SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS

A Research Summary for Decision Makers

Edited by Joan Ogden and Lorraine Anderson

UC DAVIS
INSTITUTE OF TRANSPORTATION STUDIES

Institute of Transportation Studies
University of California, Davis
One Shields Avenue, Davis, California 95616

Chapter 9: Transition Scenarios for the U.S. Light-Duty Sector[1]

Joan Ogden, Christopher Yang, and Nathan Parker

Besides imagining how a combination of alternative fuels and new vehicle technologies can help us meet GHG reduction targets, it is important to consider how transportation—particularly the light-duty sector—might make the transition to a low-carbon future. The light-duty vehicle (LDV) sector accounts for about two-thirds of energy use and greenhouse gas (GHG) emissions from transportation in the United States. Automakers are targeting light-duty markets for advanced electric-drive technologies such as plug-in hybrids and hydrogen fuel cell vehicles. In this chapter, we analyze and compare alternative scenarios for adoption of new LDV and fuel technologies that could enable deep cuts in gasoline consumption and GHG emissions by 2050. We also estimate the transitional costs for making new vehicle and fuel technologies economically competitive with gasoline vehicles. We do this with the caveat that concentrating only on the light-duty fleet may miss important constraints, especially for biofuels—which may be needed to make liquid fuels for air and marine transportation.

Our Scenarios

We analyze and compare these scenarios:

- **Efficiency**—Currently feasible improvements in gasoline internal combustion engine vehicle (ICEV) and hybrid electric vehicle (HEV) technology are introduced.
- **Biofuels**—Large-scale use of low-carbon biofuels is implemented.
- **PHEV success**—Plug-in hybrid electric vehicles (PHEVs) play a major role beyond 2025.
- **FCV success**—Hydrogen fuel cell vehicles (FCVs) play a major role beyond 2025.
- **Portfolio**—More-efficient ICEVs + biofuels + PHEVs + FCVs are implemented in various combinations.

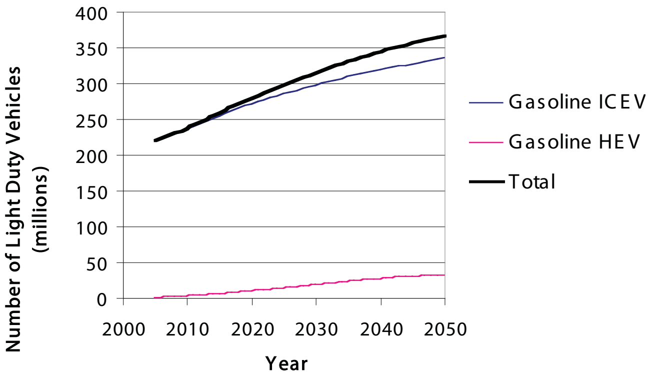
All scenarios assume the same total number of vehicles and vehicle miles traveled, but the vehicle mix over time is different for each scenario. We compare each scenario to a reference scenario where modest improvements in efficiency take place and use of biofuels increases but no electric-drive vehicles are implemented. We estimate future GHG emissions and gasoline use for each scenario.

The reference scenario

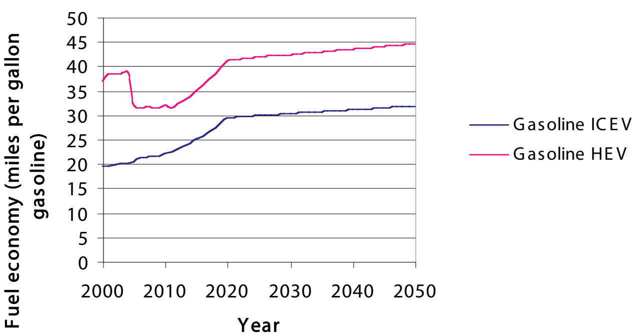
Our reference scenario is based on projections to 2030 by the U.S. Department of Energy.[2] We use the Energy Information Administration's high oil price case—where oil prices in the period from 2010 to 2030 are projected to vary from $80 to $120 per barrel—for the number of vehicles and their fuel consumption, oil prices, and other factors. We extend these projections to 2050, assuming that the average growth rate between 2010 and 2030 remains the same for the two decades that follow.

In this scenario, ICEVs continue to dominate the light-duty sector. HEVs gain only about 10 percent fleet share by 2050. The fuel economies of these vehicles (that is, the on-road fuel economies, which are 20 percent lower than EPA sticker fuel economies) follow Energy Information Administration (EIA) projections, meeting 2020 fuel economy standards, with only modest improvements beyond this time. HEVs reach an on-road fuel economy of 44.5 mpg in 2050, while conventional gasoline cars reach 31.7 mpg.

REFERENCE SCENARIO: NUMBERS OF LDVS AND FUEL ECONOMIES TO 2050



In our reference scenario, gasoline internal combustion engine vehicles (ICEVs) continue to dominate the light-duty sector. Gasoline hybrids (HEVs) gain only about a 10-percent fleet share by 2050.



The fuel economy of new LDVs meets 2020 fuel economy standards and improves only modestly beyond that time. HEVs reach an on-road fuel economy of 44.5 mpg in 2050, while conventional gasoline cars reach 31.7 mpg.

In the reference scenario, a significant amount of biofuel is used: 12 billion gallons of corn ethanol are produced by 2015 (and production stays at this level to 2050), and a growing amount of cellulosic ethanol is produced after 2012. In 2050, corn ethanol production is 12 billion gallons and cellulosic ethanol production an additional 12 billion gallons.

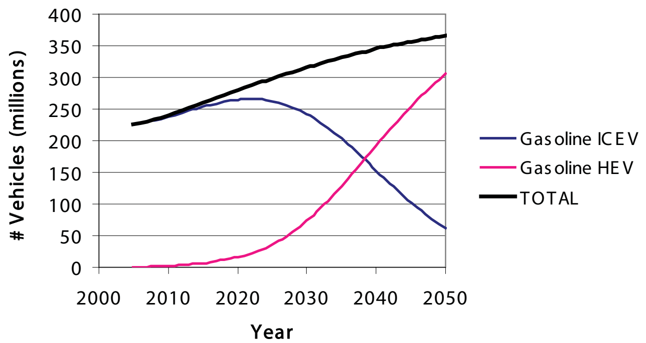
The efficiency scenario

In our efficiency scenario, improvements in engines and other vehicle technologies are implemented at a more rapid rate than in the reference scenario. The fuel economy of ICEVs and HEVs is assumed to increase as follows:

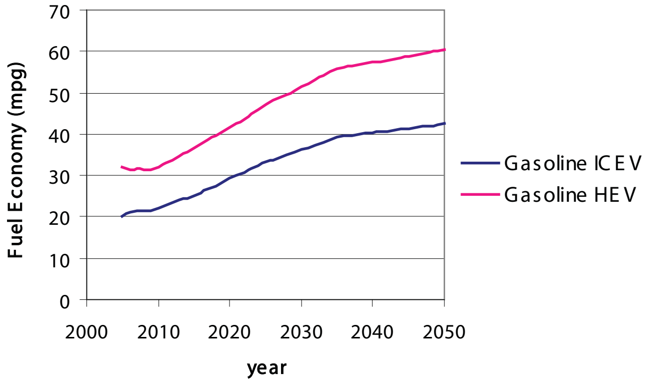
- 2.7 percent per year from 2010 to 2025
- 1.5 percent per year from 2026 to 2035
- 0.5 percent per year from 2036 to 2050

In addition, HEVs become the dominant technology, comprising 80 percent of the fleet by 2050. Fuel economy for ICEVs and HEVs approximately doubles by 2050, when HEVs average 60 mpg and ICEVs 42 mpg.

EFFICIENCY SCENARIO: NUMBERS OF LDVS AND FUEL ECONOMIES TO 2050



In our efficiency scenario, HEVs become the dominant technology, comprising 80 percent of the fleet by 2050. Numbers of ICEVs on the road drop off sharply after 2025 and are exceeded by numbers of HEVs by 2038.



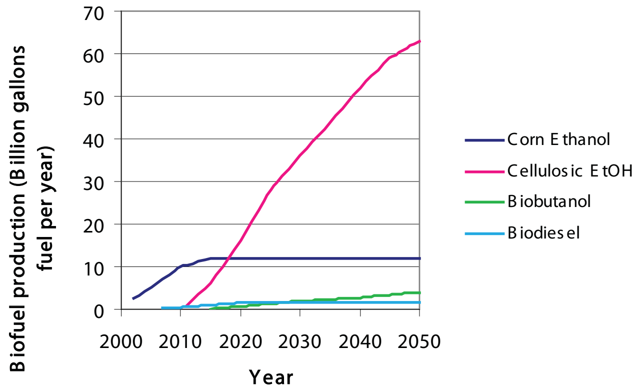
On-road fuel economy for ICEVs and HEVs approximately doubles by 2050, when HEVs average 60 mpg and ICEVs 42 mpg.

The biofuels scenario

In our biofuels scenario, we assume that biofuels are introduced at a rapid rate, reaching an optimistic total of 75 billion gallons per year in 2050. Production of corn ethanol levels off, but cellulosic ethanol grows rapidly, reducing carbon emissions (well-to-wheels GHG emissions for cellulosic ethanol are only 15 percent those of gasoline). Competition with food crops and indirect land-use impacts on GHG emissions are not considered in this analysis. As discussed in Chapter 8, liquid biofuels may be required in heavy-duty aviation and marine applications, where electric battery and hydrogen fuel cell drivetrains are not practical. This could limit the amount of biofuel available for light-duty vehicles. It is important to note that this particular biofuel scenario is not the only feasible path forward: other scenarios are discussed in Chapter 1, using large amounts of "drop-in" biofuels similar to gasoline and diesel in addition to cellulosic ethanol (see Chapter 1). Moreover, the uncertainties in biofuel GHG emissions could influence the amount of carbon reductions that could be achieved with biofuels. These issues are discussed in Chapters 1, 6, and 12.

We assume that ICEVs capable of running on biofuels will have only a small incremental cost compared to gasoline vehicles, and that these vehicles can be mass-produced quickly. Further, we assume that biofuel vehicles will have the same fuel economy as gasoline cars.

BIOFUELS SCENARIO: BIOFUELS PRODUCTION TO 2050



In our biofuels scenario, we assume that biofuels are introduced at a rapid rate, reaching 75 billion gallons per year in 2050. Production of corn ethanol levels off, but cellulosic ethanol grows rapidly.

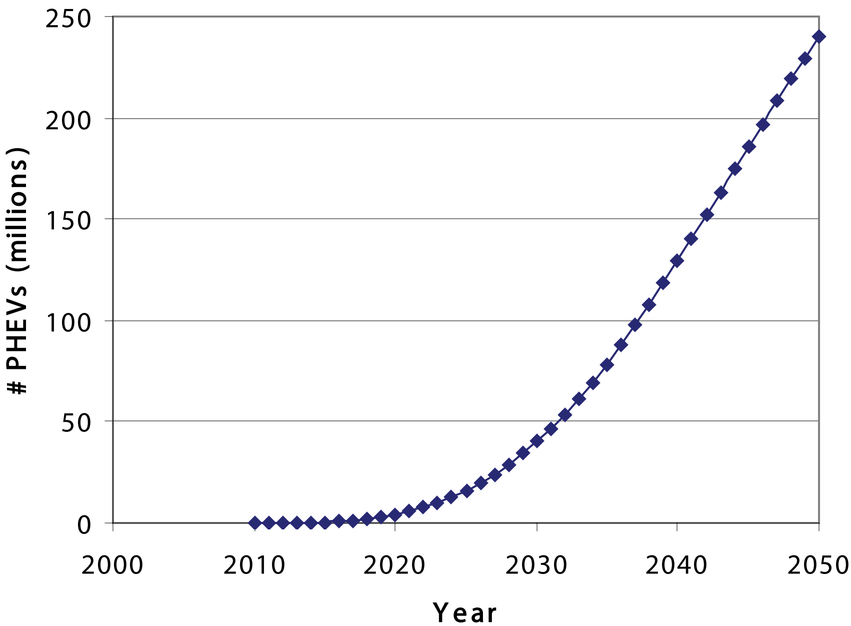
These are optimistic estimates for implementing large-scale biomass supply systems, as Chapter 1 indicates. Studies by Parker et al.[3] suggest that about 24 billion gallons gasoline equivalent (or 36 billion gallons of ethanol) might be available at less than $3.25 per gallon gasoline equivalent in 2018. Beyond this level of production fuel costs rise rapidly, making biofuels less economically attractive. Advances in energy crop yields, crop yields and conversion efficiencies may increase the production potential by 2050.

The PHEV success scenario

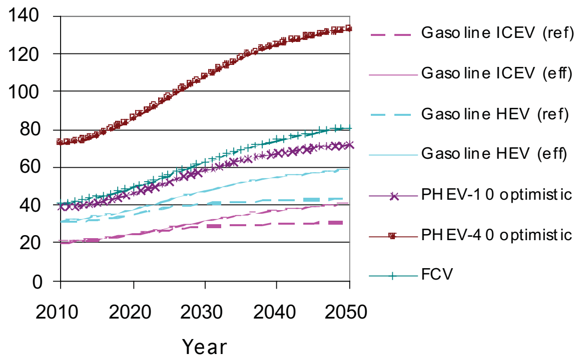
Following the 2009 National Academies report on plug-in hybrids,[4] we analyze an optimistic market penetration scenario for plug-in hybrids, where PHEVs are introduced in 2010 and markets grow rapidly. This case assumes strong policy support for PHEVs so that 1 million vehicles are on the road in 2017 and 10 million by 2023; by 2050, about two-thirds of all light-duty vehicles are PHEVs. The National Academies also analyzed a more pessimistic case where PHEVs account for about 30 percent of the fleet in 2050 and market growth is slower. This case was not economically attractive and for simplicity is not presented here.

Two types of PHEVs are modeled: a PHEV-10, which has a battery large enough to provide a 10-mile all-electric range, and a PHEV-40, with a larger battery that offers a 40-mile all-electric range. We calculated the fuel economies (averaged over the driving patterns of the entire fleet) for gasoline ICEVs and HEVs (based on both reference scenario and efficiency scenario fuel economies), PHEV-10s, and PHEV-40s. The gasoline fuel economy of PHEVs increases over time at the same rate as that of HEVs in the efficiency scenario. We assume that PHEVs will incorporate all the most efficient aspects of evolving HEV technology, as well as lighter-weight materials, streamlining, and so on.

PHEV SUCCESS SCENARIO: NUMBERS OF PHEVS AND FUEL ECONOMIES TO 2050



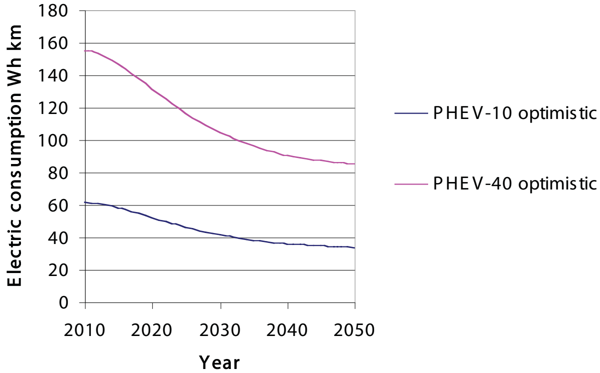
We analyze an optimistic case in our PHEV success scenario. PHEVs are introduced in 2010, and 1 million vehicles are on the road in 2017 and 10 million by 2023; by 2050, about two-thirds of all light-duty vehicles are PHEVs.



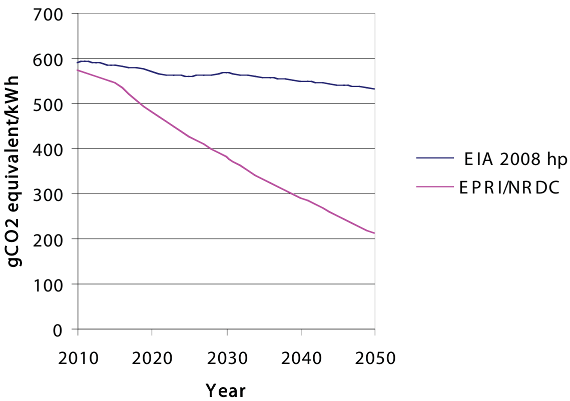
We assume that fleet average fuel economy for all different types of vehicles increases over time. Gasoline fuel economy is highest for PHEVs with a 40-mile electric range (note that this does not include electricity use, which is shown in the next figure). Fuel economy for FCVs is given in gasoline-equivalent energy.

PHEVs also drive some fraction of their total miles on electricity. For a PHEV-10, we assume that about 19 percent of the miles are driven on electricity, and for a PHEV-40, about 55 percent of the miles.[5] The source of electricity has a strong impact on the environmental benefits of PHEVs versus HEVs.[6] We analyze two possibilities for the future electricity system. One is a business-as-usual grid based on projections by the U.S. Department of Energy.[7] The other is a low-carbon grid based on studies by the Electric Power Research Institute (EPRI) and the Natural Resources Defense Council (NRDC).[8] In the low-carbon grid, emissions per kWh are reduced by about two-thirds through a variety of more-efficient and lower-carbon generation technologies, including advanced renewables, carbon capture and sequestration (CCS), and nuclear power.

PHEV SCENARIO: ASSUMED ELECTRICITY USE AND GRID GHG EMISSIONS TO 2050



We averaged the assumed electricity use per kilometer over the fleet drive cycle for PHEV-10s and PHEV-40s over time. For a PHEV-10, we assume that about 19 percent of the miles are driven on electricity, and for a PHEV-40, about 55 percent of the miles.



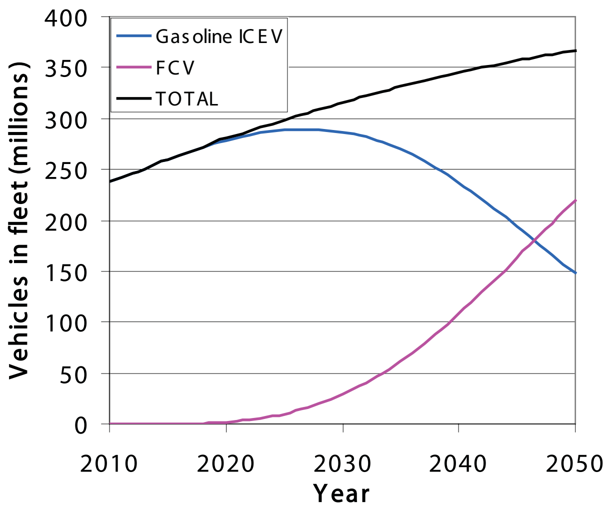
The environmental benefits of PHEVs will hinge on how electricity is generated. We compared GHG emissions per kilowatt hour of electricity for a business-as-usual future grid (EIA) and a low-carbon future grid (EPRI/NRDC). In the low-carbon grid, emissions per kWh are reduced by about two-thirds through a variety of more-efficient and lower-carbon generation technologies, including carbon capture and sequestration (CCS), advanced renewables, and nuclear power.

The FCV success scenario

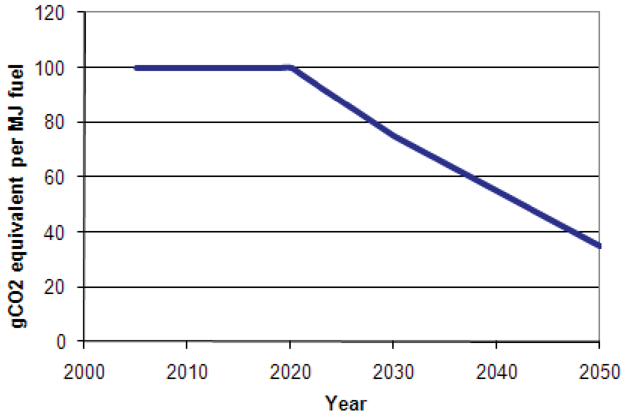
Finally, we consider a range of cases where hydrogen fuel cell vehicles are successfully developed. We assume that hydrogen fuel cell vehicles (FCVs) are introduced beginning in 2012, reaching 10 million on the road by 2025 (4 percent of the fleet) and 60 percent of the fleet by 2050.[9] Initially, hydrogen is produced from natural gas, but over time energy sources that emit less carbon are used to produce hydrogen: biomass gasification and coal gasification with carbon capture and sequestration (see Chapter 3).

As with electric vehicles, the source of hydrogen makes a difference in the well-to-wheels GHG emissions of FCVs. Following the modeling in "The Hydrogen Fuel Pathway," we assume that hydrogen is made from progressively lower-carbon sources over time. As with electricity in the low-carbon case, we assume that the GHG emissions per megajoule (MJ) of fuel will fall by about two-thirds by 2050 through expanded use of renewables and carbon capture technology in hydrogen production.

FCV SCENARIO: NUMBERS OF VEHICLES AND ASSUMED GHG EMISSIONS FROM H_2 TO 2050



In the FCV success scenario, hydrogen fuel cell vehicles (FCVs) are introduced beginning in 2012, reaching 10 million on the road by 2025 (4 percent of the fleet) and 60 percent of the fleet by 2050.

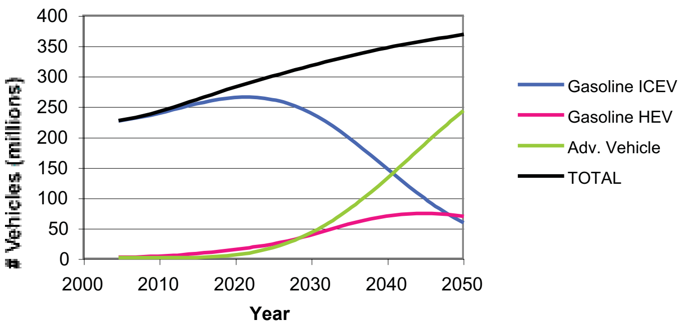


We assume that well-to-wheels GHG emissions per MJ of hydrogen will decrease over time. Before 2025, we assume that H_2 will be made primarily from on-site steam methane reforming. Later, centralized H_2 plants using biomass or coal with CCS will be phased in.

The portfolio scenarios

We have just described single-pathway scenarios based on implementing efficiency, biofuels, PHEVs, and FCVs. But it is more likely that a range of policies will be put into place to incentivize higher-efficiency gasoline vehicles while advanced vehicle technologies (like PHEVs and FCVs) and new fuels (biofuels and hydrogen) are being developed. To model this, we developed a series of portfolio scenarios that combine efficiency and advanced vehicles and fuels in different ways. In one of our portfolio scenarios, we combined the efficiency scenario with the rapid introduction of advanced vehicles. We added the introduction of low-carbon biofuels (similar to the biofuels scenario) to the mix in another portfolio scenario.

PORTFOLIO SCENARIO: NUMBERS OF LDVS TO 2050



In this portfolio scenario, advanced vehicles (PHEVs or FCVs) are deployed rapidly so that their number surpasses that of ICEVs after 2040, when the number of HEVs peaks.

Comparing Strategies to Reduce Gasoline Use and GHG Emissions

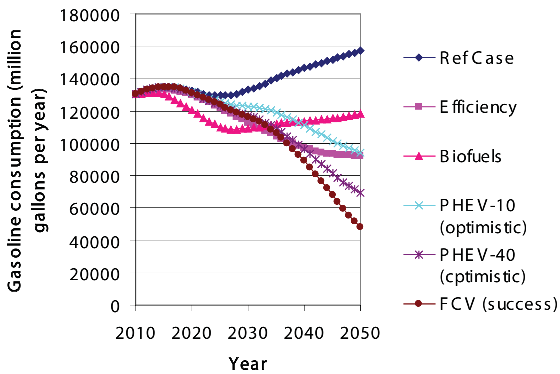
We have outlined our reference scenario, four single-pathway scenarios, and our portfolio approach in terms of numbers of light-duty vehicles and fuel economies. Now let's compare the different scenarios with respect to gasoline use and GHG emissions.

Gasoline use

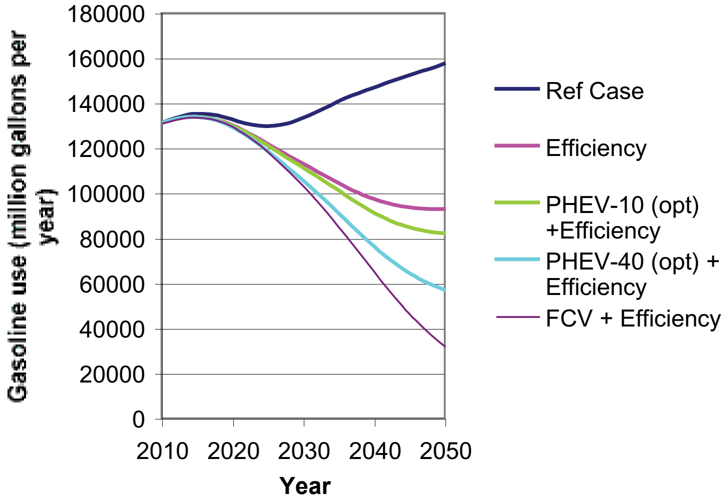
First we consider gasoline use in our single-pathway scenarios. With rapid deployment of biofuels, it would be possible to displace gasoline use starting before 2020, although the effect of biofuels plateaus because of constraints on production. None of the other options results in noticeable gasoline savings before about 2025, because of the time required to bring new vehicle types into the fleet. After 2025, the efficiency scenario leads to a rapid decrease in gasoline use compared to the reference case. If we replace a certain number of gasoline ICEVs with FCVs or PHEVs without changing the ICEV efficiency, there is a major decrease in gasoline use beyond 2030. In the long term, FCVs yield the greatest reduction in gasoline use of the technologies considered.

What about the portfolio scenarios, where efficiency technologies are implemented in ICEVs and HEVs along with rapid adoption of advanced electric-drive technologies such as PHEVs or FCVs and introduction of low-carbon biofuels? We find in our scenario combining the efficiency case with introduction of advanced vehicles that gasoline use starts to decline rapidly after about 2015. When we combine the efficiency case with introduction of advanced vehicles and low-carbon biofuels, we find that gasoline use starts to decline immediately and reaches 0 before 2050 for the case where FCVs are combined with efficiency and biofuels. Clearly, any portfolio approach is superior to any of the single-pathway approaches in terms of how soon and how much it will reduce gasoline use.

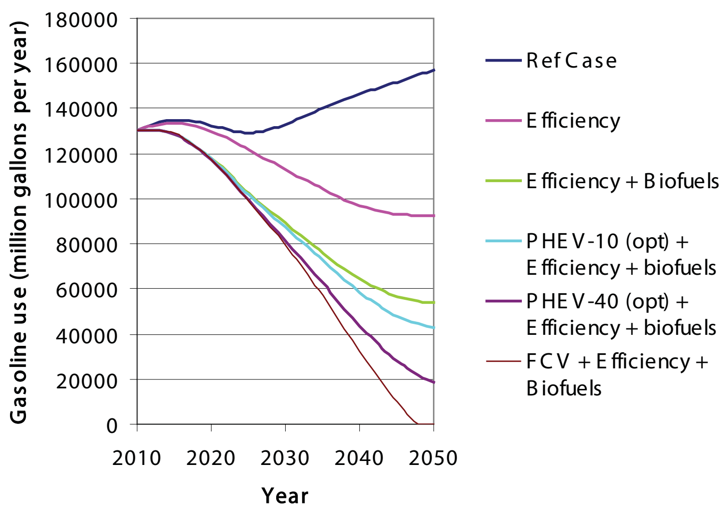
GASOLINE USE FOR OUR SCENARIOS TO 2050



Gasoline use does not decrease noticeably before about 2025 in our single-pathway efficiency, PHEV and FCV scenarios because of the time required to bring these new vehicle types into the fleet. Biofuels could have an impact earlier, but after an initial reduction starting before 2020, the effect of biofuels plateaus because of constraints on production. In the long term, FCVs yield the greatest reduction.



In one portfolio scenario, we combined the efficiency case with introduction of advanced vehicles. Gasoline use starts to decline rapidly after about 2015 in this scenario.



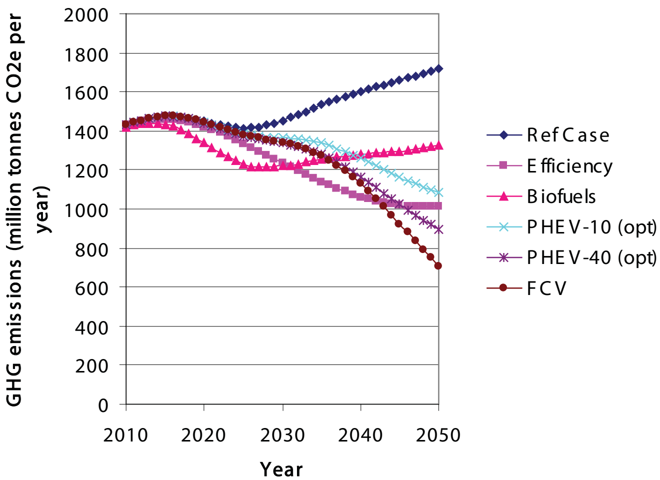
In another portfolio scenario, we combined the efficiency case with introduction of advanced vehicles and low-carbon biofuels. Gasoline use starts to decline immediately and reaches 0 before 2050 for the case where FCVs are combined with efficiency and biofuels.

GHG emissions

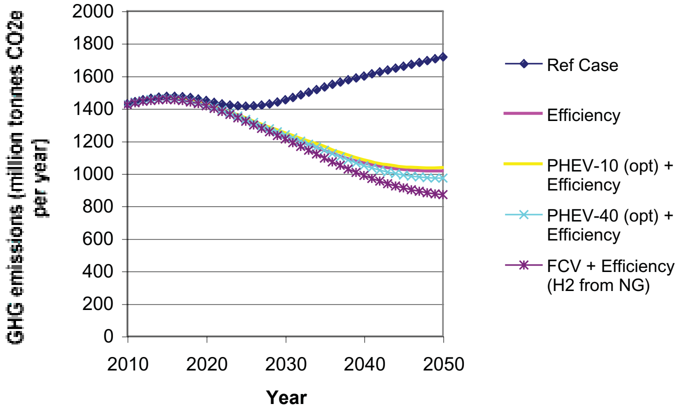
Trends similar to those for gasoline use hold for GHG emissions in single-pathway scenarios. PHEV and FCV scenarios don't show a marked decrease in GHG emissions before about 2030. No single pathway can meet societal goals for deep cuts in carbon (such as an 80-percent reduction) by 2050.

The importance of moving to a low-carbon energy supply can be seen when we compare the GHG emissions for the reference case, the efficiency case, and portfolio scenarios combining advanced vehicles with efficiency and with efficiency plus biofuels. Assuming a business-as-usual energy supply (the EIA fossil-intensive electric grid and H_2 made from natural gas), GHG emissions with PHEVs + efficiency are no lower than those from improved ICEV efficiency alone, and FCVs + efficiency show only about a 10-percent reduction by 2050. By contrast, assuming a low-carbon grid and H_2 production from low-carbon sources, GHG emissions trend lower in the three advanced vehicle cases. This highlights the importance of decarbonizing the energy supply (electricity and fuels) as advanced vehicles are introduced.

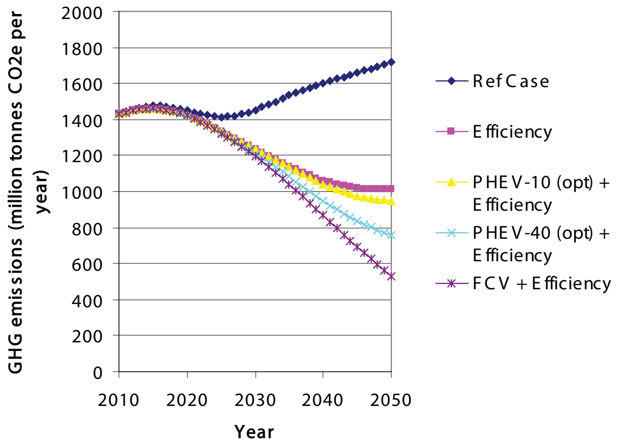
GHG EMISSIONS FOR OUR SCENARIOS TO 2050



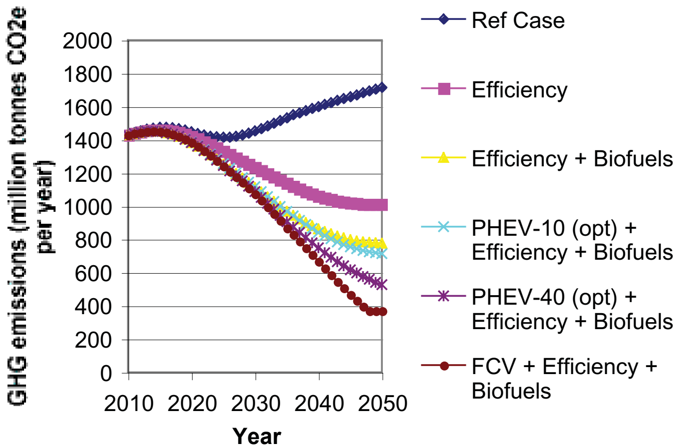
No single pathway can meet societal goals for deep cuts in carbon (such as an 80-percent reduction) by 2050. The PHEV and FCV scenarios don't show a marked decrease in GHG emissions before about 2030.



Assuming a business-as-usual energy supply (the EIA fossil-intensive electric grid and H_2 made from natural gas) for a portfolio scenario combining the efficiency case with introduction of advanced vehicles, GHG emissions from PHEVs or FCVs are not much lower than those from improved ICEV efficiency alone.



Assuming a low-carbon grid and H_2 production from low-carbon sources for a portfolio scenario combining the efficiency case with introduction of advanced vehicles, GHG emissions trend lower in the three advanced-vehicle cases than for efficiency alone.



Assuming a low-carbon grid and H_2 production from low-carbon sources for a portfolio scenario combining the efficiency case with introduction of advanced vehicles and biofuels, GHG emissions fall off sharply in the three advanced-vehicle cases.

Comparing Transition Costs

What will it cost to make the transition to biofuels, PHEVs, and FCVs? One of the major challenges facing any new alternative-fuel vehicle is reaching economic competitiveness with gasoline vehicles. Initially, the new vehicles are manufactured in small quantities and the cost is much higher than for a comparable gasoline vehicle, which is a major disincentive to consumers. Getting enough new alternative vehicles on the road to bring down costs is a key issue. For new fuel infrastructure, the analogous problem is putting in enough fueling stations to make it convenient for consumers and to bring down the cost of the fuel. The question is how much money must be invested in the first million or so vehicles and the early infrastructure to reach cost competitiveness.

To study this "buydown" process for alternative vehicles, we developed a transition model to aggregate transition costs over the entire fleet, based on models for evolving vehicle and fuel infrastructure. For PHEVs and FCVs, this includes buying down the vehicle cost and building new infrastructure. For biofuels, the delivered fuel cost is the main concern, since we expect that the cost of vehicles that can run on biofuels will be quite similar to the cost of gasoline vehicles. The issue is scaling up the biofuel supply chain to reach competitive fuel costs.

Vehicle costs

For both PHEVs and FCVs, we assume that vehicle costs will come down with learning and scaled-up manufacturing.

The key enabling technology for PHEVs is the battery. Although current PHEV battery costs are still too high to compete ($1000/kWh with a lifetime of five years; see Chapter 4), battery costs are projected to shrink to $250 to $400/kWh with a lifetime of ten to twelve years assuming technology improvements and economies of scale in mass production. For purposes of plotting the retail price of PHEVs, we assumed that batteries follow a learning curve trajectory from current costs to a "learned-out" mass-produced cost. [10] We analyzed two levels of technical progress for PHEVs, based on the recent National Research Council study: "optimistic" and "DOE goals."[11] In the optimistic case, the learned-out cost of batteries in 2030 is $360/kWh of nameplate capacity. In the DOE goals case, battery cost is roughly half of this, and these goals are achieved by 2020.

KEY PERFORMANCE AND COST ASSUMPTIONS FOR PHEV BATTERIES

	2010	2020	2030
Battery lifetime			
Optimistic	8 years	12 years	15 years
DOE goals	8 years	12 years	15 years
Battery pack cost per kWh nameplate			
Optimistic	$625	$400	$360
DOE goals	$625	$168–280 (DOE 2014 goal)	$168–280

Initially, hydrogen vehicles will be much more costly than gasoline vehicles, but as fuel cell and hydrogen storage technology improve and scale economies of mass production take hold, the price should fall rapidly. We estimated the retail price of a hydrogen fuel cell car based on a learning curve model developed by Greene et al.[12] For "learned-out" technology, the National Research Council H_2 success case finds a retail price difference of $3,600 between a hydrogen and a gasoline car.[13] (For the NRC H_2 partial success case, the price difference is about $6,100.)

KEY COST ASSUMPTIONS FOR FCVS

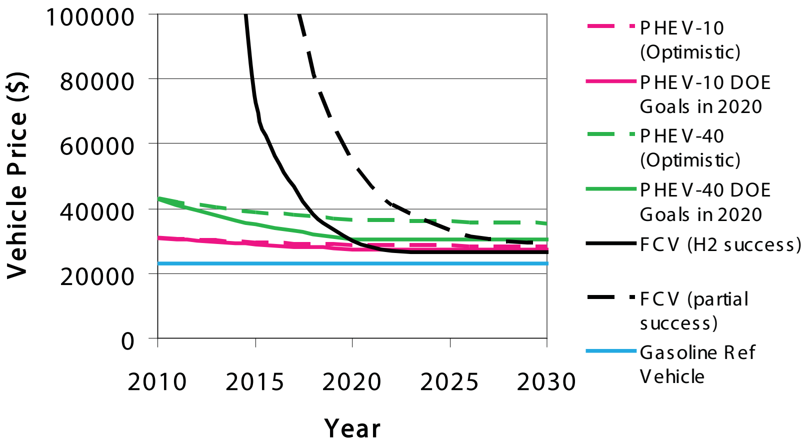
	2010	2020	2025-2030
Fuel cell system cost per kW			learned-out
H2 success	$1,000	$60	$50
Partial success	$1,000	$100	$75
H2 storage cost per kWh			learned-out
H2 success			$10
Partial success			$15

PROJECTED PRICE PREMIUM FOR PHEVS AND FCVS

This is the premium over the price of a gasoline ICEV that a purchaser of a PHEV or an FCV will pay. For reference, the price of the 2011 Chevy Volt is $41,000, about $24,000 more than a comparable Chevy ICEV car.

	2010	**2020**	**2030**
PHEV-10			
Optimistic	$7,700	$5,600	$5,100
DOE goals	$7,700	$4,500	$4,500
PHEV-40			
Optimistic	$20,000	$13,500	$12,200
DOE goals	$20,000	$7,600	$7,600
	2015	**2020**	**learned-out 2025-2030**
FCV			
Partial success	$120,000	$31,000	$6,100
H2 success	$39,000	$7,000	$3,600

PROJECTED RETAIL PRICE OF FCVS AND PHEVS TO 2030



Assuming a maximum practical market penetration scenario, the retail prices of new PHEV-10s and PHEV-40s are projected to drop somewhat in the period from 2010 to 2030 in the NRC optimistic case and DOE goals case but still remain above the price of a conventional ICEV. We assume that the price of FCVs will fall rapidly after their introduction in 2012, to the point where the price premium will be only $3,600 by 2025.

Infrastructure and fuel costs

As described in "The Hydrogen Fuel Pathway," we assume that early hydrogen infrastructure will be built in a phased or regionalized manner where hydrogen vehicles and stations are initially introduced in selected large cities like Los Angeles and New York and move to other cities over time. This so-called lighthouse concept reduces early infrastructure costs by concentrating development in relatively few key areas. We also assume that the delivered hydrogen cost will drop sharply over time and become competitive with gasoline. We used the UC Davis SSCHISM model to design hydrogen infrastructure and find the delivered hydrogen cost over time.[14]

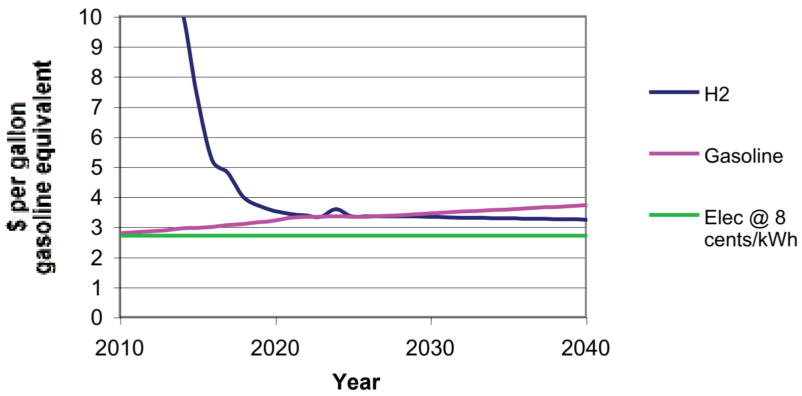
HYDROGEN FUEL SUPPLY IN THE U.S. OVER TIME, HYDROGEN SUCCESS SCENARIO

	2020	**2035**	**2050**
Number of cars served (percentage of total fleet)	1.8 million (0.7%)	61 million (18%)	219 million (60%)
Infrastructure capital cost	$2.6 billion	$139 billion	$415 billion
Total number of stations	2,112 (all on-site SMR)	56,000 (40% on-site SMR)	180,000 (44% on-site SMRs)
Number of central plants	0	113 (20 coal, 93 biomass)	210 (79 coal, 131 biomass)
Pipeline length (mi)	0	39,000	80,000
Hydrogen demand (tonnes/day)	1,410 (100% NG)	38,000 (22% NG, 42% biomass, 36% coal w/CCS)	120,000 (31% NG, 25% biomass, 44% coal w/CCS)

Source: National Research Council, Transitions to Alternative Transportation Technologies, A Focus on Hydrogen *(Washington, DC: National Academies Press, 2008).*

For PHEVs, we assume that the electricity cost for vehicle charging is 8 cents per kilowatt-hour. The capital cost for residential charging is $1,000–2,000 per charger.[15] We do not include costs for upgrades in transmission and distribution of electricity or building new power plants.

ASSUMED HYDROGEN COST, GASOLINE PRICE, AND ELECTRICITY PRICE TO 2040



We assume that the cost of delivered hydrogen will decrease rapidly starting in about 2015 and will become competitive with the price of gasoline by about 2025 on a gasoline-equivalent-energy basis. Counting the higher efficiency of fuel cells compared to gasoline cars, hydrogen competes on a fuel-cost-per-mile basis before 2020. Electricity at 8 cents per kWh is already less expensive than gasoline on a gasoline-equivalent-energy basis and we assume electricity prices for charging will stay at this level.

For biofuels, we assume as mentioned earlier that the main issue is scaling up the supply chain to reach cost competitiveness with conventional fuels like gasoline or diesel on an equivalent-energy basis. To estimate investment costs, we assume that the biofuel supply chain is built up over time, at costs determined by a national U.S. model.[16]

Several studies have estimated the costs to meet U.S. policy goals for biofuels. The U.S. Environmental Protection Agency[17] estimated that it would cost about $90 billion to meet the 2022 goal under the Renewable Fuel Standard of producing 36 billion gallons per year of bioethanol (enough to displace about 24 billion gallons per year of gasoline). More than 80 percent of the investment cost was for biorefineries, with the remainder for distributing bioethanol to users. Another study by Sandia National Laboratory[18] found that fuel infrastructure investments of about $390 billion would be required to produce 90 billion gallons of bioethanol per year in 2030 (displacing about 60 billion gallons of gasoline).

Studies by STEPS researchers Nathan Parker and Bryan Jenkins suggest that about $100-360 billion of investments in biorefineries would be needed to meet the U.S. Renewable Fuel Standard goal of 36 billion ethanol equivalent gallons of biofuel (displacing 24 billion gallons of gasoline) by 2022. The cost of biofuels should fall initially, with technology learning and scale economies for biorefineries. But beyond annual production levels of about 34 billion gasoline-equivalent gallons of biofuels, the fuel cost is estimated to climb sharply. The steep climb occurs once low-cost, environmentally desirable biomass resources have been exploited. STEPS analysis suggests an upper limit on the amount of economically competitive domestic biofuels at perhaps 20–30 percent of the fuel demand in the light-duty sector. (This limit is sensitive to assumptions about biomass productivity, biorefinery conversion efficiency, land-use constraints, and interactions with other sectors of economy.)

Because biofueled vehicles could be introduced quickly and at similar cost to gasoline vehicles, the rate of fuel supply build-up will determine the transition time for biofuels. The amount of low-cost biofuels available nationally is limited. Demands for liquid fuels from sectors such as aviation and marine may further limit the amount of biofuels that can be used in the light-duty sector (Chapter 8).

Cash flows

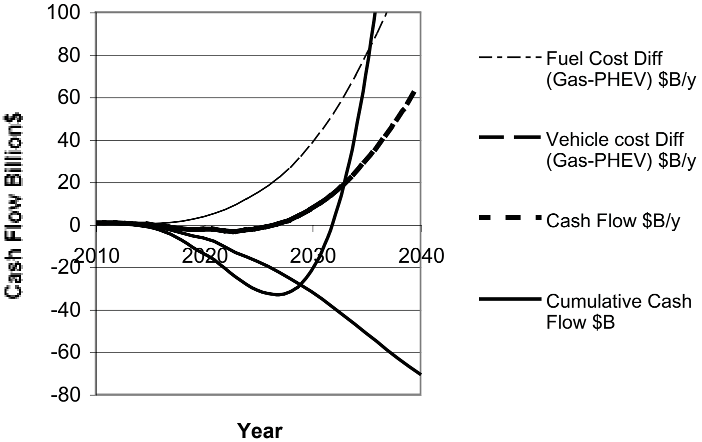
Based on these assumptions about PHEVs and FCVs, we conducted a transition cash-flow analysis to determine the investment costs required for PHEVs and FCVs to reach cost competitiveness with reference scenario gasoline vehicles. We estimated two components of this transition cost over time:

1. The incremental price of buying alternative-fuel vehicles (AFVs) each year, instead of gasoline cars; this is summed over all the AFVs sold in a given year and is the aggregated extra cost paid by consumers each year to buy AFVs instead of gasoline cars.
2. The difference between the annual cost of fuel for these AFVs and the annual cost of gasoline to go the same distance.

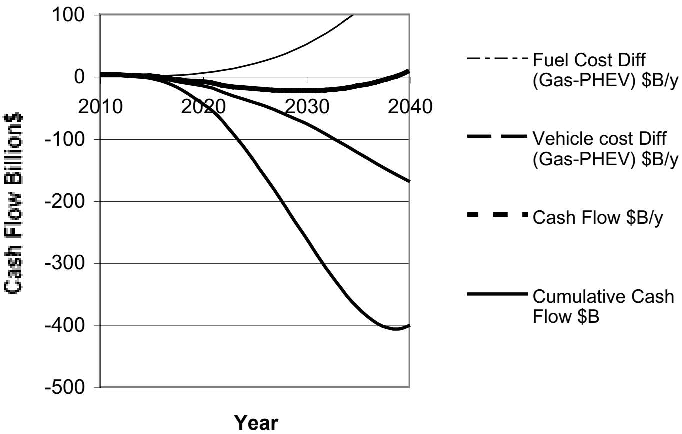
The annual cash flow or cost difference between a transition (where the alternative is introduced) and "business as usual" (all gasoline cars) is the sum of the vehicle first cost increment and the fuel cost increment. Cost competitiveness is achieved in the break-even year, when the total incremental cost for all the new AFVs bought that year is balanced by the annual fuel cost savings for all AFVs on the road in comparison to the reference gasoline vehicles.

NET CASH FLOWS FOR PHEVS AND FCVS, TRANSITION YEARS

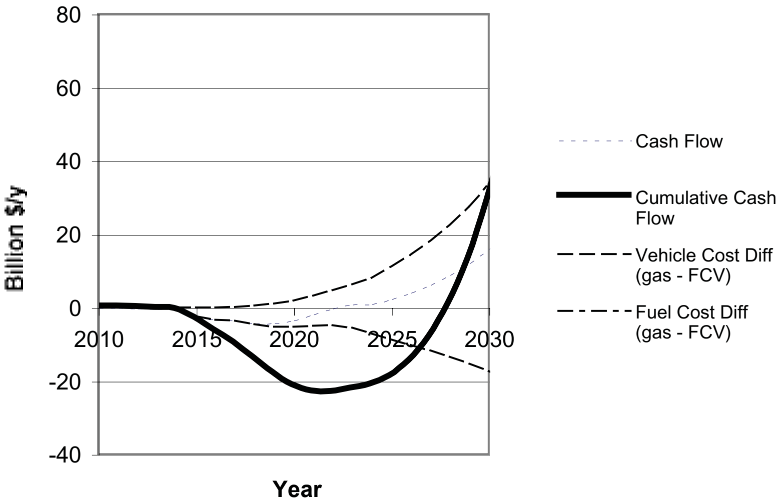
Positive cash flow values indicate that the cost of advanced vehicles and/or fuel is lower than the cost of gasoline vehicles and/or fuel.



*For the PHEV-10, case under optimistic technical assumptions, the break-even year is 2028 and the buydown cost is $33 billion. Source: National Research Council Transitions to Alternative T*ransportation Technologies, Plug-in Hybrid Electric Vehicles *(Washington, DC: National Academies Press, 2010).*



For the PHEV-40, maximum practical case under optimistic technical assumptions, the break-even year is 2039 and the buydown cost is $400 billion. Source: , NRC, Transitions to Alternative Transportation Technologies, Plug-in Hybrid Electric Vehicles *(Washington, DC: National Academies Press, 2010).*



For FCVs, the break-even year is 2023 and the buydown cost is $22 billion. Source: National Research Council, Transitions to Alternative Transportation Technologies, A Focus on Hydrogen *(Washington, DC: National Academies Press, 2008).*

Transition costs for PHEVs and FCVs compared

In the table below we compare the costs for different scenarios for the introduction of PHEVs and FCVs. The break-even year is the year when annual buydown subsidies equal fuel cost savings for the fleet. The cumulative cash flow difference for PHEVs does not take into account infrastructure costs for home rewiring, distribution system upgrades, and public charging stations, which might average more than $1,000 per vehicle.

The PHEV-10 and H_2 FCV have similar buydown costs and timing, but the NRC PHEV-40 "optimistic" case gives a longer and more costly transition, because of the assumed relatively high battery cost out to 2020 and beyond. To examine what would be required to bring PHEV-40s to competitiveness more rapidly, we carried out two sensitivity analyses: "DOE Goals" assumes the DOE battery cost and technology goals for the PHEV-40 are met by 2020, showing the importance of technology breakthroughs. Reducing costs this rapidly would significantly reduce subsidies and advance the break-even year relative to the NRC "optimistic" technical progress cases. "High Oil" assumes oil costs twice that in the base case, or $160/bbl in 2020, giving results similar to meeting DOE's cost goals.

COMPARISON OF TRANSITION COSTS FOR PHEVS AND FCVS

	PHEV-10 Optimistic	**PHEV-40 Optimistic**	**PHEV-40 Sensitivity Cases**		**FCV**	
			High Oil	**DOE Goals**	**Success**	**Partial**
Break-even year	2024	2039	2025	2024	2023	2033
Cumulative cash flow to break-even	$24 billion	$408 billion	$41 billion	$24 billion	$22 billion	$46 billion
Cumulative vehicle retail price difference to break-even	$82 billion	$1,639 billion	$174 billion	$82 billion	$40 billion	$82 billion
Number of vehicles at break-even	10 million	132 million	13 million	10 million	5.6 million	10 million
Infrastructure cost at break-even	$10 billion (in-home charger @$1,000)	$132 billion (in-home charger @$1,000)	$13 billion (in-home charger @$1,000)	$10 billion (in-home charger @$1,000)	$8 billion (H2 stations for first 5.6 million FCVs)	$19 billion (H2 stations for first 10 million FCVs)

ALTERNATIVES VS. THE COST OF BUSINESS AS USUAL

The last section of this chapter has focused on the costs of making a transition to alternative fuels and vehicles, but we should note that continuing a petroleum-based fuel supply also has significant costs. Oil supply investment costs are growing rapidly, especially for exploration and production, with oil companies drilling deeper wells in more remote areas. Much of the oil capacity that will be needed in 2030 has not been built yet and will require development of new oil fields and investments in refineries that can deal with heavier crudes, oil sands, and gas to liquids. The International Energy Agency's *World Energy Outlook 2008* has estimated that oil supply infrastructure development between 2007 and 2030 will cost about $6.3 trillion globally for a new supply capacity of about 50 million barrels of oil per day (enough to fuel a fleet of about 1.3 billion cars, assuming an average fuel economy of 25 mpg and a vehicle driven 15,000 miles per year). In North America alone, the oil infrastructure costs for that period are estimated to be $1 trillion, or an average of $45 billion per year.

How would the capital outlay compare for alternative fuels versus oil? The IEA estimates that about $1.3 trillion would be for oil refineries and fuel transport, the remaining $5 trillion for exploration and production (drilling oil wells). The investment for oil refineries and transport is then about $1,000 per vehicle served. Counting exploration and production, total oil supply investment costs would be about $5,000 per vehicle.

By contrast, the capital cost for biofuels would be about $90–3600 billion to build biorefineries and biofuel transport capacity to fuel about 30 to 60 million cars, or $3,000–6,000 per vehicle served (assuming a 25-mpg vehicle that travels 15,000 miles per year). The biofuels analogy to oil exploration and production is developing land for biofuel production. However, these costs are likely to be very small compared to drilling oil wells, especially if low-carbon residues are employed (if the land is already developed for another purpose). And even for energy crops, land costs are treated more as rents or operating costs than capital costs.

For hydrogen or electricity, 80 percent of the transition costs are associated with the vehicle, with infrastructure accounting for only 20 percent of the total. The National Research Council has estimated that infrastructure capital costs would be $1,000–2,000 per car for PHEVs (including only the in-garage charger but not electricity transmission or generation or primary resources to make electricity). For hydrogen, infrastructure capital costs are estimated to be $1,400–2,000 per car, including hydrogen production, delivery, and refueling equipment, but not the capital costs for development of primary resources to make hydrogen—for example, natural gas wells, biomass resources, or wind farms.

The average annual transition cost to bring FCVs or PHEVs to cost competitiveness is about $4–8 billion per year over a 10-to-15-year period, and roughly 20 percent of this for infrastructure (or $0.8–1.6 billion per year). The cumulative infrastructure transition cost is roughly $8–12 billion, compared to projected capital expenditures in North America of perhaps $100–150 billion for oil refineries and fuel transport, and an additional $600–800 billion for exploration and production between 2007 and 2030. (This doesn't count oil investments that might be made abroad to serve North American markets). We could launch an alternative fuel infrastructure for much less than we are planning to spend on oil, and at a comparable investment cost per vehicle served.

Summary and Conclusions

- Only a portfolio approach can meet goals for an 80-percent reduction in GHG emissions by 2050. Substantial cuts in gasoline use are possible through improved efficiency of vehicles (about a 40-percent reduction from the reference case in 2050), use of low-carbon biofuels (a 15-percent reduction), and implementation of PHEVs (45 to 55 percent) or FCVs (60 percent). However, no single-pathway approach yields deep enough cuts in carbon emissions to add up to an 80-percent reduction by 2050. On the other hand, portfolio approaches combining improvements in ICEV efficiency with rapid introduction of PHEVs or FCVs and low-carbon biofuels can cut gasoline use to near zero by 2050 (depending on the amount of biofuel available for light-duty vehicles) and meet goals for an 80-percent reduction in GHG emissions.

- To realize the potential GHG benefits of PHEVs and FCVs, it is essential to decarbonize electricity and hydrogen production over time. If we rely on current grid technologies and hydrogen production from natural gas, there is little benefit compared to a strategy that stresses ICEV efficiency without advanced vehicles. For both PHEVs and FCVs, the buydown of vehicles could occur before substantial decarbonization of the fuel supply, but to realize the full benefits of these electric-drive vehicles, a parallel transition to a low-carbon energy supply is needed. We did not cost out this transition to low-carbon energy explicitly—it comes in through the fuel cost.

- The transition timing and costs are similar for PHEVs and FCVs. In each case, it will take fifteen to twenty years and 5 to 10 million vehicles for the new technology to break even with initial purchase and fuel supply costs for a reference gasoline car. Total transition costs are in the range of tens to hundreds of billions of dollars. For radically new types of vehicles like these, there is a need to buy down the cost of the vehicle through improvements in technology and scale-up of manufacturing. (Vehicle buydown costs are typically 80 percent of the total transition cost, and infrastructure costs 20 percent for both PHEVs and FCVs). For hydrogen, the fuel cost is initially high and comes down by focusing scaled-up development in lighthouse regions.

- For biofuels, the main transition cost is for improving second-generation biorefinery technology and scaling up the supply chain to the point where biofuel competes with other liquid fuels. In the United States, the total investment to this point is estimated by various studies to be perhaps $90–360 billion for biorefineries, fuel storage terminals, feedstock, and fuel transport to provide enough fuel for 30 to 60 million cars.

- Bringing new vehicle and fuel technologies to cost competitiveness will require fifteen to twenty years and a total investment of tens to hundreds of billions of dollars. Although this sounds like a lot of money, it is small compared to the investment in the existing gasoline system and the money flows in the current energy system. Maintaining and expanding the existing petroleum infrastructure is projected to cost about $1 trillion in North America alone between 2007 and 2030, an average of $45 billion per year. Perhaps 20 percent of this capital is for building refineries and fuel transport; the remainder is for exploration and production. By contrast, the average infrastructure costs during a transition to hydrogen FCVs or PHEVs would be $0.5–1 billion per year.

Notes

1. This chapter is based on studies done at UC Davis in support of National Academies assessments of hydrogen fuel cell vehicles (NRC, *Transitions to Alternative Transportation Technologies, A Focus on Hydrogen* (Washington, DC: National Academies Press, 2008)) and plug-in hybrid electric vehicles (NRC, *Transitions to Alternative Transportation Technologies, Plug-in Hybrid Electric Vehicles* (Washington, DC: National Academies Press, 2010)), and on N. Parker, Q. Hart, P. Tittmann, C. Murphy, M. Lay, R. Nelson, K. Skog, E. Gray, A. Schmidt, and B. Jenkins, *National Biorefinery Siting Model: Spatial Analysis and Supply Curve Development* (Denver, CO: Western Governors' Association, 2010).
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3. N. Parker et al., *National Biorefinery Siting Model*.
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9. NRC, *Transitions to Alternative Transportation Technologies, A Focus on Hydrogen* (Washington, DC: National Academies Press, 2008).
10. This follows NRC, *Transitions to Alternative Transportation Technologies, A Focus on Hydrogen* (Washington, DC: National Academies Press, 2008) and NRC, *Transitions to Alternative Transportation Technologies, Plug-in Hybrid Electric Vehicles* (Washington, DC: National Academies Press, 2010); J. Ogden, "A Comparison of Buydown Costs for Hydrogen Fuel Cell Vehicles and Plug-in Hybrid Vehicles," presented at the 2009 National Hydrogen Association Meeting, Columbia, SC, March 30–April 2, 2009.
11. *This follows NRC, Transitions to Alternative Transportation Technologies, A Focus on Plug-in Hybrid Electric Vehicles* (Washington, DC: National Academies Press, 2010).
12. D. Greene, P. Leiby, and D. Bowman, "Integrated Analysis of Market Transformation Scenarios with HyTrans," ORNL/TM-2007/094 (Oak Ridge National Laboratory, June 2007).
13. NRC, Transitions to *Alternative Transportation Technologies, A Focus on Hydrogen* (Washington, DC: National Academies Press, 2008).
14. C. Yang and J. Ogden, "U.S. Urban Hydrogen Infrastructure Costs Using the Steady State City Hydrogen Infrastructure System Model (SSCHISM)," presented at the 2007 National Hydrogen Association Meeting, San Antonio, TX, March 18–22, 2007. A beta copy of the model is posted on Christopher Yang's website at UC Davis Institute of Transportation Studies, available at www.its.ucdavis.edu/people.
15. K. Morrow, D. Karner, and J. Francfort, "Plug-in Hybrid Electric Vehicle Charging Infrastructure Review," INL/EXT-08-15058 (Idaho National Laboratory, November 2008).
16. The model was developed by N. Parker, Q. Hart, P. Tittmann, C. Murphy, M. Lay, R. Nelson, K. Skog, E. Gray, A. Schmidt, and B. Jenkins in *National Biorefinery Siting Model: Spatial Analysis and Supply Curve Development* (Denver, CO: Western Governors' Association, 2010).
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