could match or even decline from 2005 levels.

Another potential mode-shift could occur in California if people switch from using airplanes to rail or bus for long-distance intercity transport between the major population centers in northern California (Sacramento and the Bay Area) and southern California (Los Angeles and San Diego). High-speed rail is one alternative that could play an important role in electrifying long-distance instate transportation. Decisions to shift modes will be based upon a number of tradeoffs, including cost, time, convenience, safety and other factors.

Historically, there has been significant growth in travel demand over the last few decades particularly in aircraft and automobiles. Future trends of improved vehicle efficiency and rising incomes should

reduce the per mile cost of vehicle travel and continue to lower the percentage of disposable income devoted toward fuel costs. For example, at $4/gallon in a 30 mpg vehicle, the marginal cost of 1,000 miles of travel is $133. Even with higher fuel prices in the future, the trend towards much higher efficiency advanced vehicles will reduce the marginal fuel cost per mile and the financial incentive to limit travel demand.

Travel demand in other sectors such as freight rail and trucking, aviation, and marine is also expected to grow. There has not been as much analysis of how travel demand growth in these sectors might be mitigated in California beyond rising fuel prices, but it is expected that in the absence of efforts to slow growth, the demand in these subsectors would increase significantly.

Travel demand reductions are not explicitly included in the technology scenarios. But it is one of the key multiplicative factors for determining transportation emissions. All else equal, a 30% reduction in the growth of VMT per capita will reduce fuel use and emissions in light-duty by 30% relative to the BAU case. Thus, these measures should be an important tool for reducing transportation energy usage and resulting GHG emissions in all transportation subsectors.

III. Challenges for Widespread Adoption of Advanced Vehicles by 2050

Achieving a significant reduction in total greenhouse gas emissions, energy use or other parameter of interest relative to the baseline year relies on two key factors: the reduction in energy use or emissions that a given vehicle can provide and the extent to which the efficient vehicle is adopted into the total fleet. While there exist extremely efficient vehicles which use less fuel, the rate of adoption of these efficient technologies can be a major barrier to meeting targets for energy use and emissions between now and 2050.

California has approximately 26 million light duty vehicles (LDVs, i.e. passenger cars and trucks) on the road. Each year, approximately 1.7 million new vehicles are sold and almost that many are retired. By 2050, sales are expected to be approximately 2.7 million vehicles/year with the fleet of LDVs expected to rise to 40-45 million.

Vehicles have historically had a 15 year average lifespan and vehicle sales are approximately 6-7% of the fleet. As a result, if the historical rate prevails it will take at least two decades for a new car technology to become the dominant percentage of the fleet even if sales growth is very high. However, newer cars tend to be driven more than older cars, so share of VMT for a new technologies can be somewhat higher than their fleet share.

An illustration of the challenge of transitioning to new technologies is illustrated by the recent experience with hybrid electric vehicles (HEVs), such as the Toyota Prius. HEVs had a high rate of growth, with sales growing about 50% annually between 1999 and 2009. However, because HEVs started out with very low sales volumes (thousands to tens of thousands per year), it took them a decade to reach a market share of 5% of new car sales in California (~100,000 vehicles/yr). The size of the hybrid market will likely continue to grow as incremental prices come down and the most recent CAFE targets (likely to be 49.6 mpg for 2025)[2] and gasoline prices drive automakers to produce more fuel efficient vehicles.

Hybrid sales provide a useful benchmark for considering other advanced vehicle options with regard to four key factors:

- *Price*: Hybrids were offered for sale at higher prices relative to a comparable conventional vehicles, but the price differential (several thousand dollars) was not too large and fuel savings and tax credits could make life-cycle costs comparable to conventional vehicles.
- *Sales mix*: Hybrids started out with a very limited set of models (compact sedans) from a few manufacturers (Honda and Toyota) and took several years to proliferate to other body types (SUVs, pickups, larger sedans) and other OEMs (Ford, GM, Nissan, Hyundai, etc.).
- *Performance and convenience*: Hybrids offered performance (range, cargo, acceleration) and refueling convenience that was comparable to a conventional vehicle. In California and other locations, certain hybrids were permitted in high occupancy vehicle (HOV or carpool) lanes, providing greater utility than a conventional vehicle.
- *Perception*: Hybrids were seen as environmentally friendly, advanced technologies (Heffner 2008).

2 Fuel economy values used for CAFE purposes are significantly higher (~20%) than on-road fuel economy and EPA labels.

Studying these factors will also help determine the rate of adoption and also maximum market penetration of advanced vehicle technologies such as plug-in hybrid electric vehicles (PHEVs), fuel cell vehicles (FCVs) and BEVs. It is clear that these vehicles will face similar if not greater challenges than HEVs. For one thing, the price differential for advanced vehicles will be higher than for HEVs (Kromer 2007, Plotkin 2009). Another key difference between hybrids and other advanced vehicles is the fact that fuel cell and plug-in vehicles have additional infrastructure needs (refueling stations or chargers). PEVs will also require drivers to change how they refuel their vehicle, although home-based charging may be more convenient. Taken as a whole, these factors will likely slow the rate of sales growth for these vehicles as well as limiting the potential size of the market for these vehicles.

Based upon these considerations, increasing the rate of adoption of advanced vehicle technologies will likely require reducing the price differential for advanced vehicles, offering a greater number of different makes and models that appeal to a wider cross-section of new car buyers, and offering performance and convenience (including range and refueling) that is equivalent to or better than competing conventional, hybrid and other advanced vehicles. This is, of course, very challenging to accomplish, especially in the early years of a vehicle rollout. Technology mandates such as the Zero Emission Vehicle (ZEV) mandate in California might help pull technologies into the fleet mix. Also, government subsidies (tax credits and rebates) or feebates can also lower the first cost to car buyers. In the longer-term, many studies have indicated that after these advanced vehicles are in the market for some years and the technology is mature, they would compete with conventional gasoline vehicles on a lifecycle cost basis (NRC 2008, NRC 2010, Bandivdekar 2008, Greene 2007), especially in a future with significant carbon constraints.

Vehicles sales for new technologies are often modeled as a logistic or "S"-curve where growth is exponential in nature in the early years and then growth levels off in later years. In the early years, the technology is still maturing, so manufacturers offer it on only a few platforms as they become more familiar with the technology. Thus, sales are initially low because customers only have a limited number of models to choose from. While early adopters are often eager to purchase these vehicles, the majority of consumers may not have heard of or understand the new technology, and might wait until better information is available about safety, reliability and costs. However, because vehicle introductions may involve only thousands or tens of thousands of vehicles per year, the percentage growth of these markets can be high. Over time, sustained sales growth in these vehicle platforms could lead to their becoming dominant in the fleet and eventually growth in sales will have to slow as there are fewer consumers without these vehicles and those that remain may be particularly risk-averse or have some specific reason to avoid the new technology. Eventually, market share growth will level off, at a point which may not be 100% of the market.

In order for these advanced vehicles to have a significant impact on statewide energy use and greenhouse gas emissions, they will need to make up a significant portion of the total fleet. Yet, the length of time it takes to commercialize and introduce these vehicles into the market, the impediments (cost and convenience) to rapid market adoption, and the slow process of fleet turnover all pose significant impediments to achieving high fleet shares (e.g. 80%) by 2050.

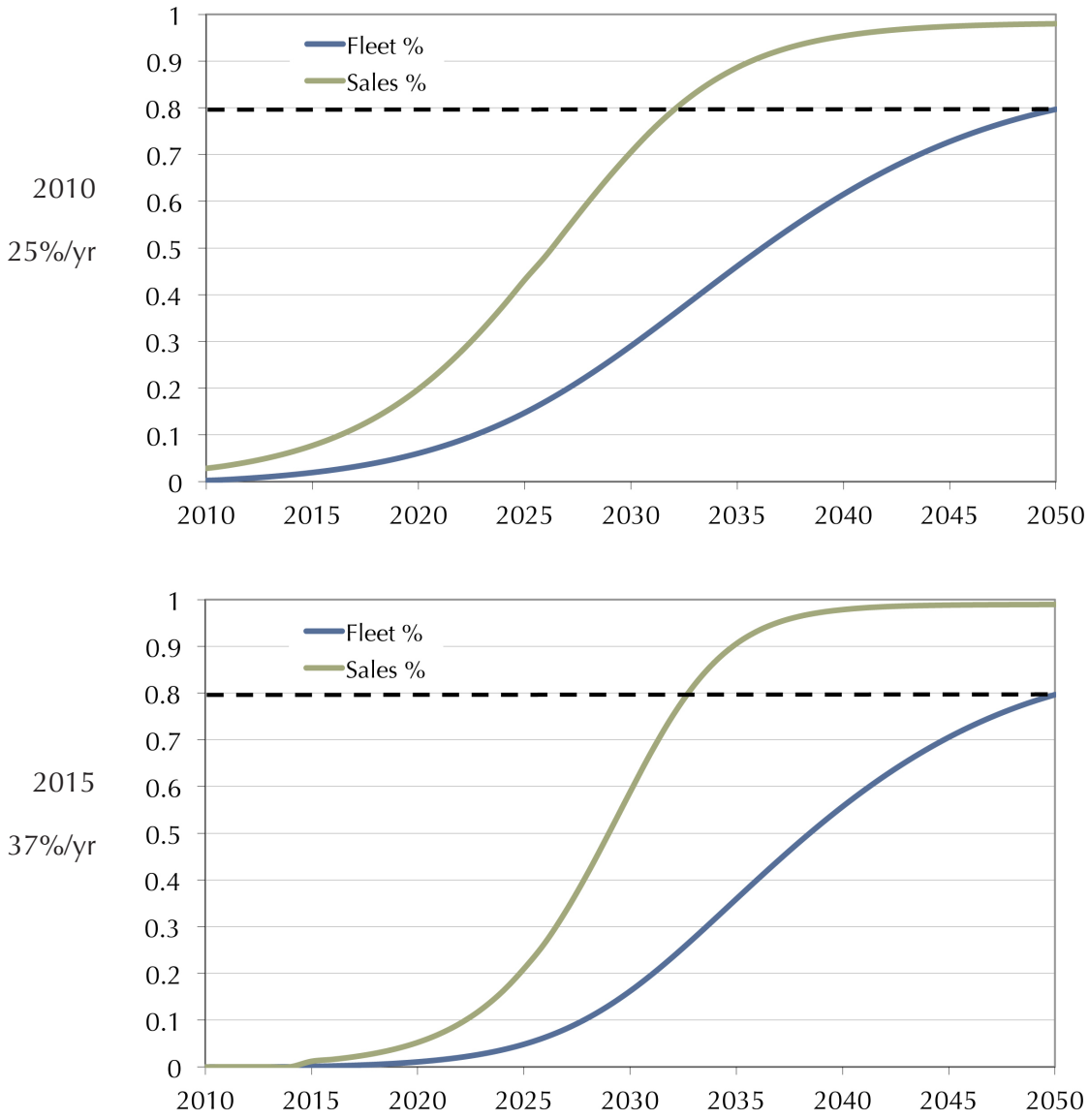


Figure 1. Introduction year and annual sales growth rate for hypothetical advanced vehicle introduction to reach 80% fleet share in 2050

Figure 1 demonstrates the tradeoff between rate of growth and introduction year needed to achieve an 80% fleet share by 2050. This demonstrates that the earlier the introduction of the vehicle, the lower the annual growth rate needs to be in order to achieve the target fleet share. Also important to note is that the curves reach about 50% market (sales) share around 2030 and need to achieve 90+% market share in 2035-2040.

Another important element of time lag in the system is the vehicle product development cycle. It takes approximately five years to develop, test, and manufacture a production car or truck. Figure 2 shows a number of parallel activities that a vehicle maker needs to undertake in order for a vehicle to be launched, including final design of components and powertrain, vehicle integration, supplier, sales and service development (Ogden 2009).

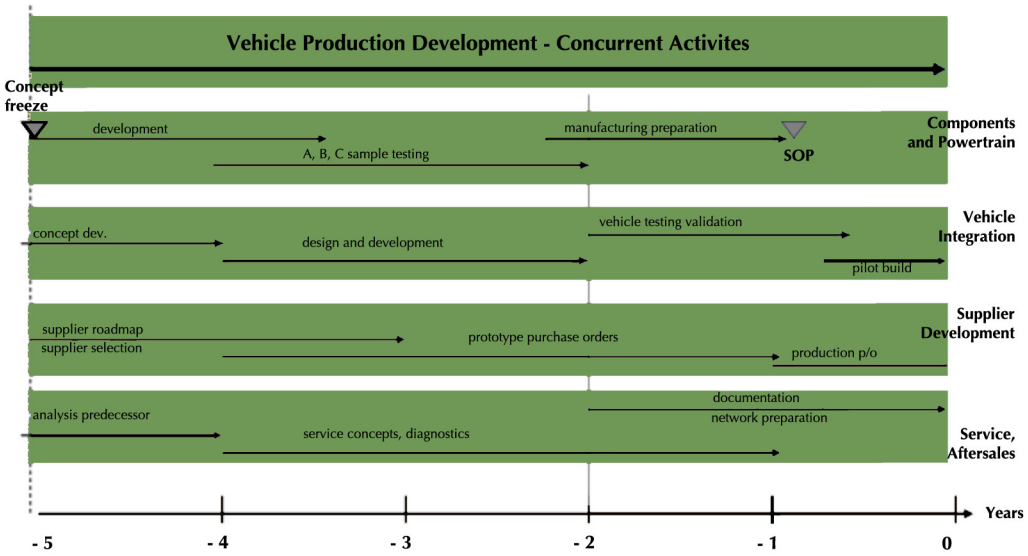


Figure 2. Vehicle production development activities needed to introduce new vehicle model (Ogden 2009)

One of the most important factors for the adoption of advanced technologies is vehicle cost. The purchase price of FCVs, BEVs and PHEVs will depend in part on the manufacturing costs of fuel cells, hydrogen storage, and batteries. Currently the cost of these components is quite high. Bringing the costs of these vehicle components down is a key to making these vehicles affordable and increasing sales once they are commercialized. Several distinct factors can determine the cost of a technology, including system design, manufacturing scale, and materials costs. Over time, costs can be reduced because of a number of key elements: (1) time-dependent technological change, (2) economies of scale, and (3) learning-by-doing (Greene 2007). The first element describes the effects of research and development in both fundamental science and applied engineering related to the design of the technology. The second element refers to cost reductions that derive from manufacturing a product at large scale, and the third element refers to greater efficiencies in the manufacturing process that result from experience, both within the company and across the industry.

Ultimately, to the extent that materials are a critical part of the system design (e.g. platinum in fuel cells, carbon fiber in compressed H_2 storage tanks, and lithium in batteries or neodymium in electric motors), these commodity costs can have a large role in determining the ultimate price for a vehicle component, regardless of how large a production run or how efficient manufacturing can become. While none of these material constraints appear to be show-stoppers (Gruber 2011, Sun 2011), technology and system design breakthroughs that limit the reliance of these components on expensive and rare materials may be needed to bring down the costs of these technologies.

One of the challenges with assessing the likelihood of significant penetration of any advanced technology vehicle is that it depends upon the uncertain status of a number of different policies, external commodity and energy prices, and alternative advanced technologies. Given that some form of low-carbon light-duty vehicle technology is required, the most likely candidates to succeed are biofuel, electricity or hydrogen-powered vehicles (or a combination). All of these options have significant uncertainty with respect to technology attributes and cost trajectory over time. There may be complementary roles for these different technologies to play, as BEVs may be more appropriately used in smaller commuting vehicles, while FCVs and PHEVs are used in longer-range vehicles and

biofuels are used in other transportation sectors where liquid fuels are still required (aviation and heavy-duty) because of weight, range or other key constraints.

All subsequent discussions of fuel economy or electricity consumption (mpg, mpgge, kWh/mi etc) is meant to convey real-world, on-road energy consumption, rather than CAFE or other any other test cycle number.[3] It is also assumed that the historical rate of vehicle retirement will continue into the future (i.e., there will be no policies to accelerate stock turnover and retirement of vehicles).

3 On-road fuel economy is typically around 20-25% lower than CAFE numbers (20% is assumed here).

IV. Conventional Liquid Fueled Vehicles

	Vehicle Energy Intensity *(E)*		Fuel Carbon Intensity *(C)*		Well to Wheels Carbon Intensity *(E x C)*
	MPGGE	kWh/mi	gCO_2/gge	gCO_2/kWh	gCO_2/mi
1990 CA Fleet Average [a]	19.8	1.68	10,997	330	555
2007 Conventional Gasoline [a]	22.0	1.52	10,997	330	500
2016 CAFE Standard [b]	28.4	1.17	9897	297	387
2025 CAFE Standard [b]	40	0.83	9897	297	247
2050 ICE [c]	42	0.79	9897	297	236
2050 Hybrid [c]	64	0.52	9897	297	154

Table 2. 2050 values for vehicle energy, fuel carbon and vehicle carbon intensity for ICE and hybrid vehicles used in this analysis compared to existing vehicles and policy goals.

[a] historical vehicle attributes; [b] policy goals (equivalent on-road fuel economies); [c] assumed attributes of 2050 new vehicle.

The most cost-effective means of reducing fuel use and greenhouse gases from light-duty vehicles in the near-term is to improve conventional internal combustion engine (ICE) vehicles that burn liquid fuels (Bandivdekar 2008 and Burke 2011). Lower-carbon liquid fuels (such as biofuels), especially if they have similar chemistry to today's petroleum-based diesel and gasoline fuels, would be relatively easy to integrate into the current fuel infrastructure system and require little behavioral change from consumers. Given the low efficiency associated with internal combustion engines, especially gasoline engines, there is considerable potential to improve their performance. Table 2 (above) shows the improvements in energy intensity that could be achieved for 2050 high efficiency ICEs and hybrid vehicles in a realistic scenario relative to current vehicles and policy goals. These improvements in fuel economy are the result of a number of currently available options, including improving engine and transmission efficiencies (including the use of diesel engines), reducing weight and aerodynamic drag, and hybridization, and are reflective of technically achievable fuel economy from a number of different studies (e.g. Bandivdekar 2008, Plotkin 2009, Greene 2011).

Improving the efficiency of vehicles through hybridization will slightly increase the cost of vehicles (+$1000-3000 or 5-15%), though prices could come down even more as better batteries and motors are developed for EVs and PHEVs (Kromer 2007). The adoption of these vehicles is likely to continue to increase, as HEVs are a mature technology, are likely needed to meet more stringent CO2 and fuel economy standards (163 grams/mi and 49.6 mpg in 2025) and their total life-cycle costs are similar to conventional vehicles (i.e. higher capital cost is offset by lower fuel costs). These are all Bin 1 technologies, available in volume today, though they will likely continue to improve and be refined over time.

In addition, adoption of these new efficient ICE vehicle technologies would not require any consumer or infrastructure changes since no major fuel or infrastructure switch is required. It is reasonable to think that these advances can be brought into 100% of the fleet by the 2050 timeframe, leading to a very significant improvement in vehicle fuel efficiency.

We estimate that HEV efficiency can triple fuel economy from today's levels, cutting energy consumption per mile by two-thirds. However, there are limits to the potential of internal combustion engine vehicle (ICEV) efficiency improvements. Conventional ICEs and HEV technologies will not be able to reduce energy use in an average vehicle by 80%, let alone for the growing fleet of vehicles. Given the growth in population, total numbers of vehicles and VMT per capita out to 2050, total energy use for light duty vehicles would likely be relatively flat or decline slightly compared to 1990 levels if only advanced ICE and hybrid vehicles were adopted (Bandivdekar 2008, NRC 2008). Additionally, the limited amount of available low carbon liquid fuels (biofuels) means that continued usage of liquid fuels rather than conversion to electricity or hydrogen in the light-duty sector would require additional usage of petroleum-based fuels and resulting GHG emissions. More advanced technologies based upon electrification of the light-duty drivetrain will be required to reduce energy use and emissions further (assuming use of low net-carbon sources for electricity or hydrogen). However, conventional and hybrid vehicles still play an important role in reducing liquid fuel usage in the realistic scenarios (described in sections V and VI) since advanced drivetrain technologies (FCVs and PEVs) do not provide 100% of VMT in 2050.

V. Plug-In Electric Vehicles

Plug-in electric vehicles (PEVs), which include pure battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) are a promising technology that can significantly increase vehicle efficiency, reduce the use of petroleum, use a decarbonized energy carrier and reduce greenhouse gas emissions from the light-duty sector.

	Vehicle Energy Intensity ***(E)***		**Fuel Carbon Intensity** ***(C)***		**Well to Wheels Carbon Intensity** ***(E x C)***
	MPGGE	kWh/mi	gCO_2/gge	gCO_2/kWh	gCO_2/mi
1990 CA Fleet Average [a]	19.8	1.68	10,997	330	555
2007 Conventional Gasoline [a]	22	1.52	10,997	330	500
2050 Hybrid [b]	64	0.52	9897	297	154
2050 PHEV on "gasoline" [b]	64	0.52	9897	297	154
2050 BEV/PHEV on "electricity" [b]	126	0.264			
Renewable electricity			0	0	0
Natural gas combustion cycle			13,300	400	106
Current average CA electricity			14,000	420	111
Coal steam			39,600	1188	314

Table 3. 2050 values for vehicle energy, fuel carbon and vehicle carbon intensity for BEV and PHEV vehicles used in this analysis.

[a] historical vehicle attributes; [b] assumed attributes of 2050 new vehicle

Table 3 shows the on-road energy use assumed for PEVs in the realistic cases. These values, which represent technically achievable fuel economy by 2050, can be significantly more efficient than the current fleet, could reduce energy intensity by much more than 80%, consistent with the results of multiple studies (Greene 2011, Plotkin 2009, Bandivdekar 2008). Coupled with low-carbon sources of electricity and liquid fuels (for use in PHEVs), PEV well-to-wheels carbon intensity (CO_2/mile) could be well below 80% of current levels. PHEVs in actual use alternate driving in electric and hybrid modes, depending upon the vehicle's battery size, the trip, and the recharging habits of the owners. PHEVs and BEVs are much more efficient running on electricity than hybrids running on gasoline (by a factor of 2, see Table 3). As a result, PHEVs will likely use more energy in the form of liquid fuel than electricity (Kromer 2007).[4] However, any means of increasing the use of electricity in a PHEV (such as using a larger battery size or creating additional opportunities to charge via public infrastructure) will lead to greater savings in liquid fuel usage and likely significant GHG savings (for every unit of electricity used, 2 units of liquid fuels are saved).

4 If 50% of a PHEV's miles are driven using electricity, and driving on electricity is twice as efficient as gasoline, then only 1/3 of the vehicles fuel use will come from electricity while 2/3 will come from gasoline.

PEV Technology and Costs

The main challenges to electric vehicle technology achieving a high fleet share by 2050 are related to adoption rates, fleet turnover, costs and infrastructure. The issue of adoption relates to the commercialization date and uptake in the early market. The latest commercial PEVs (Chevy Volt and Nissan Leaf) were first commercialized in limited numbers (~10,000 per year) in early 2011 timeframe and as a result, will require high rates of growth to achieve large fleet share in 2050.

While a range of battery sizes may be available, an incremental approach that emphasizes production and sale of vehicles with relatively small battery packs (e.g. PHEV10s) reduces the cost difference between PEVs and conventional vehicles while still allowing for increased battery manufacturing volumes. These vehicles will run primarily on liquid fuels but incorporate increases in battery manufacturing volumes, with associated reductions in cost per kWh. Over time, larger capacity battery systems should become more economical. While larger battery systems are currently available now, they may appeal primarily to early adopters; a more incremental approach, with inherently lower costs, could appeal more to a wider range of potential PEV buyers (Axsen and Kurani 2010). Additionally, infrastructure can be added incrementally as early adopters do not have to rely on ubiquitous public charging to fuel their vehicles. Charging at home can incur non-negligible costs associated with upgrading wiring, installation of a separate meter and the cost of a dedicated charger, estimated to be $800-$2100 per charger for level 1-2 charging (NRC 2010).

The cost, durability and weight/size of batteries are the most significant issues with PEVs becoming a dominant vehicle in the light-duty vehicle market. There are several recently commercialized vehicles and many more prototype and demonstration vehicles that greatly improve vehicle fuel economy while still satisfying consumer expectations about drivability and performance (Turrentine 2011). However, driving range limitations in pure BEVs and the cost of these battery-powered vehicles could be a major barrier to their widespread adoption (Bandivdekar 2008 and Burke 2011).

Bringing down the cost of batteries is the challenge most cited for commercialization of plug-in vehicles (BEVs and PHEVs). The cost of batteries will come down with increasing scale of manufacturing, but improved electrode and electrolyte chemistries and system designs are also needed to improve performance and reduce materials and system cost. According to the DOE, the four primary technical barriers for advanced batteries to overcome are (1) cost, (2) energy density, (3) abuse tolerance and (4) lifetime (DOE 2009). Figure 3 shows that even if very aggressive cost targets are met for battery costs, achieving long range BEVs will be very expensive (Kromer 2007).

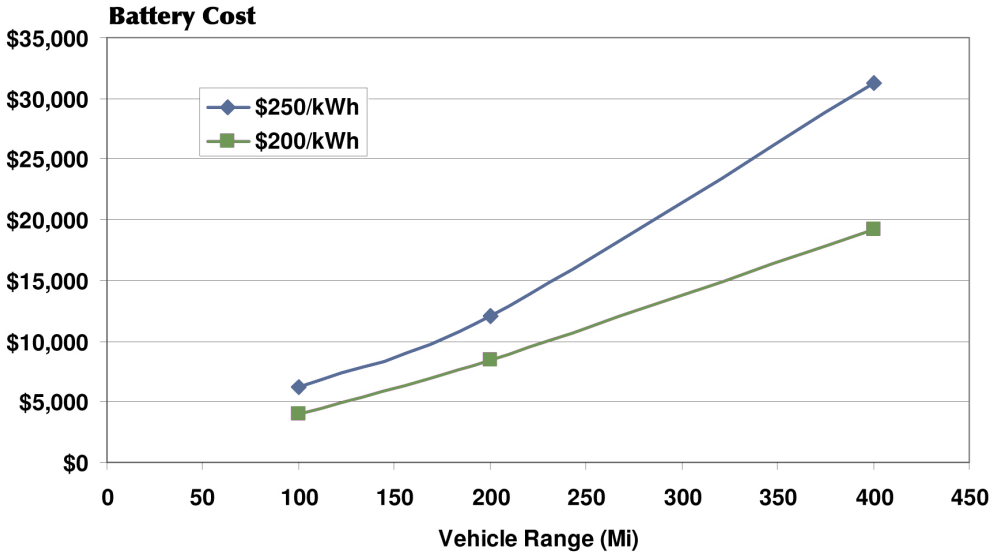


Figure 3. Battery pack costs for BEV sedan as a function of assumed per kWh price (source: Kromer 2007)

There do not appear to be any major materials limitations surrounding the use of PEVs. Lithium is one concern since significant use of lithium ion battery-powered PEVs would vastly exceed current annual lithium production (Tahill 2006). However, there appear to be ample reserves of lithium, and while significantly increased demand from around the world could drive lithium commodity prices higher, lithium makes up a small portion of total system costs (Gruber 2011).

Moreover, PEV batteries could have significant residual value after their use in a vehicle. Often the discussion of battery life revolves around degradation of capacity by around 20%, meaning that 80% of the usable capacity is still available. While this may not be acceptable for use in a vehicle, these batteries could still be used in stationary applications including utility services (e.g. transmission support, regulation and spinning reserves, load leveling, renewable firming, power reliability), load following and remote power. The residual cost of the battery will depend upon the value of these services, taking into account costs associated with removal, testing and refurbishing of battery packs (Weinstock 2002, Neubauer 2010). Battery leasing is one means for this residual value to result in lower initial costs to the purchaser of the vehicle.

Recently the federal government has announced the Electric Drive Vehicle Battery and Component Manufacturing Initiative, which is part of the U.S. Recovery Act. This initiative allocates $2.4 Billion dollars for grants supporting the construction (including production capacity increase of current plants), of U.S. based manufacturing plants to produce batteries and electric drive components.

The ARB's ZEV analysis concluded that Li-ion PHEV batteries would likely meet the technical requirements and cost targets for this application. Costs for these battery systems are currently high (~$1000/kWh) but battery technology has been improving at a rapid rate; many analysts and manufacturers believe that at high-volume production costs could be brought down to levels that begin to make PEVs affordable (Kalhammer 2007, Mock 2009). Table 4 shows the incremental costs associated with various types of EVs relative to a conventional gasoline vehicle in 2030. The PHEV has an incremental cost between $3,000 and $6,100 (depending upon the all-electric range) while the 200-mile range BEV has an incremental cost of over $10,000. These costs are for mass-produced vehicles where battery costs are relatively low ($250/kWh for BEV and between $270/kWh and $420/kWh for the PHEV).

Component	HEV	PHEV-10	PHEV-30	PHEV-60	FCV	BEV
Battery Cost, $/kWh	$750 ($600)	$420 ($340)	$320 ($260)	$270 ($215)	$750 ($600)	$250 ($200)

Component	Turbo	Diesel[57]	HEV	PHEV-10	PHEV-30	PHEV-60	FCV	BEV
Drive Train:								
Motor/Controller	--	--	$600	$800	$800	$800	$1,400	$1,400
Engine/Transmission	$500	$700	$200	$100	$100	$100	-$3,500	-$3,500
Fuel Cell	--	--	--	--	--	--	$3,000 ($4,500)	--
Energy Storage:								
Battery	--	--	$900 ($750)	$1,500 ($1,200)	$2,800 ($2,200)	$4,600 ($3,700)	$1,000	$12,000 ($8,600)
H_2 Storage (150L)	--	--	--	--	--	--	$1,800	--
Miscellaneous:								
Exhaust	$0	$500	$0	$0	$0	$0	-$300	-$300
Wiring, etc	--	--	$200	$200	$200	$200	$200	$200
Charger	--	--	--	$400	$400	$400	--	$400
Total	**$500**	**$1,200**	**$1,900 ($1,700)**	**$3,000 ($2,700)**	**$4,300 ($3,700)**	**$6,100 ($5,200)**	**$3,600 ($5,100)**	**$10,200 ($6,900)**

Table 4. Estimated incremental cost of PHEV and BEVs over conventional vehicle in 2030. Optimistic values are in parentheses (Kromer 2007).

While vehicle cost is an important barrier, especially to near-term vehicle adoption, the need for public charging stations for electric vehicles is also a widely discussed challenge. The need for near-term public infrastructure does not appear to be as significant as for other alternative fuels such as hydrogen, especially early on in the introduction of electric vehicles. Early adopters of PEV technologies are a self-selected group that will have access to some form of charging at home. Additionally, PHEVs are able to run on gasoline as well so owners will not be terribly inconvenienced if their batteries are depleted far from a convenient charging location. As PEVs become mass market vehicles, greater availability of public charging will increase the utility of PEVs by allowing some drivers to use a BEV for a greater proportion of their trips and increasing the proportion of PHEV miles driven on electricity.

When one considers how to achieve very high market penetration for PEVs, infrastructure will likely be an important issue, especially the lack of universal home charging. There are an estimated 54 million garages for the 247 million registered cars in the United States (Lowenthal 2008) and as a result, it is likely that a majority of light-duty vehicles would not have access to a dedicated overnight charging spot and plug to charge their batteries overnight. Survey research in California found that only approximately 50% have access to a convenient 110V plug at home and/or work (Axsen and

Kurani 2009). In some cities like San Francisco, where one might expect a higher rate of adoption of green technologies, only 16% of cars are parked in garages overnight and the rest are parked in the street or parking lots, which have limited access to electrical outlets. Thus, the lack of convenient residential charging could be a serious barrier to high fleet share for BEVs and negate much of the benefits associated with PHEVs (if they are forced to rely primarily on gasoline rather than electricity).

These limitations in residential charging accessibility lead to the question of whether a public charging infrastructure can bridge the gap. However, public charging is not likely to be a complete substitute for home-based charging because of the length of time (hours) required to recharge batteries at low or moderate power (<10kW), and the need to charge frequently, given that the electric range is much less than the gasoline range of a conventional vehicle. It is possible that very high power charging, which can charge batteries in tens of minutes rather than hours, or battery swapping could help reduce the reliance on home-based charging, but these alternatives are unlikely to eliminate it entirely.

Given that initial PEV commercialization has just taken place, these vehicles and their underlying technologies are primarily Bin 1 technology. PEV infrastructure and charging technology falls within both Bin 1 (low to medium power charging) and Bin 2 (high power charging). However, despite commercialization, and high efficiency of existing models, PEV technology has not yet demonstrated that it will be economically competitive with alternatives or meet mass-market range and durability requirements. For example, continued improvements in battery design and manufacturing are needed to achieve cost reductions. Large-scale deployment of PEVs, which would take several decades, can require additional electricity generation capacity, and upgrades to transmission and distribution systems, which are not significant technology advances, but would result in some additional costs. Large numbers of PEVs would also be accompanied by new "smart grid" technologies and systems to manage their charging (Bins 1 and 2).

Realistic PEV Case

The Realistic Case for PEV adoption is driven by a couple of key factors, which present important barriers for the adoption of PEVs, both in the near-term and in the long-term. In short, it is unlikely that they can make up 80% of light-duty vehicles (i.e. passenger cars and trucks) by 2050.

As stated earlier, the cost of PEV batteries is expected to be quite high in the near-term and remain substantially higher than conventional and hybrid vehicles in the longer-term. Lower fuel (i.e. electricity) costs can help reduce or potentially eliminate the life-cycle cost difference, but high initial costs will be a significant barrier to rapid vehicle penetration. As with hybrids, early PEVs will be available from only a few of the automotive OEMs in a limited range of models, mainly small and medium size sedans. This limited availability coupled with high initial vehicle costs will be a barrier to their rapid deployment.

While some PEVs are sold in this case (in the range of up to 3-5% of new car sales by 2020), the vast majority of vehicles will still be powered exclusively by gasoline. Yet these gasoline vehicles still can be made significantly more efficient with a number of existing technologies that will be brought to bear to help meet the California Pavley standards and national CAFE standards.

In the 2015-2030 timeframe, more OEMs introduce PEVs in different models and vehicle sizes. Battery costs will fall significantly because of a worldwide growth and greater experience in battery manufacturing and production. The market has moved well beyond early adopters and the general public - at least those with suitable garage space to park and charge their car overnight - begins to

buy plug-in vehicles. Subsidies and other financial incentives for PEV purchases will be phased out as vehicle costs decline, though some policies, such as feebates, may continue to persist. The majority of PEVs sold will be PHEVs, with increasing average battery capacity thus reducing average gasoline usage. Impacts on electricity generation and capacity will remain quite small as even in 2030 with 8% of the total fleet being some form of plug-in vehicle, electricity demand for vehicles comprises less than 2% of the 2008 total system electricity demand. Hybrid vehicles grow to become the dominant type of new car sold (>50% in 2030), though PHEVs and BEVs also grow become one quarter of the new car market in 2030.

In the period between 2030 and 2050, the growth of plug-in vehicles would continue with a shift towards higher levels of electrification, greater all-electric range, and larger battery packs. PEVs will continue to be more expensive to manufacture and purchase than conventional and hybrid vehicles. In this timeframe, vehicle costs decline to match the learned-out costs found in Table 4.

Maximum fleet share for PEVs appears to be limited due to two factors. The first is that the cost of batteries for larger vehicle sizes (i.e. light trucks, vans and SUVs) is significantly higher than for smaller vehicles, so the incremental costs associated with large PEVs pose a major challenge. The second factor is the large percentage of consumers who do not have dedicated off-street vehicle parking at their home at night. These two factors inform the scenario that PEVs achieve a reasonable, but still optimistic fleet share of 58% (35% PHEVs and 23% BEVs) in 2050. To achieve this level of fleet share, PEVs would need to make up over 50% of new car sales after 2036 and reach 69% of new car sales in 2050.

In 2050, BEVs make up 23% of all vehicles in the fleet and are used by commuters and people who do not mind the range limitations associated with BEVs (~100-200 miles) (see Figure 4). PHEVs sold in 2050 are primarily large-battery PHEVs (i.e. 40+ mile all-electric range) to minimize liquid fuel use. Fleetwide fuel economy in 2050 exceeds 70 mpgge (gasoline plus electricity) and total fuel usage (including electricity) is over 45% below 2005 levels. In 2050, the average new vehicle fuel economy is 86 mpgge (BEVs achieve 126 mpgge[5] (0.265 kWh/mi), PHEVs achieve 91 mpgge, HEVs achieve 64 mpg and conventional ICEVs get 42 mpg).

In the 2040 to 2050 timeframe, liquid fuel usage drops significantly (see Figure 5) and electricity demanded by vehicle recharging is in the range of 14-29% of 2008 total system electricity demand. This large pool of battery storage (somewhere between 500-1000 GWh), which is stationary and plugged in much of the day, could be used by the utilities to help provide important grid services. By controlling when charging occurs, utilities could help to level demand and firm the use of intermittent renewables. Utilities should also be able to provide very fast response for frequency/voltage regulation and spinning reserves, which is useful in a grid with high levels of intermittent renewable generation.

5 Fuel economy for vehicles using electricity also include losses associated with 83% battery recharge efficiency and assumes 33.3 kWh is equivalent to a gallon of gasoline.

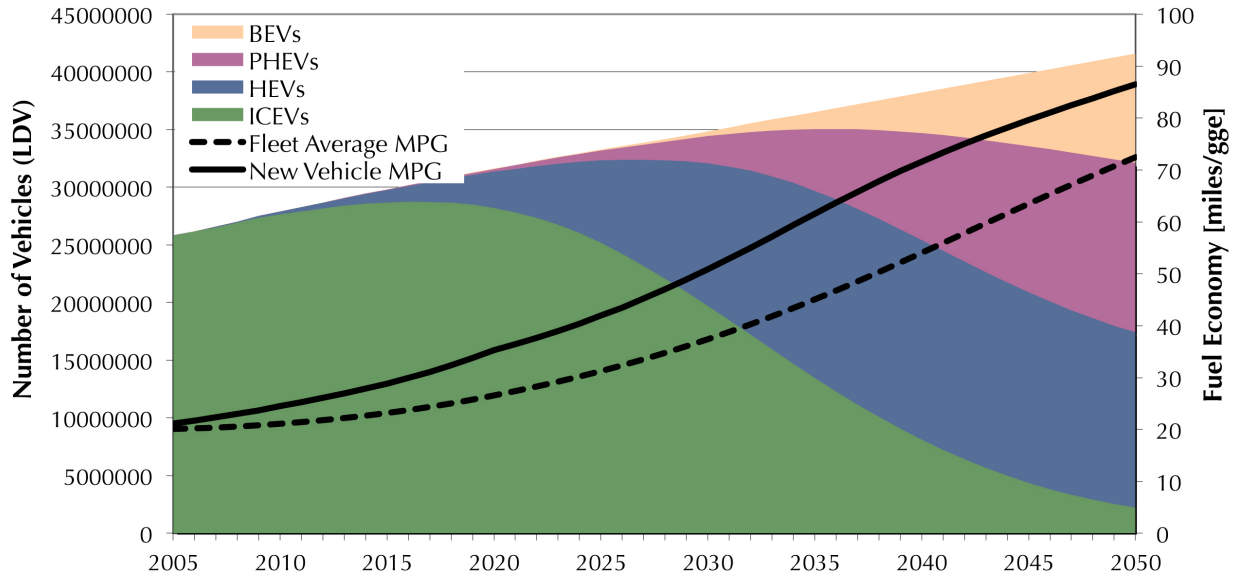


Figure 4. Vehicle fleet deployment and new vehicle and fleet average on-road fuel economy (accounting for both liquid fuels and electricity) for PEV storyline

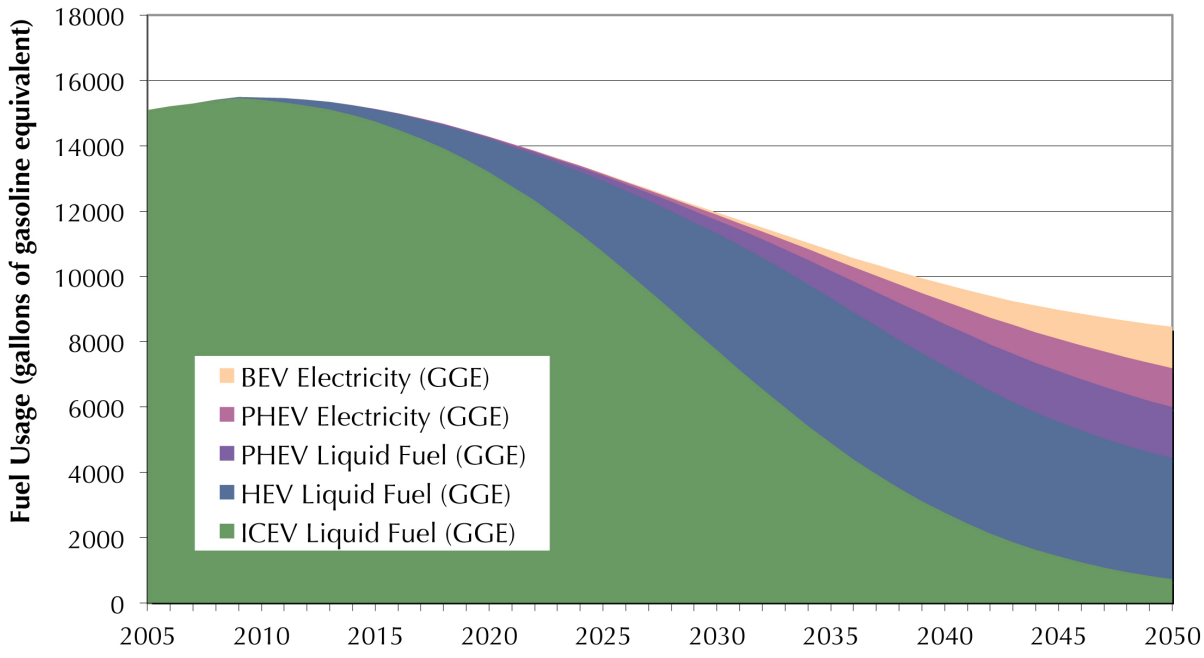


Figure 5. Total LDV fuel usage (liquid fuels and electricity) for PEV storyline

VI. Hydrogen Fuel Cell Vehicles

Fuel cell vehicles (FCVs) offer the potential for significant improvement in vehicle efficiency, reductions in petroleum usage and the ability to use a decarbonized energy carrier, which can lead to substantial reductions in greenhouse gas emissions. Table 5 shows that H_2FCVs could reduce energy intensity (MJ/mile) nearly 80% from 1990 fleet average and would be significantly better than a hybrid in 2050 (NRC 2008). Coupled with a low-carbon hydrogen fuel, the per-mile vehicle carbon intensity would be even lower. A key challenge in meeting a high fleet share in 2050 is the relatively slow rate of fleet turnover (~15 years) and the timing for mass-market introduction of FCVs and associated refueling infrastructure.

	Vehicle Energy Intensity *(E)*		**Fuel Carbon Intensity *(C)***		**Well to Wheels Carbon Intensity *(E x C)***
	MPGGE	kWh/mi	gCO_2/gge	gCO_2/kWh	gCO_2/mi
1990 CA Fleet Average	19.8	1.68	10,997	330	555
2007 Conventional Gasoline	22	1.52	10,997	330	500
2050 Hybrid	64	0.52	9897	297	154
2050 H_2 Fuel Cell Vehicle	90	0.37			
Renewable or Nuclear H_2			0	0	0
Onsite Natural Gas			10,700	321	119
H_2 from Coal			21,500	645	239
H_2 from Coal with CCS			2,000	60	22

Table 5. 2050 values for vehicle energy, fuel carbon and vehicle carbon intensity for FCVs used in this analysis.

FCV Technology and Costs

A hydrogen fuel cell vehicle uses an electrochemical energy conversion device, i.e. a fuel cell stack, to convert hydrogen fuel and air into electricity, water and heat. This process is around 50% efficient, significantly higher than an internal combustion engine running on gasoline. Hydrogen is a form of electrification since the FCV has an electric drivetrain (electric motors and controllers) and is typically hybridized as well. In fact, FCVs became the focus of intense research and development along with significant policy and popular attention in the 1990s, in part because it was believed that they would be able to overcome the limitations of BEVs in terms of range and refueling.

Considerable research progress has been made on the proton exchange membrane fuel cell (PEMFC) and other aspects of the FCV system but more progress is still needed, on issues ranging from fuel cell materials costs and durability to on-board hydrogen storage. Although not yet producing commercial versions, automakers are demonstrating many hundreds of FCVs around the world, and driving them many millions of miles (Wipke 2011); thus they are Bin 2 technologies. Substantial financial commitments and technical progress have been made in recent years by the automotive

industry, private entrepreneurs, and the U.S. Department of Energy (DOE). These suggest that H_2FCVs and hydrogen production technologies could be ready for commercialization in the 2015-2020 time frame.

Current fuel cell manufacturing costs are quite high, in part because they are development prototypes produced in small numbers rather than mass-produced commercialized products. It is estimated that manufacturing costs would drop by an order of magnitude (to $51/kW or approximately $3,000 for a vehicle fuel cell system) if automakers started mass production of fuel cells using today's technology. However, these large volumes are unlikely to occur for at least several years after initial market introduction, so incremental FCV prices will remain high for some time. As was the case with HEVs, these high costs and limited makes and models are likely to slow the rate of introduction of FCVs. Consequently, very high rates of sustained annual growth would be required after 2025 to achieve an 80% fleet share in 2050 (also seen in other studies, e.g. NRC 2008).

Hydrogen storage and the fuel cell stack are the two primary technology challenges for fuel cell vehicles. Hydrogen storage is an important component of automotive fuel cell systems because of the challenges associated with storing sufficient quantities of hydrogen gas on board the vehicle to ensure adequate range for consumers (typically assumed to be greater than 300 miles before refueling). Hydrogen storage systems are significantly heavier and larger than those designed for liquid fuels, and space can be an issue on FCVs. Current demonstration FCVs store hydrogen at high pressures (5,000 or 10,000 psi) in a composite (e.g. carbon fiber) wrapped polymer bladder and/or aluminum tank and are commercially available (Bin 1), though costly. However, meeting the DOE's hydrogen energy density and cost goals is not possible using current compressed hydrogen storage systems (Figure 6). Liquid hydrogen storage improves energy density, but it is highly energy intensive requiring 8-11 kWh of electricity per kg hydrogen to cool the gas to its liquid state; this approach appears unlikely to make further large improvements in terms of energy density. A breakthrough in promising H_2 storage options such as carbon nanotubes or metal alanates will likely be needed to meet the performance specifications laid out by the DOE targets.

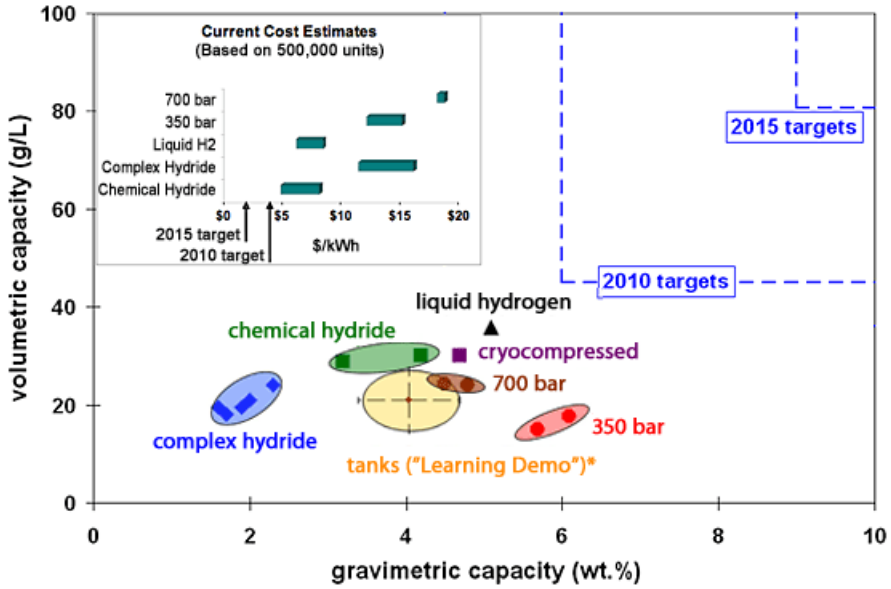


Figure 6. Hydrogen storage technology and cost status compared to DOE targets (DOE 2009).

However, meeting the DOE goals for hydrogen storage may not be necessary as several studies and real world demonstrations have indicated that it is possible to achieve sufficient driving range in a FCV using compressed H_2 storage even if the DOE targets are not met (NRC 2008, Kromer 2007). Using a combination of improved vehicle efficiency and better packaging of H_2 storage, Honda's 2007 FCX achieves a large increase in range over past prototypes (~270 miles) using a 5000 psi tank; Toyota's 2007 FCV using 10,000 psi compressed storage was able to achieve real-world driving range of over 350 miles per tank. Thus, many automakers and analysts do not believe that using near-term compressed gas storage technologies represent an insurmountable barrier to initial commercialization. However, further improvements to storage technologies to improve technical (weight and volume) performance and, importantly, lower storage costs will be helpful in speeding FCV adoption.

The fuel cell stack is the primary energy conversion device in a fuel cell vehicle, combining hydrogen fuel and air to produce electricity that is used to power the vehicle.

	Today	***2015 Goals***
In-use durability (hrs)	2000	5000
Vehicle range (miles/tank)	280-400	300
Fuel Economy (mi/kg H2)	72	60
Fuel Cell Efficiency	53-58%	60%
Fuel Cell System Cost ($/kW)	51	30
H2 Storage Cost ($/kWh)	15-23	10-15(NRC)
		2-4 (USDOE)

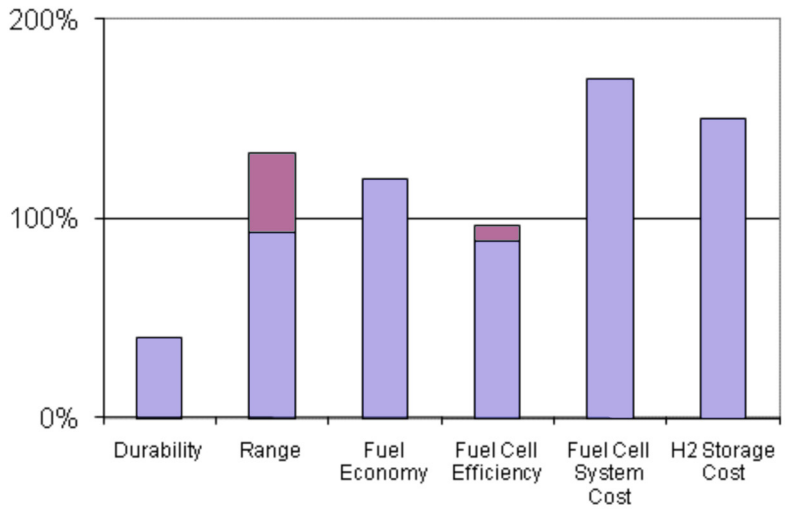


Figure 7. Fuel cell stack technical and cost targets relative to estimated current values assuming mass production (Ogden 2009).

Figure 7 shows estimates of what current fuel cell system designs would cost if scaled up to high volume production and technical targets for fuel cell performance including range, durability and fuel economy. Progress in fuel cell technology has led to substantial cost reductions, such that high-volume mass produced costs for FCVs in the 2020 time frame could be less than $10,000 more than conventional vehicles (Kromer 2007, Plotkin 2009). Kromer (2007) estimates that a mass-produced H_2FCV in 2030 could cost as little as $3,600 more than a similar gasoline vehicle (see Table 4). Fuel cell stack durability (related to membrane and electrocatalyst stability) is still lacking but many initial questions about freeze and heat tolerance appear to have been answered.

Platinum is one of the main costs for the fuel cell stack and is seen as one of the challenges and opportunities to reducing fuel cell costs. There is a significant research effort to try to lower platinum loadings without sacrificing cell durability, power density and efficiency. Promising laboratory-scale test results have been presented using loadings that are greater than a factor of 10 lower than current levels. Several studies estimate that a reasonable lower bound for platinum loading to be 0.1 to 0.2 g Pt/kW fuel cell stack (Kromer 2007, Kalhammer 2007), which would amount to 4-8 grams of Pt for a FCV, which is not much more than the amount of platinum in a catalytic converter (2-4 g) and could amount to as little as a few hundred dollars (Sun 2011). Achieving these low levels of platinum loading could reduce fuel cell system costs to as little as $22/kW (Kromer 2007). For 100 million FCVs, these platinum loadings would imply that the total platinum in the FCV fleet (assuming high rates of recycling) would be approximately 400-1200 tonnes of platinum, which is significantly higher than the current annual production of ~200 tonnes/yr and would likely lead to higher platinum prices. However, platinum availability is not expected to be a major long-term impediment to FCVs as long as adequate recycling occurs and continued progress is made on reducing platinum usage (including the use of alternative electrocatalyst materials).

Beyond the challenges associated with the vehicle technology, mass adoption of H_2FCVs will also require the simultaneous deployment of H_2 refueling stations and, ultimately, the development of large plants to produce hydrogen and infrastructure to deliver it to H_2 stations in an efficient and cost-effective manner. This 'chicken and egg' problem will initially limit the regions where H_2FCVs would be sold and there are discussions to roll out FCVs and H_2 stations in a staged manner, beginning in large, dense metropolitan areas such as Los Angeles and then expanding to smaller cities over time (Ogden 2009). This approach will help lower the cost of providing infrastructure but will also require significant amounts of coordination at many levels between auto and energy companies, station providers, and governments. Early infrastructure "cluster" strategies that co-locate vehicles and stations in lighthouse cities could allow good fuel access for consumers even with a sparse, relatively low-cost fueling network. Although hydrogen will be initially costly, costs will become more competitive as demand grows and the system scales up (Ogden 2011). This approach would also slow the rollout of FCVs, since the availability of hydrogen fuel will be limited. These issues will make it challenging for H_2FCVs to achieve very high market share of new car sales 15-20 years after market introduction, and a high fleet share 30 years after market introduction. However, several studies have shown that high fleet penetration of FCVs (60-90%) could be possible throughout the US by 2050 if subsidies are provided and cost targets are met, which could mean even higher penetration in California (Greene 2007, NRC 2008).

At a sufficiently large scale, the cost of delivering hydrogen to vehicles is expected to be cheaper than gasoline on a per-mile basis, but as with vehicle costs, early stations and production facilities will also be expensive and high early market capital investment costs and uncertainty about profitability will slow investment and the rate of infrastructure deployment (NRC 2008, Ogden 2009, Ogden 2011). As described in these studies, subsidies on H_2 fuel will probably be needed for the first decade to ensure that vehicle owners are not put off by high initial H_2 pump prices. Hydrogen infrastructure generally falls into Bins 1 and 2. Many different hydrogen production technologies and

processes are relatively well-established (e.g. natural gas reforming, coal gasification, electrolysis). Additionally, many associated technologies and processes are also commercially available (hydrogen purification, compression and transport). Hydrogen vehicle refueling infrastructure technologies and systems, such as dispensers, cascade storage systems, onsite reformers, are not widespread but are currently being demonstrated at dozens of refueling stations involving hundreds of FCVs, including many in California. Breakthroughs in vehicle-based hydrogen storage technologies could also make a significant difference in the costs associated with transporting and storing the hydrogen at the refueling station.

However, despite the rapid development of these technologies, FCVs are unlikely to supply all of light-duty VMT in 2050. FCV technology has not yet been commercially introduced, though automakers have stated they will introduce FCVs in 2015-2020. While the current design of the fuel cell stack appears to offer acceptable efficiency and performance, durability and cost are key areas for needed improvements to help bring about widespread adoption. This could be largely accomplished with further engineering refinement and large-scale manufacturing of existing technology. However, additional R&D on fundamental science and system engineering will continue to improve the technology with respect to efficiency, performance, durability and help reduce costs. Low production volumes will mean high costs for the first few tens of thousands of vehicles, which will consequently require substantial subsidies (either from automakers and/or government). Some analyses indicate that with coordinated policies focused on hydrogen infrastructure development and subsidies on vehicles and fuel to bring down costs, FCVs could take off and become the dominant vehicle type (Greene 2007, NRC 2008) because of lower lifecycle costs relative to gasoline vehicles at sufficiently high production volumes.

Realistic Combined FCV and PEV Scenario

This scenario combines FCVs with the currently developing PEV market. FCVs are expected to be commercially introduced in California in 2015 at low volume and initially in limited markets, including Southern California and the San Francisco Bay Area. This limited release helps to ensure a coordinated rollout of refueling stations with vehicle sales and helps reduce the costs associated with infrastructure deployment and minimize the chicken and egg problem. In addition to stations in the urban areas, a few bridging stations will be required to ensure that FCV owners can travel between major cities (Ogden 2011, CAFCP 2010, CAFCP 2009).

As in the PEV scenario, the first few years will have only a few automakers selling FCVs in a few models, though larger cars and trucks/SUVs are more likely because packaging of the fuel cell and hydrogen storage system will be easier due to their lower weight and volume constraints compared with smaller cars. And as with the PEV scenario, advanced technologies will take a while to become a significant portion of the fleet, so the major determinant of energy use and emissions before 2030 is the efficiency of conventional and hybrid vehicles running on gasoline and the ability to control VMT growth.

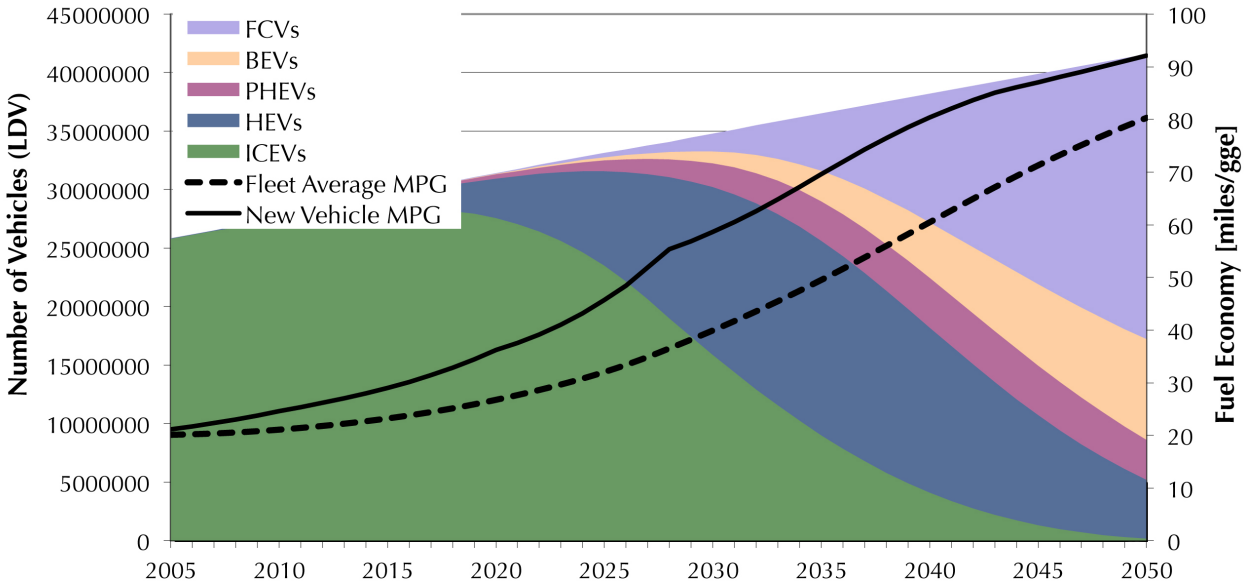
Between 2020-2030, FCV sales will grow rapidly as new manufacturers begin building FCVs in many more makes and models. By 2030, 20% of new vehicles are FCVs, 12% are PEVs and 67% are hybrids, while conventional gasoline vehicles no longer sold. Infrastructure rollout continues and most hydrogen is still produced by onsite natural gas refueling stations with some contribution from renewable sources consistent with the state requirement of 33% renewable H_2. However, the growth of FCVs and their concentration in major metropolitan areas makes centralized production more economical even taking into account the cost of delivery.

After 2030, FCV sales would grow quickly so that FCVs make up the vast majority of sales and compose 59% of the fleet by 2050 while PEVs make up 29% (see Figure 8). By 2035, BEVs are sold in greater numbers than PHEVs as FCVs are used for vehicles needing longer range and quick refueling while BEVs are used for commuting and shorter range driving.

Most Californians (90+%) live in high density areas that could be covered by hydrogen refueling stations and FCVs can be offered in all vehicle types (cars, trucks and SUVs), so there does not appear to be any significant technical limitation to the ultimate FCV sales and market penetration. BEVs are assumed to make up a greater proportion of smaller cars while FCVs are a larger fraction of the larger trucks and SUVs.

In 2050, the fleet average fuel economy in this scenario would be approximately 80 mpgge, while new vehicle fuel economy would be over 90 mpgge. Hydrogen demand in 2050 is 4.8 billion gallons of gasoline equivalent per year, while electricity is about 1.4 billion gge (46,179 GWh/yr, equal to 16% of 2008 electricity demand) and liquid fuels is only at 1.4 billion gge.

Figure 9 shows total light-duty fuel energy usage is approximately 49% below 2005 levels and light-duty liquid fuel usage is 91% lower than 2005 levels.



To achieve this level of FCV penetration, hydrogen specific policies will be needed to help facilitate the building of refueling infrastructure and to 'buy down' the cost of vehicles and infrastructure (NRC 2008). As previously mentioned, these policies will need to encourage and rely upon significant levels of coordination between government and the automobile, H_2 production and refueling station industries. In the US, the National Research Council estimated these subsidies could reach around $55 billion by 2023, at which time lifecycle costs would be comparable to conventional vehicles.

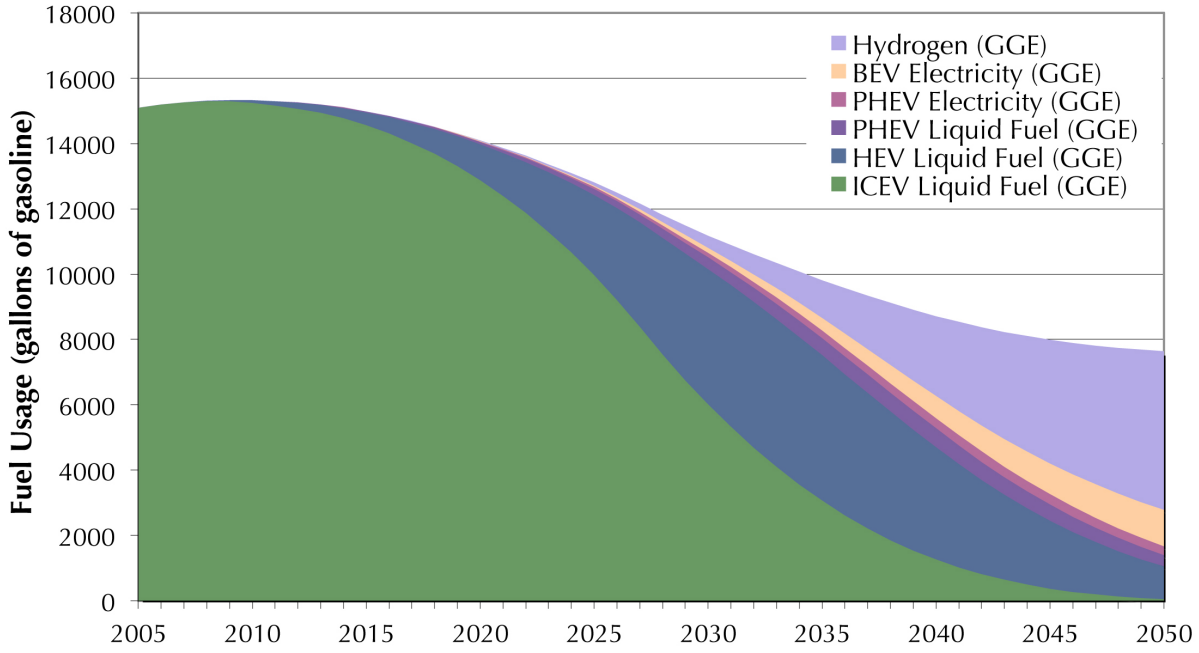


Figure 9. LDV fuel use by year

By 2040, large centralized production of hydrogen with pipeline delivery makes up the majority of hydrogen supply. Large infrastructure capital investments are made to build large production plants and to build and install a pipeline system serving a widespread network of public refueling stations. A mixture of sources, fossil with CCS, biomass and renewables is used to produce hydrogen. This infrastructure is capital intensive, but with significant economies of scale, and the levelized cost of hydrogen could reach $3-$4/kg at the refueling station (equivalent to $3-$4/gallon of gasoline on an energy basis). However, since hydrogen can be used in a FCV more efficiently than in a gasoline vehicle (about 40% more efficient than a hybrid and twice as efficient than a conventional vehicle) this is equivalent to $2.10-$2.80/gallon of gasoline on a per mile basis when compared to the hybrid.

VII. Aviation Technologies

The aviation subsector consists primarily of commercial passenger and freight service whose propulsion energy is generated by jet turbines powered by petroleum-based jet fuel (kerosene) or aviation gasoline. The large majority of aircraft-miles and energy use are associated with transporting commercial passengers.

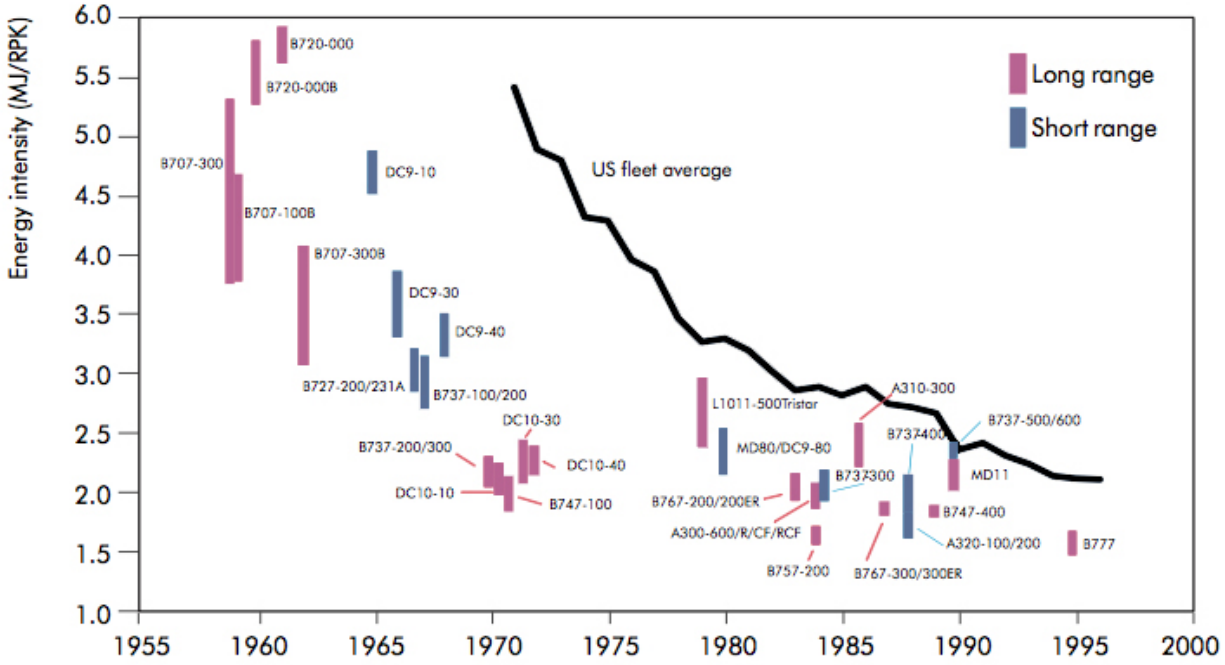
Commercial passenger aviation is expected to continue to grow over the next few decades. The Annual Energy Outlook (AEO) estimates that US passenger seat miles will grow 50% over the next few decades to 2030 (AEO 2009), outstripping population growth significantly. Other analyses have estimated that total US domestic aircraft miles could triple between 1990 and 2050 (McCollum 2009), with 80% growth already occurring between 1990 to 2007 (ORNL 2009). In the business as usual and median scenarios, passenger miles per capita increase 90% from the 1990 baseline. Coupled with a doubling of the population, this means that total aircraft passenger miles would quadruple to 350 billion passenger miles in 2050.

A key question about airline GHG and energy usage is whether state regulation over GHG emissions will cover only miles flown within the state (in-state travel) or whether regulations will be national or even international in scope and as a result, cover all aircraft miles that have an origin or destination in the state (total travel). One formulation (Yang 2009) calculates and allocates emissions in their overall case as resulting from all instate trips and one half of trips that enter or leave the state. This represents the fuel that is required from the state's energy system.

Most analyses of future aviation technology do not expect any major shift for the commercial passenger aviation sector to alternative propulsion systems by 2050. There are no future technologies that appear promising enough to meet the stringent requirements associated with commercial aircraft travel, including high energy density fuel, high power to weight ratio, and operation under severe conditions (temperature and pressure).

Alternative fuels also have to meet stringent requirements and the near-term potential for using alternative fuels is limited. For any alternative fuel system, gravimetric energy density (MJ/kg) is a major consideration. Currently produced biofuels, such as ethanol or biodiesel, are not compatible with current engines and do not appear suitable for the aviation sector. Near-term options include hydroprocessed renewable jet (HRJ) fuel and Fischer-Tropsch (FT) fuels, which are "drop-in" replacements that do not require significant modification to current aircraft engines. Another option that has been explored is hydrogen, which is theoretically a fuel with a very high gravimetric energy density. However, current systems for liquid H_2 storage dramatically reduce system energy density, and the use of H_2 would require significant redesign of aircraft (to store H_2) and engines (to use H_2), so it is not considered here.

Fuel consumption can be reduced by improving propulsion efficiency, improving aerodynamics, lightening the aircraft and operational improvements. Figure 10 shows how fuel consumption per passenger kilometer for different aircraft and the U.S. fleet average has continuously declined over time.



Notes: 1) The bar for each aircraft reflects varying configurations; the line shows estimated fleet average for the United States across all existing aircraft. 2) RPK = revenue passenger kilometre = number of passengers carried x distance flown (in km).

Figure 10. Historical aircraft energy intensity, new aircraft and U.S. fleet average (IEA 2008b)

Because fuel is a major cost element for airlines, it is expected that even in the absence of significant policy, new aircraft energy intensity will continue to decrease by about 1-2% per year. These reductions come from the use of more efficient jet engines, advanced lightweight materials, and improved aerodynamics (winglets and longer wingspans) (IEA 2008, Schäfer 2009) and result in a reduction in fleet average energy intensity by 30% in 2050. Many of these technologies have already been demonstrated and employed on existing state-of-the-art aircraft such as the Airbus A380, the future Airbus A350, and the Boeing 787.

Beyond these expected changes, additional improvements can be made to increase fuel efficiency. These include advanced jet engines, laminar flow control and more substantial changes/redesigns such as blended wing aircraft designs; these options have the combined potential to decrease energy intensity by an additional 35%. With these aggressive changes, fleetwide energy intensity could be lowered by as much as 70-80% per passenger mile.

Changes to how aircraft could be operated include improved air traffic management and optimized flight paths, communications and navigation systems, and changes in aircraft descent patterns. Improvements in these operational elements are expected to reduce global aircraft energy use by 10% in 2050 (McCollum 2009b).

An important challenge for the reducing the impact of aircraft travel on climate change is that emissions of several aircraft pollutants at high altitude appear to have a greater warming effect than when emitted at lower altitude. Emissions of water vapor, N_2O, NOx and sulfur can create clouds and form ozone, which can increase radiative forcing, though these effects can be short lived. There

are several studies on this topic but the actual impact of high altitude aircraft, in terms of equivalent greenhouse gas emissions like a CO_2 equivalent, is highly uncertain and is not accounted for in this analysis. If the impact is significant, it could be that combustion based aircraft, even those using a net-zero carbon liquid fuel (such as a biofuel) or liquid H_2, would still produce water vapor and NOx and could still contribute to warming. If this were the case, it would make it exceedingly difficult to address GHG emissions in the aviation sector.

With aggressive application of advanced technologies to reduce aircraft energy intensity (Bins 1 and 2) it is expected that a 70-80% reduction in energy intensity is technically feasible. Even with this extreme level of efficiency, the expected increase in population and airline travel makes meeting an 80% reduction in total aviation fuel usage impossible. The realistic cases in this study rely on a more reasonable estimate of the potential energy intensity reduction of 50-55%. This level does not appear to require the very highest costs that the deepest energy use reductions might require but leads to an overall increase in the energy use in the aviation sector in 2050. The use of a low-cost and abundant low carbon "drop-in" replacement fuel that is similar to current jet fuel could help aviation significantly lower emissions relative to 1990.

VIII. Heavy Duty Vehicles

Heavy duty vehicles mostly consist of large trucks with diesel engines that are designed to carry goods and freight and can come in a variety of sizes (up to 75 feet long and 100 tons). Durability, efficiency, and fuel costs are important considerations for these vehicles. To date, heavy trucks have primarily used efficient diesel engines for energy conversion, because of their efficiency, durability and high power output. The challenge for lowering GHG emissions from the heavy-duty truck sector is that alternative fuels and drivetrains may not be acceptable for the demanding applications that the vehicles are used for.

The big barrier for the use of electricity and hydrogen as alternative fuels is in energy storage. The energy density of electricity storage in batteries or hydrogen in compressed gas tanks (as are being discussed for light-duty EVs and FCVs) is much lower than diesel fuel on a gravimetric and volumetric basis. This energy storage challenge would negatively impact vehicle cargo capacity and range. Long-haul trucks typically have a fuel capacity exceeding 200 gallons of fuel and can drive over 1,000 miles between refuelings (Lutsey 2009). Storing enough energy in the form of batteries or compressed hydrogen to achieve comparable range would significantly impinge on the cargo space, reducing the potential value of cargo as well as adding significantly to the vehicle weight, hurting fuel economy. Also critical is the issue of power density for fuel cells and batteries relative to diesel engines. Diesel engines are quite efficient, with peak efficiencies around 45% (although average efficiency over a drive cycle is less than 40%). Thus, the main approaches to reducing energy use and GHG emissions from long-haul heavy-trucks are likely to come from further improvements to the engine and drivetrain efficiency, other vehicle based efficiency measures (weight, aerodynamics and rolling) and logistics, rather than from adopting advanced electric or fuel cell drivetrains.

Heavy-duty trucking miles are growing significantly, making it challenging to reduce fuel usage in this subsector by 80%. Heavy truck miles driven in California are expected to triple from 1990 to the year 2030 (Caltrans 2005) and quadruple by 2050.

Significant efforts are underway to improve the efficiency of heavy trucks. The Environmental Protection Agency's (EPA) Smartway certification program is expected to reduce fuel consumption from 18-28% vs. conventional trucks. The program includes new vehicles as well as upgrades/ retrofits, which can help bring about changes in the fleet faster than relying on new vehicles sales alone.

More advanced and costly options for reducing energy usage include hybridization and adding a bottoming cycle, which can reduce fuel consumption an additional ~10-15%. Making trailers longer or adding multiple trailers can also reduce energy usage by up to 27%. The maximum expected reduction in fuel consumption using all of these techniques is expected to be around 50% for a new truck in the 2020 timeframe (Kamakate 2009). Fleet turnover, as with light-duty vehicles, means that there will be a delay between when new vehicles are sold into the fleet and when the average fleet characteristics match those of the new vehicles. Given that heavy-duty trucks are driven much more than passenger cars, their lifetimes, even considering their longer lasting engines, are generally shorter than 15 years.

Besides vehicle and engine efficiency, there are other means of reducing in-use fuel consumption of heavy-duty vehicles, through better operation and logistics. Intermodal shifts are another means of reducing truck miles. Shifting some freight loads to higher efficiency modes such as rail is a potential option, but may be limited for other reasons such as cost, flexibility, travel time, and reliability.

The maximum potential reduction in new heavy-duty truck energy usage appears to be around 50%. Achieving this reduction per truck fleetwide would involve significant changes such as longer or double trailers, hybridization and many other aerodynamic and efficiency options for all trucks and changes in operations and logistics, which is probably not feasible and cost-effective for all trucks. Thus a 30% improvement in heavy-duty long-haul trucks is used in the realistic case.

For smaller, short-haul trucks such as delivery vans (e.g. UPS/FedEx trucks), it appears more likely that they may able to make use of more efficient electric drive technologies using batteries or fuel cells. In California, a mix of 63% long-haul and 37% local trucking is used; it is assumed that 50% of these short-haul trucks can be converted over to an electric-drive train (i.e. 18% of the total) while the remainder (82%) would continue to use highly efficient diesel engines. Electric drive technologies used in smaller, short-haul and delivery trucks could essentially double the efficiency of the baseline 1990 vehicle.

The usage of alternative diesel-like fuels does not appear to have any technological barriers for heavy trucks, but while these fuels could reduce GHG emissions, they would not lower actual fuel consumption, and we need to reduce both in order to meet the 2050 target. Thus, total heavy truck energy usage even with aggressive application of these efficiency technologies (reducing per mile energy usage by 50%) would essentially double from 1990 to 2050.

IX. Energy Usage Realistic Cases

Two distinct realistic scenarios were developed (PEVs and Combined PEV and FCV) and are meant to present reasonable, yet still technologically optimistic scenarios of what could happen in the future. A number of elements are common to both storylines, including the fuel economy and VMT assumptions for light-duty vehicles and assumptions about the other transportation sectors, including aviation, marine and rail sectors. Energy use, broken out by different fuel types, liquid fuels, electricity and hydrogen, is presented for each of these scenarios. Greenhouse gas emissions are not presented in the discussion of the transportation sector because this section deals primarily with the potential for reductions in energy demand, rather than the supply of low-carbon transportation fuel. However, the CEF fuels and electricity analyses have identified sufficient quantities of very low carbon hydrogen and electricity, while also determining that there is likely to be a shortfall in terms of sufficient low-carbon liquid fuels (i.e. biofuels) (CCST 2011a). As a result, transportation demands that require liquid fuels will continue to use some level of petroleum-based fuels (i.e. diesel, gasoline, bunker fuel oil, jet/kerosene).

A number of current California policies are relevant to the electrification (including hydrogen) of the fleet. First is the ZEV mandate, which requires a certain number of zero-emission and partially zero emission vehicles in the state (i.e. BEVs, PHEVs and FCVs). The mandate requires 7,500 pure ZEVs in 2012-2014 and 25,000 by 2015-2017. Other key regulations are the AB 1493 (i.e. "Pavley") and CAFE standards, leading to new vehicle fuel economies of 35 mpg by 2016 and 49.6 mpg by 2025. The low carbon fuel standard (LCFS) mandates reductions in the average carbon intensity of fuels (gCO_2e/MJ fuel) by 10% in the year 2020. Each of these regulations incentivizes the adoption and operation of plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell vehicles (FCVs).

For LDVs, the individual cases (PEV and Combined PEV and FCV storylines) significantly reduce total energy use in the light-duty sector relative to 1990 (55-67% reduction). The difference between the two storylines in terms of liquid fuel usage is interesting. In the PEV case, about 72% of LDV fuel still comes from liquid fuels, while this value is only 15% in the combined case. This is a function of the significant fleet of PHEVs (about 60% of all PEVs), their significant use of liquid fuels (about 50% of energy usage is liquid fuels) and the large number of conventional and HEVs still in the fleet (about 40%). Whereas, FCVs that use only hydrogen make up 59% of all vehicles in the fleet in the combined storyline. A reduction in carbon intensity of approximately 55% would enable LDVs to achieve an 80% reduction in emissions relative to 1990. However, there is significant potential to reduce electricity, hydrogen and liquid fuel carbon intensity by much more (70% or more) and the low levels of liquid fuel usage make it easier to produce the required quantity of low carbon fuels (biofuels, electricity and hydrogen).

Figure 11 shows that the remaining transportation subsectors primarily use liquid fuels such that overall, in 2050 liquid fuels would make up the majority of fuel usage (PEV: 87% combined: 77%). Total energy use for all transportation is reduced only slightly from 1990 values (16-24%) because of significant demand increases in aviation, marine and heavy-duty. While light duty exhibits a significant reduction in fuel usage, most other sectors do not show reductions as large, because of increased transportation demand and lower potentials for reduced energy use per mile.

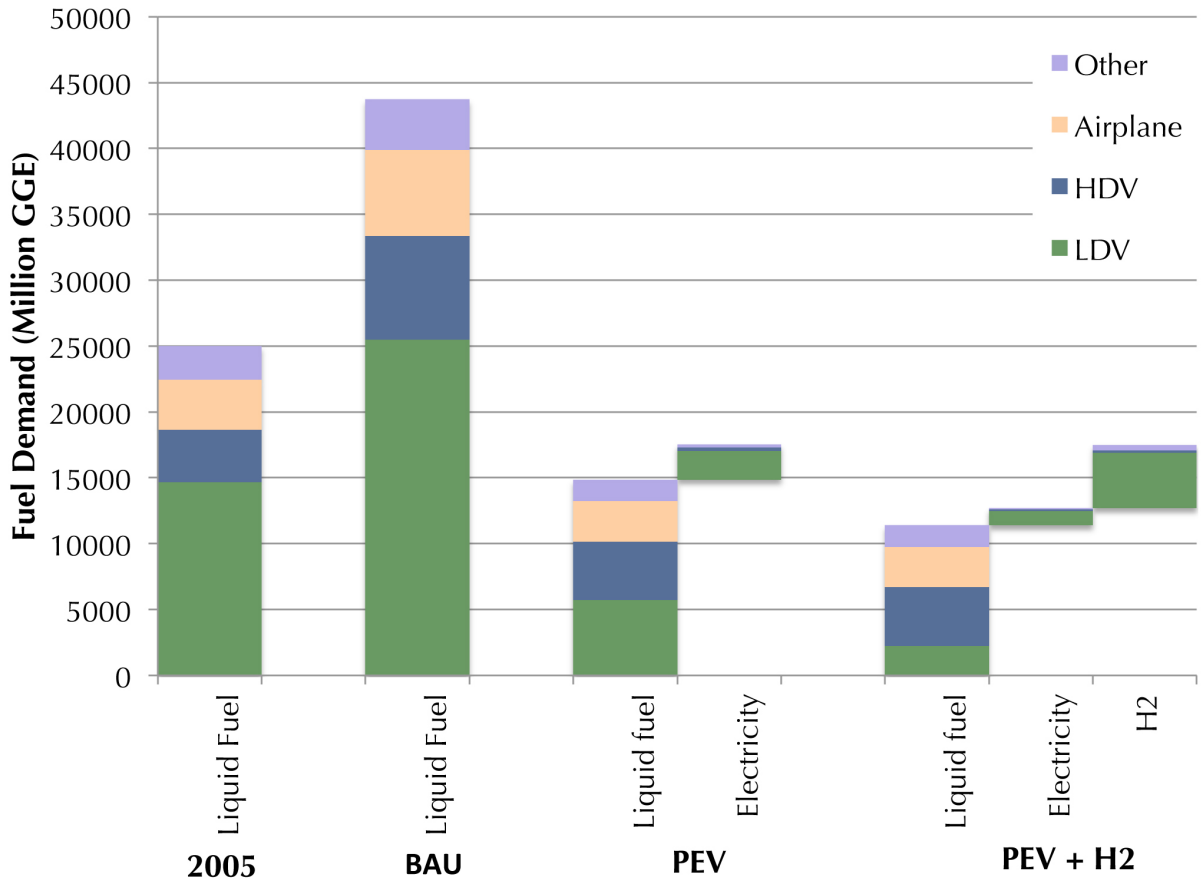


Figure 11. Total transportation fuel use broken down by subsector and fuel type for each scenario

X. Report Discussion and Conclusions

Transportation vehicle efficiency and electrification are important tools for reducing the demand for energy and the generation of greenhouse gas emissions from the transportation sector. However, given the projected population increase and the expected growth in per capita travel demand (for light-duty as well as aviation, heavy-duty and other sectors), efficient vehicle technology alone cannot meet the goal of reducing emissions from transportation by 80%. The addition of low-carbon fuels including biofuels, electricity and hydrogen, as well as options to reduce travel demand, are important for reducing transportation emissions beyond what vehicle efficiency can do alone.

It is expected that there will be limited supply of low-carbon biofuels available for use in the transportation sector and other sectors of the energy system. At the margin, this means that the ability to reduce the liquid fuel usage by one gallon would likely correspond to burning one less gallon of high carbon petroleum fuels and resulting emissions. Reducing liquid fuel usage in transportation can be accomplished by electrifying vehicles to use electricity or hydrogen, increasing energy efficiency of vehicles that continue to use liquid fuels, and reducing travel demand. Electrification of vehicles also has the added benefit of greatly increasing energy efficiency per mile of travel.

Substantial reductions in travel demand appear to be possible but would require significant changes in behavior, development and land use patterns, or price signals associated with driving and/or fuels. These behavior change options and the policies that might bring them about will be important for achieving deep GHG reductions but for clarity, they are not included in the technology scenarios.

Plug-in electric vehicles and hydrogen fuel cell vehicles are two important technologies that can greatly reduce energy use and emissions in the light-duty sector. PHEVs do not suffer from the range limitations and high costs that are expected from BEVs. However, because of their limited battery sizes, they are not able to reduce liquid fuel usage as much as BEVs or FCVs. There are important fleet turnover issues in the near-term that slow the growth of PEVs and FCVs and limit their ability to greatly reduce emissions or energy use before 2030. Nonetheless, they have an important role to play in reducing energy use and emissions in 2050. The ultimate market penetration and effectiveness of PEVs could be limited by the lack of universally available home-based charging options, limited energy storage (i.e. range), longer refueling times associated with charging batteries and high cost of batteries, especially for larger vehicles.

The addition of FCVs to the median (PEV) scenario allows FCVs to be used by drivers who do not have access to convenient home-based charging, want longer range and faster refueling, and also allows for electrification of larger vehicles than would be cost-effective with battery technology. FCVs will need to overcome high costs associated with fuel cells and hydrogen storage, as well as fuel availability issues which will require deployment of stations and vehicles in a coordinated fashion. Very low carbon intensity electricity and hydrogen should be available in sufficient quantities in 2050 to supply their use in transportation.

Even without a major shift in the drivetrain technologies associated with other transportation subsectors (aviation, heavy-duty trucks, marine) there is significant potential for improved efficiency and use of low-carbon liquid fuels to reduce emissions. The two realistic scenarios which push advanced technologies yield a total fuel usage in the transportation sector that is approximately 30% below 2005 and over 60% below BAU on an energy basis. The combined PEV + FCV scenario is able to reduce liquid fuel demand by approximately four billion gge relative to the PEV scenario.

The main conclusions from this analysis are as follows:

- Without policy intervention, total travel demand in every transportation subsector is expected to increase between 50 and 100% from 2005 to 2050 due to population growth and increasing travel demand per capita, with the most growth occurring in light-duty, heavy-duty and aviation sectors (Caltrans 2008, AEO 2011).

- Total transportation energy demand could be reduced 30% relative to 2005 levels in 2050 through improving overall vehicle efficiency (which includes the use of advanced electric-drivetrains such as PEVs and FCVs). Additional reductions in energy use would accrue if options to control travel demand were also included.

- Improving efficiency with conventional combustion and hybrid technologies is the easiest and most cost-effective method for reducing fuel usage from the transportation sector, but this approach is not enough by itself to achieve 80% reductions in GHG emissions if petroleum fuels continue to be used.

- Electrification of vehicles using plug-in electric vehicles (PEVs) or hydrogen fuel cell vehicles (FCVs) can further improve efficiency of light-duty vehicles (LDVs) while also lessening the reliance on liquid fuels and allowing for use of very low carbon sources for electricity or hydrogen.

- From a technology standpoint, PEVs and FCVs are commercially available (Bin 1) or demonstration phase (Bin 2) technologies,[6] though key component costs (batteries, fuel cells and H_2 storage) are currently high and would need to be reduced by a factor of 2 or more for widespread adoption.

- Achieving high fleet penetration of efficient and alternatively fueled light-duty vehicles by 2050 will require rapid market adoption in the next decades.

- High initial costs, consumer unfamiliarity with advanced technologies, and limited availability of those technologies across vehicle makes and models will slow the market expansion of advanced light-duty vehicles. The relatively slow penetration of hybrid vehicles into the market since 2000 is suggestive of the challenges facing PEV and FCV adoption; arguably electric drive vehicles could face even more difficult barriers.

- Because less than 50% of car owners have access to dedicated, off-street parking at home, and because battery costs will be high for larger vehicle sizes, universal PEVs adoption appears unlikely.

- Hydrogen fuel cell vehicles (FCVs) will offer a range around 300 miles, and 5 minute refueling time, potentially avoiding the PEV limitations, making them potentially attractive for larger vehicles (light trucks and SUVs) and those without access to dedicated, off-street parking. FCVs are a useful complement to BEVs, which have limited range and long refueling times.

- Even with substantial conversion of light-duty and some other sectors to electricity and hydrogen, liquid fuel demand will remain strong, likely exceeding the availability of sustainable, low-carbon biofuel supplies and thereby necessitating some continued use of petroleum-based fuels.

6 See main report (CCST 2011) for more detailed description of technology readiness bins.

- Aviation, marine and heavy-duty trucks, are likely to continue to use liquid hydrocarbon fuels (from petroleum or biofuels) because of fuel energy density considerations. Technologies that improve the efficiencies of these systems can thus directly reduce fossil fuel demand.
- A policy framework targeting efficiency and low-carbon fuels exists to bring about GHG reductions in the light-duty and heavy-duty sectors, but may need to be expanded to other transportation subsectors, such as aviation and marine.

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Appendix B: Acronyms

AEO	Annual Energy Outlook
ARB	Air Resources Board
BAU	Business-As-Usual
BEV	Battery Electric Vehicle
CAFE	Corporate Average Fuel Economy
DOE	United States Department of Energy
EPA	Environmental Protection Agency
EV	Electric Vehicle
FCV	Fuel Cell Vehicle (running on hydrogen)
FT	Fischer-Tropsch
gge	Gallons of Gasoline Equivalent
GHG	Greenhouse Gas
H_2	Hydrogen
HEV	Hybrid Electric Vehicle
HOV	High Occupancy Vehicle
HRJ	Hydroprocessed Renewable Jet Fuel
ICEV	Internal Combustion Engine Vehicle (i.e. conventional gasoline or diesel vehicle)
LCFS	Low Carbon Fuel Standard
LDV	Light Duty Vehicle
mpg	Miles per Gallon
mpgge	Mles per Gallon of Gasoline Equivalent
OEM	Original Equipment Manufacturer
PEMFC	Proton Exchange Membrane Fuel Cell
PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
VMT	Vehicle Miles Traveled
ZEV	Zero Emission Vehicle

(Footnotes)

1 Future gasoline carbon intensity is assumed to be 10% lower than 2007 value because of the Low Carbon Fuel Standard (LCFS) but could be even lower if the stringency of the standard is increased

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