Plug-in and regular hybrids: A national and regional comparison of costs and CO_2 emissions

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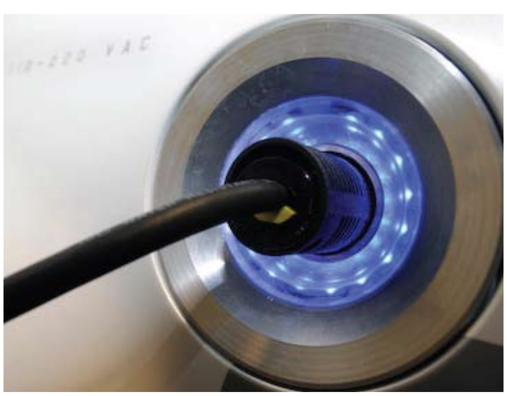

Plug-in and Regular Hybrids: A National and Regional Comparison of Costs and CO_2 Emissions

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Executive Summary

Growing concern about climate change and the rising cost of oil are leading policy analysts and consumers alike to pay close attention to a variation of a hybrid electric vehicle known as a plug-in hybrid, which promises to reduce gasoline consumption significantly. This paper compares plug-in hybrids and regular hybrids to evaluate which technology leads to lower carbon dioxide (CO_2) emissions and lower costs regionally and nationally under a variety of scenarios.

As its name suggests, drivers can plug a plug-in hybrid into an electrical outlet to charge the vehicle's battery. Plugging in saves gasoline but consumes electricity. In most parts of the country, electricity generation relies on fossil fuels, which means that plug-in hybrids would lead to an increase in electricity sector fossil fuel consumption and CO_2 emissions. At the same time, though, plug-in hybrids would reduce direct vehicle CO_2 emissions. Taking all CO_2 emissions into account, will net emissions go up or down as a result of plug-in hybrids? The answer to this question depends on whether one compares plug-in hybrids to regular hybrids or conventional vehicles, whether or not there is a price associated with CO_2 emissions (and how high the price is), and the region of the country.

How much plug-in hybrids can reduce CO_2 emissions depends primarily on whether there is a comprehensive climate policy that provides a price signal for CO_2 emissions. In the absence of such a policy, plug-in hybrids and regular hybrids reduce about the same number of tons of CO_2 nationally when displacing conventional vehicles. Because the mix of electricity generation varies regionally, plug-in hybrids in some regions not only have higher CO_2 emissions than regular hybrids but have higher CO_2 emissions than conventional vehicles when no CO_2 price signal is present.

In the presence of a CO_2 price signal, the electricity sector becomes less carbon-intensive and, by extension, so do plug-in hybrids since they draw energy from the electricity system. With a CO_2 price signal, plug-in hybrids reduce moderately more CO_2 emissions nationally than regular hybrids. Carbon-intensive regions become less carbon-intensive—enough that plug-in hybrids have lower net emissions than conventional vehicles—but not so much that plug-in hybrids have lower net emissions than regular hybrids in these regions. With respect to carbon mitigation, policymakers may want to focus on regular hybrids for certain regions rather than plug-in hybrids, even with a CO_2 price signal. If carbon capture and storage technology is adopted in these coal-intensive regions, plug-in hybrid CO_2 emissions will improve.

Are plug-in hybrids more or less expensive than regular hybrids? The answer to this question depends largely on the price of gasoline. Plug-in hybrid vehicles are more expensive to build than hybrids, which in turn are more expensive than comparable conventional vehicles. In order for plug-in hybrids to be cost-effective, their operating costs need to be much lower than those of regular hybrids and conventional vehicles. Because conventional vehicles consume the most gasoline, as gasoline prices increase, the cost of driving a conventional vehicle increases the most. Regular hybrids consume more gasoline than plug-in hybrids, so the cost of operating a regular hybrid increases at a greater rate with increases in gasoline prices. From a system-wide cost perspective, gasoline prices would need to increase to around $6 per gallon to make plug-in hybrids cost effective; below $6 per gallon, regular hybrids are more cost effective than plug-in hybrids.[1] As of the writing of this paper, gasoline prices have settled down to less than $4 per gallon, but given the volatility of the oil market, gasoline prices could conceivably rise to $6 per gallon in the not-so-distant future.

The bottom line is that both plug-in hybrids and regular hybrids have great potential for reducing CO_2 emissions, but in order for plug-in hybrids to reach their full potential as a cost-effective climate mitigation option, barring a break-through in plug-in hybrid technology, comprehensive climate policy is needed, and gasoline prices must continue to rise. Without both climate policy and higher gasoline prices, regular hybrids may be the preferable technology. In any case, regular hybrids may be better suited than plug-in hybrids for the goal of CO_2 emission reductions in certain regions of the country unless carbon capture and storage technology is adopted along with plug-in hybrids.

[1] This calculation ignores any indirect benefits associated with reducing oil imports and improving energy security that would result with large-scale adoption of plug-in hybrid technology.

Introduction

As gas prices and greenhouse gas emissions continue to rise, many consumers are looking for an alternative to the traditional internal combustion engine. Gas-electric hybrids, or hybrids as they are commonly known, are growing in popularity. A hybrid combines a gasoline- and electric-powered drivetrain in one vehicle. Drivers need only add gasoline to a regular hybrid; the electric drive system draws its power from the gasoline engine.

Recently, a variation of the hybrid vehicle known as a plug-in hybrid electric vehicle (PHEV) has gained attention because of its potential to achieve fuel efficiency in excess of 100 MPG. The gasoline fuel efficiency of a plug-in hybrid tells only part of the story. Drivers can charge the batteries in plug-in hybrids straight from an electrical outlet in addition to adding gasoline; this supplemental electrical energy allows plug-in hybrids to achieve their impressive gasoline fuel efficiency, but consuming electricity also has a cost and generates carbon dioxide (CO_2) emissions.

Therefore, if we deploy plug-in hybrids to the degree that some have proposed, the electricity sector must respond to the additional electricity consumption of plug-in hybrids—something that could have profound implications for the electricity sector's emissions.

We use the Nicholas Institute's version of the National Energy Modeling System (NI-NEMS) from 2006 to evaluate the electricity sector's response to different projections of plug-in hybrid penetration—from 2% to 56% of all vehicles in 2030. We developed a spreadsheet model to calculate direct vehicle emissions and costs that correspond to our plug-in hybrid and hybrid projections. (See "Scenarios," "Methodology," and "Assumptions" for more details.)

For the most part, plug-in hybrids will be charged in the evening and nighttime hours when drivers are at home. This consumption profile makes base-load power a more attractive option for utilities. The greenhouse gas implications of expanded base-load power depend on the fuel mix used to supply this new generation, which in turn depends on whether or not power generators must pay a price for emitting CO_2.[2] Generally speaking, without a price on CO_2 emissions, plug-in hybrid electricity demand leads electricity generators to rely on coal-fired power plants to meet this demand. With a CO_2 price, electric utilities will have an incentive to invest in a mix of new coal, nuclear and natural gas generation. (See "Electricity Sector Implications" for more details.)

Both plug-in and regular hybrids lower CO_2 emissions nationally when they displace conventional vehicles. Which technology is more carbon-friendly and more cost-effective depends in part on the current and future costs of CO_2 and gasoline. High CO_2 prices, which lead to lower carbon intensity in the

[2] A CO_2 price can come in the form of a carbon tax or a cap-and-trade policy that places a limit on total emissions and allows emitters to trade emission allowances. The Lieberman-Warner Climate Security Act, recently debated in the U.S. Senate, is an example of a cap-and-trade policy that could provide a price signal to many sectors of the economy, including electricity and transportation.

electricity sector, can tip the scale for plug-in hybrids over regular hybrids in terms of CO_2 emissions benefits nationally. But at current gasoline prices, plug-in hybrids are far more expensive than regular hybrids. Above a gasoline price of around $6 per gallon, however, plug-in hybrids become cost-effective compared with regular hybrids and conventional vehicles. (See "National Results" for more details.)

Because the mix of electricity differs by region, the benefits of plug-in hybrids for reducing CO_2 emissions also differ by region. In comparison, regular hybrids do not vary by region. Some areas with a heavy concentration of coal in the electricity supply mix lead to higher CO_2 emissions for plug-in hybrids compared with conventional vehicles and to much higher emissions compared with regular hybrids. Even though a CO_2 price can lead to modest CO_2 emission reductions for plug-in hybrids compared with conventional vehicles, regular hybrids may be a better bet in these areas for reducing CO_2 emissions. (See "Regional Results.")

Methodology

If only one plug-in hybrid were on the road, calculating its emissions would be fairly simple: one would multiply gasoline consumption by the carbon content of gasoline, then multiply electricity consumption by the average emission rate for the electricity system supplying power. Calculating emissions for many plug-in hybrids on a national level, however, becomes much more complex. Because plug-in hybrid electricity consumption can itself change the electricity system, using an average emission rate based on the current system without plug-in hybrids is not accurate. Instead, using a dynamic electricity sector model is far more accurate than a simplified emission factor approach. Such a model can simulate the electricity sector's response to plug-in hybrid electricity consumption, including investment in and operation of new generating capacity required to supply electricity to plug-in hybrids. A model also makes possible scenarios with carbon price signals that drive changes in the electricity sector along with changes driven by plug-in hybrids.

We decided to use the Nicholas Institute's version of the National Energy Modeling System (NI-NEMS), which has a detailed, dynamic electricity market module well-suited for this analysis. We combined our electricity sector modeling with a simple vehicle model that we built in Excel (See Appendix A). Since NI-NEMS does not feature plug-in hybrid vehicles as an option, we needed a way to increase electricity consumption within the NI-NEMS transportation module—to reflect plug-in hybrid electricity use—so that the electricity module can respond. We decided to use electric vehicles as a proxy for plug-in hybrids. Fortunately, the time-of-day pattern for charging plug-in hybrids should be comparable with electric vehicles; representing consumption at the correct time of day is important for correctly modeling the electricity sector response.

We directed the model to build a certain number of electric vehicles in each region.[3] The resulting electricity consumption is equivalent to a particular number of plug-in hybrid vehicles. Because electricity consumption per electric vehicle is greater than consumption per plug-in hybrid vehicle, we needed fewer electric vehicles to reflect the equivalent electricity consumption of plug-in hybrids. We represented plug-in hybrid electricity consumption in this way for each of the 13 electricity regions in NI-NEMS based on the share of total vehicles projected by the Energy Information Administration for each region. We repeated this process by varying the number of equivalent plug-in hybrid vehicles; these variations comprise our plug-in hybrid penetration scenarios discussed in the "Scenarios" section below.

We are confident that our approach accurately reflects electricity consumption of plug-in hybrids and that NI-NEMS can effectively show how plug-in hybrids affect the electricity sector. However, we are not confident that the NI-NEMS transportation module can accurately model the effect of plug-in hybrids within the transportation sector because fewer electric vehicles are needed to equal the electricity consumption of plug-in hybrids. The NI-NEMS transportation module would not be able to account for

[3] The standard NEMS model on which NI-NEMS is based allows for electric vehicles in only a couple of regions. We modified the code slightly to allow electric vehicles to operate in all regions.

the fact that there would actually be more plug-in hybrids on the road than the electric vehicles used as a proxy. For this and other technical reasons, we decided to use NI-NEMS only for electricity sector results and to model direct vehicle emissions and costs separately in our Excel model. The following figure is a simple flowchart of our modeling process.

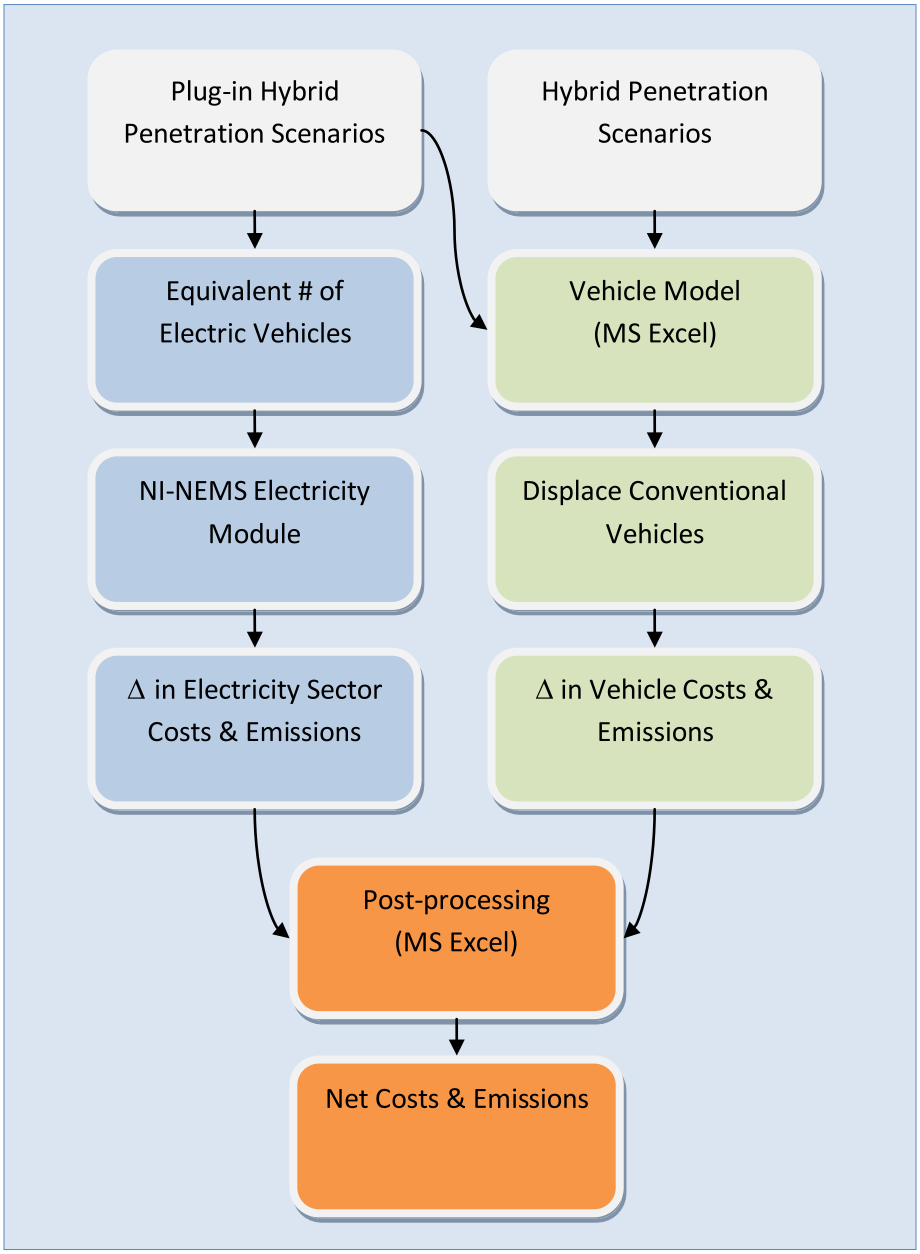


Figure 1. Simplified flowchart of the modeling and analysis of plug-in and regular hybrids. Gray steps are input assumptions, blue steps are NEMS modeling of plug-in hybrid demand, green steps are vehicle modeling in Excel, and orange steps are the integrating analysis.

Scenarios

We developed six plug-in hybrid penetration scenarios, each of which begins in 2012 and ends in 2030 with a final penetration into vehicle stock ranging from 2% to 56%. We also analyzed four additional scenarios, based on penetrations of 2% and 56%, that have CO_2 prices of $20 and $40 per ton (Figure 2).

All scenarios show the incremental effect of plug-in or regular hybrids displacing conventional vehicles (or in some cases the incremental effect of plug-in hybrids compared with regular hybrids). For scenarios without a CO_2 price, the incremental effect is relative to a reference case without a CO_2 price; for scenarios with a CO_2 price, the incremental effect is relative to a reference case with that CO_2 price. Although the two categories of scenarios—those with and without a CO_2 price—have different reference cases, they are consistent in that they reflect the isolated effects of plug-in or regular hybrids.

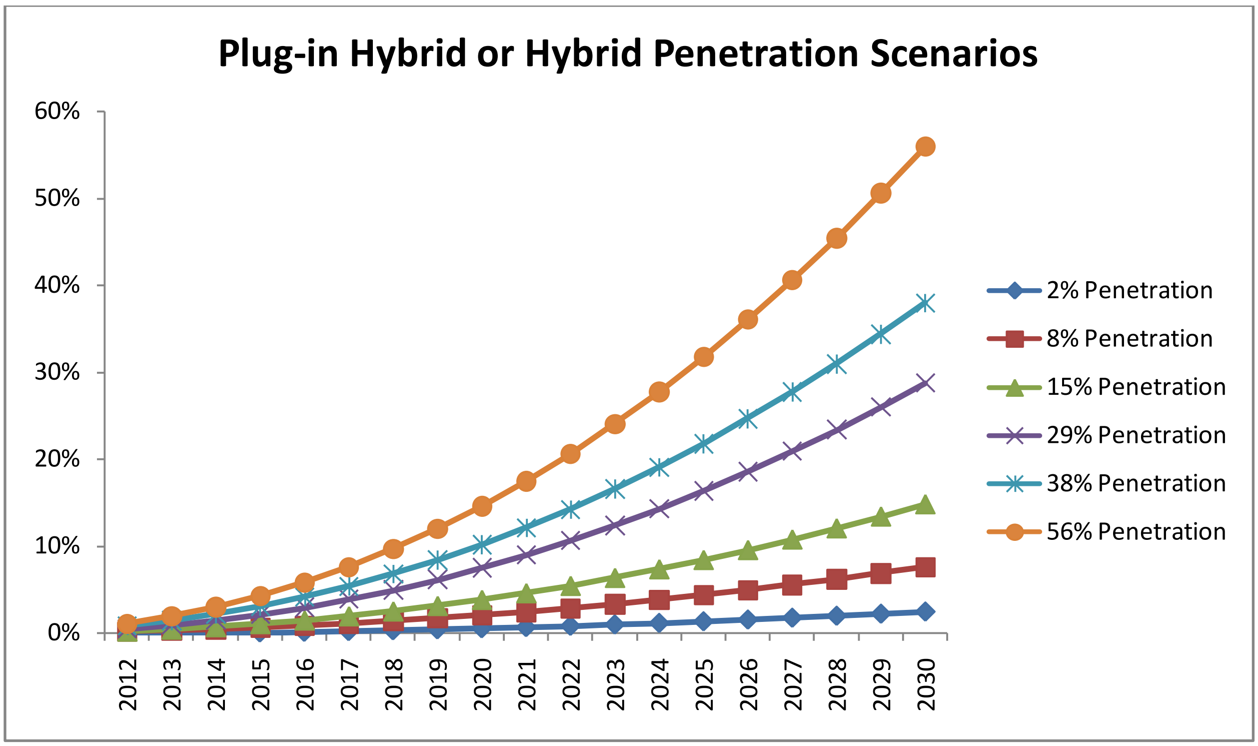


Figure 2. Plug-in hybrid and regular hybrid penetration scenarios. Each scenario assumes that either plug-in hybrids or regular hybrids will penetrate the market according to the curves plotted in the figure. For example, a "56% penetration" as mentioned in this paper means that this scenario assumes a final penetration of plug-in hybrids or regular hybrids of 56% in the vehicle stock by 2030; this same penetration scenario assumes, for example, that plug-in hybrids or regular hybrids would comprise a little less than 20% of vehicle stock by 2021. For each plug-in hybrid or hybrid that penetrates into the system, a conventional vehicle is displaced.

Assumptions

We base our physical vehicle technology assumptions primarily on a joint Electric Power Research Institute (EPRI)/Natural Resources Defense Council (NRDC) study from 2007 titled "Environmental Assessment of Plug-in Hybrid Electric Vehicles." We base our cost assumptions on a National Energy Renewable Laboratory report from 2006 titled "Cost-Benefit Analysis of Plug-in Hybrid Electric Vehicle

Technology," which provides near- and long-term incremental costs for plug-in hybrids and regular hybrids compared with conventional vehicles. We assume that the near-term costs apply to the beginning of our study period in 2012 and then assume a linear improvement in costs to the long-term NREL cost assumption by 2018. We also apply a modest improvement in costs after 2018 (Figure 3).

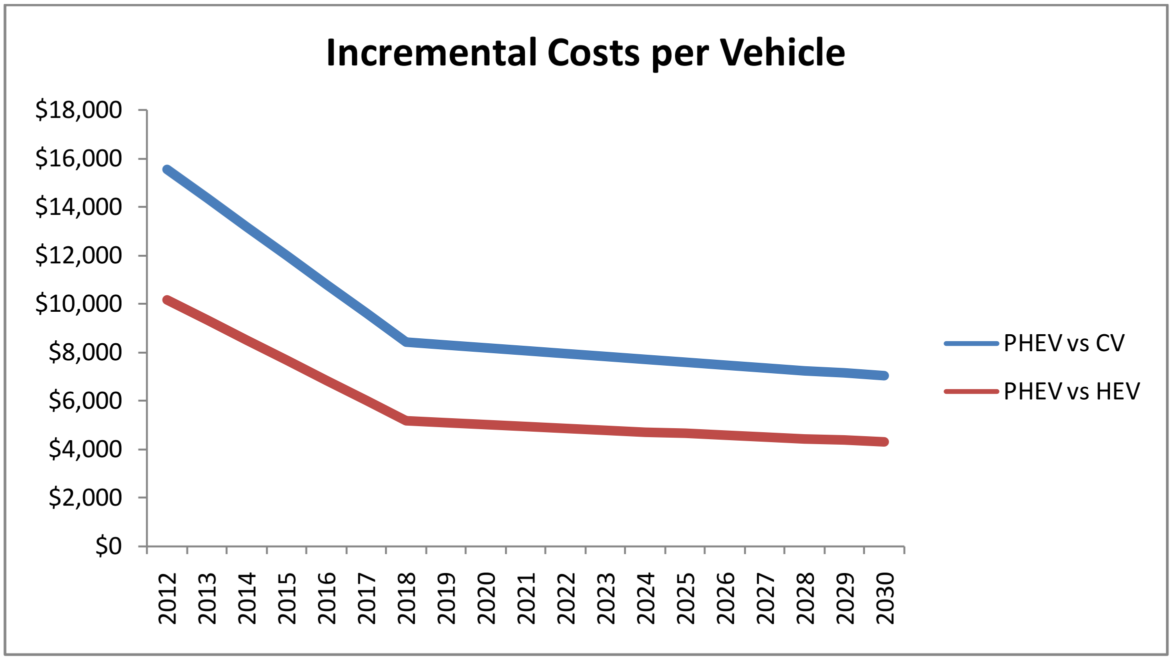


Figure 3. Incremental costs of plug-in and regular hybrids relative to conventional vehicles. Cost assumptions adapted from an NREL study, "Cost-Benefit Analysis of Plug-in Hybrid Electric Vehicle Technology."

We made the simplifying assumption that we would model a single generic vehicle class rather than model the complexities of multiple vehicle and weight classes. In other words, we do not distinguish between compact cars, full-size cars, SUVs, etc. Since we are not attempting to forecast the mix of vehicle classes with this analysis, but instead are trying to understand the implications of vehicle technology choices, we believe that this simple approach is effective.

We developed assumptions for three different technologies for our single vehicle class: a conventional vehicle (CV), a hybrid electric vehicle (HEV), and a plug-in hybrid. For each penetration scenario, we first calculate the change in costs and emissions assuming that plug-in hybrids displace conventional vehicles, then we assume that hybrids displace conventional vehicles. We also evaluate the incremental benefit or cost that plug-in hybrids offer compared with regular hybrids. In reality, there will almost certainly be a mix of conventional vehicles, regular hybrids, and plug-in hybrids. Again, since we are isolating the effects of plug-in hybrids or regular hybrids rather than forecasting the evolution of the transportation sector, we believe that our approach is appropriate.

In order to show the efficiency of our three vehicle technologies in an apples to apples comparison—plug-in hybrid efficiency cannot be captured in miles per gallon since it consumes electricity also—we converted the efficiency of the vehicles to MBTU (heat/energy input) per mile as shown in Figure 4 below. We assume that plug-in hybrids have the same gasoline engine efficiency as a regular hybrid. The difference is that plug-in hybrids have a larger battery that can go 40 miles on a charge without engaging the gasoline engine. The plug-in hybrid efficiency shown in Figure 4 represents an average of electric and gasoline drivetrain efficiency for the typical U.S. driving pattern, which we assume applies to all the vehicles in our analysis. We also assume a very modest improvement in efficiency over time.

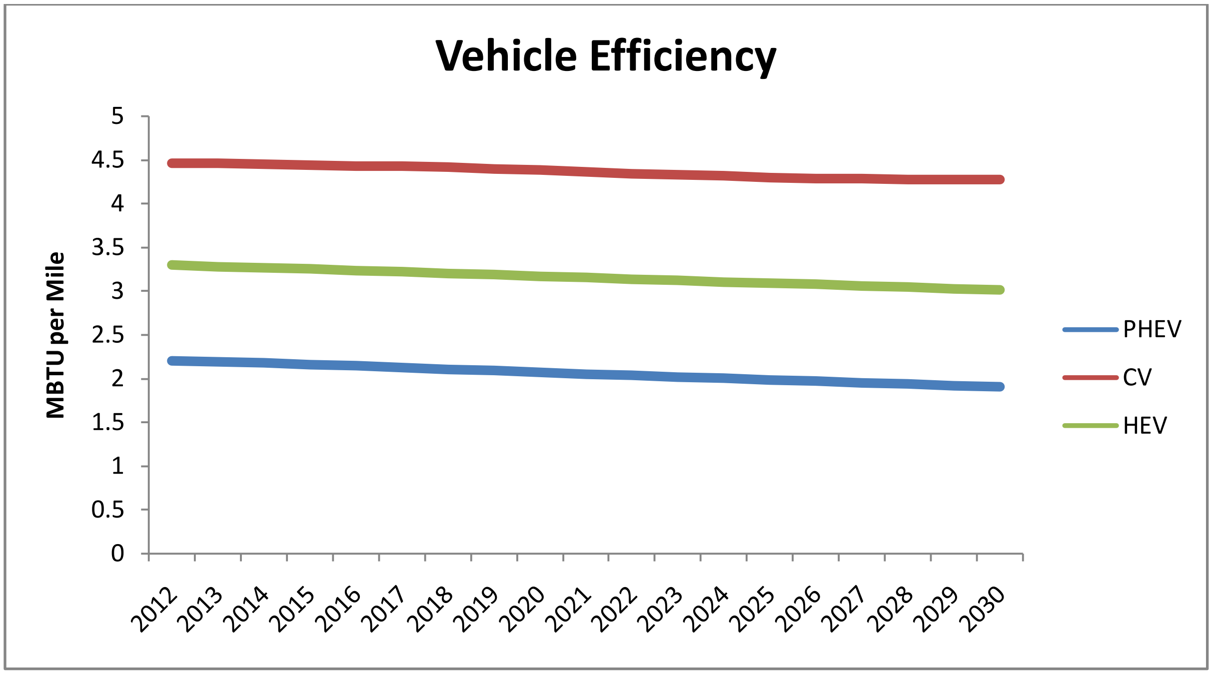


Figure 4. Vehicle technology assumptions over time expressed in MBTU per mile for plug-in hybrids (PHEV), regular hybrids (HEV), and conventional vehicles (CV).

We also assume that maintenance, repair, and insurance costs are equal among the three technology choices. Since we are interested in the difference in costs, not absolute costs, we can ignore these other costs in our analysis. Even if these costs differ by technology, the differences should be small compared to vehicle and fuel costs.

Results

Electricity Sector Implications

Because plug-in hybrids consume a significant portion of their energy in the form of electricity, the electricity sector must respond to this added consumption. Plug-in hybrids will primarily be charged in the evening and nighttime hours when drivers are at home. This load shape profile makes base-load power more attractive. In a typical region, electricity demand peaks during the day and is at its lowest during the night. Utility planners could build enough large base-load units to satisfy the peak demand, but those peaks last only a short time and would leave base-load units, which have high capital costs and low operating costs, sitting idle much of the time. Instead, utilities build only enough base-load power to allow their base-load units to run almost continuously. To meet peak demand, utilities build units with low capital cost and high operating cost, knowing that these units will be needed for only short periods of time and can be turned off when demand drops. The largely nighttime plug-in hybrid electricity consumption changes the shape of the demand curve so that utilities can build and run more base-load and fewer peaking units. The NI-NEMS modeling of plug-in hybrids confirms this logic.

Capacity

Taking a 56% plug-in hybrid penetration as an illustrative example, additional plug-in hybrid electricity consumption is directly responsible for 16.5 GW of new coal capacity by 2030 (Figure 5). Renewables also increase by around 2 GW by 2030. Over 17 GW of combustion turbines and nearly 5 GW of oil and gas steam plants are avoided or retired as a result of plug-in hybrids. Overall, capacity needs are lower with plug-in hybrids because the base-load capacity that is built in response runs more frequently and alleviates the need for around 4.5 GW of total capacity. Lower penetrations of plug-in hybrids have similar results, though combined cycle builds tend to be less consistent (builds go up and down) at different plug-in hybrid penetrations. Generally speaking, without a CO_2 price present, investment in coal and avoidance of combustion turbines (and to some extent oil and gas steam) is proportionate to plug-in hybrid electricity consumption.

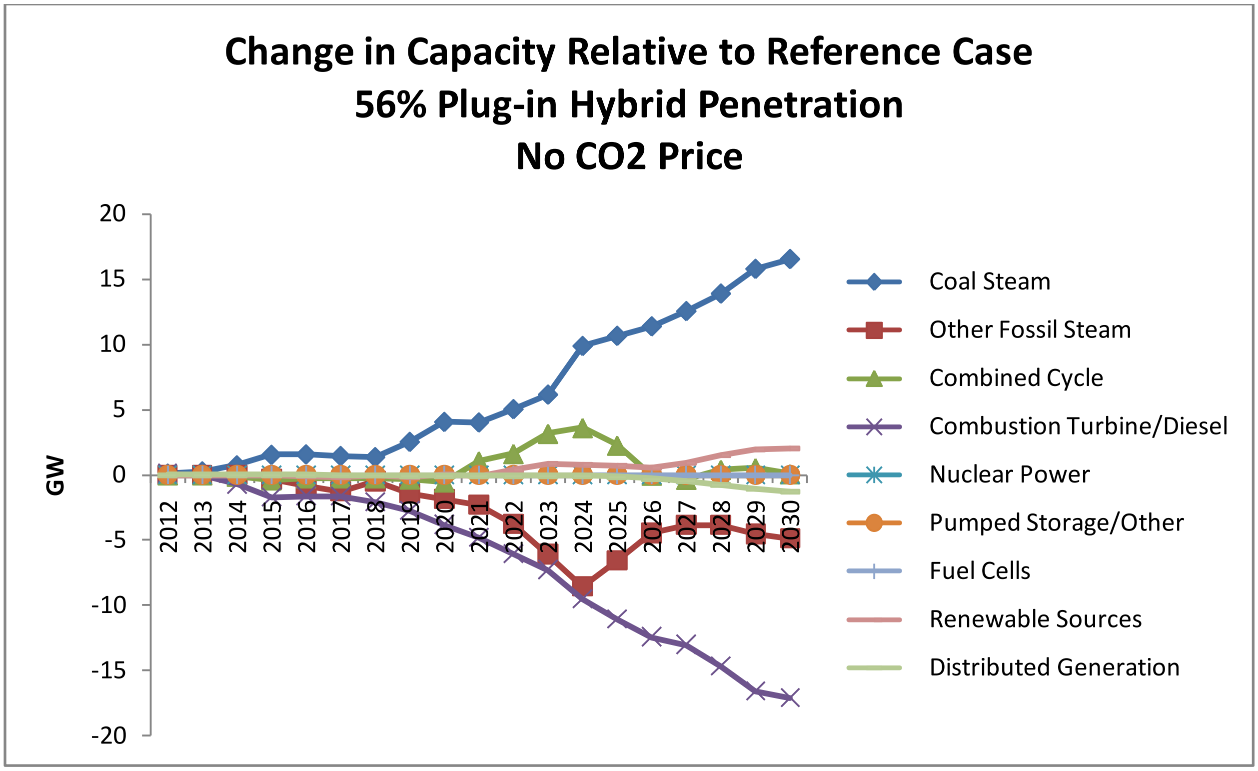


Figure 5. Change in electricity generating capacity over time compared to the reference case, with a 56% plug-in hybrid penetration.

If a \$40-per-ton CO_2 price is already present and a 56% penetration of plug-in hybrids is assumed, the investment in new generating capacity as a direct result of plug-in hybrid electricity consumption (isolated from changes already brought about by the CO_2 price) is different than it would be without the CO_2 price. In this case, plug-in hybrids are responsible for 9.5 GW of new nuclear capacity and only 9 GW of new coal capacity by 2030 (Figure 6). Also by 2030, slightly fewer combustion turbines—about 16 GW—are avoided or retired, but significantly more oil and gas steam units—about 13 GW—are avoided or retired. Overall, capacity needs are even lower because more base-load nuclear and coal units are operating, and the avoided or retired combustion turbines and oil and gas steam units run infrequently, resulting in a need for 9 GW less total capacity.

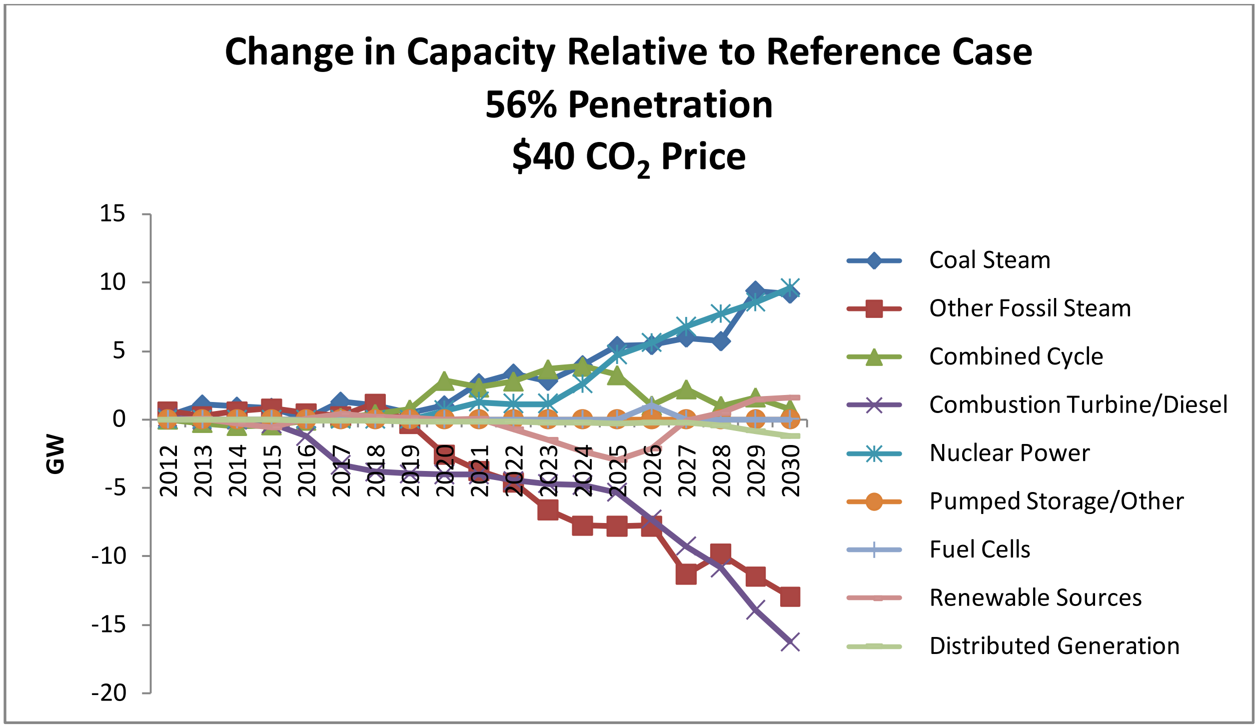


Figure 6. Change in electricity generating capacity over time compared to the reference case, with a 56% plug-in hybrid penetration and a CO_2 price of $40 per ton.

Generation

Changes in national electricity generation resulting from plug-in hybrid electricity consumption are somewhat more straightforward than capacity changes. Overall, generation increases by around 235 TWh with a 56% penetration of plug-in hybrids whether or not a CO_2 price is present. This generation increase is needed to meet the electricity demand of plug-in hybrids.

With no CO_2 price and a 56% penetration of plug-in hybrids as an example, coal generation increases by 190 TWh by 2030, while generation from natural gas and wood biomass increases by 15 and 18 TWh, respectively, and generation from other sources increases only slightly (Figure 7). Different penetrations of plug-in hybrids follow similar patterns.

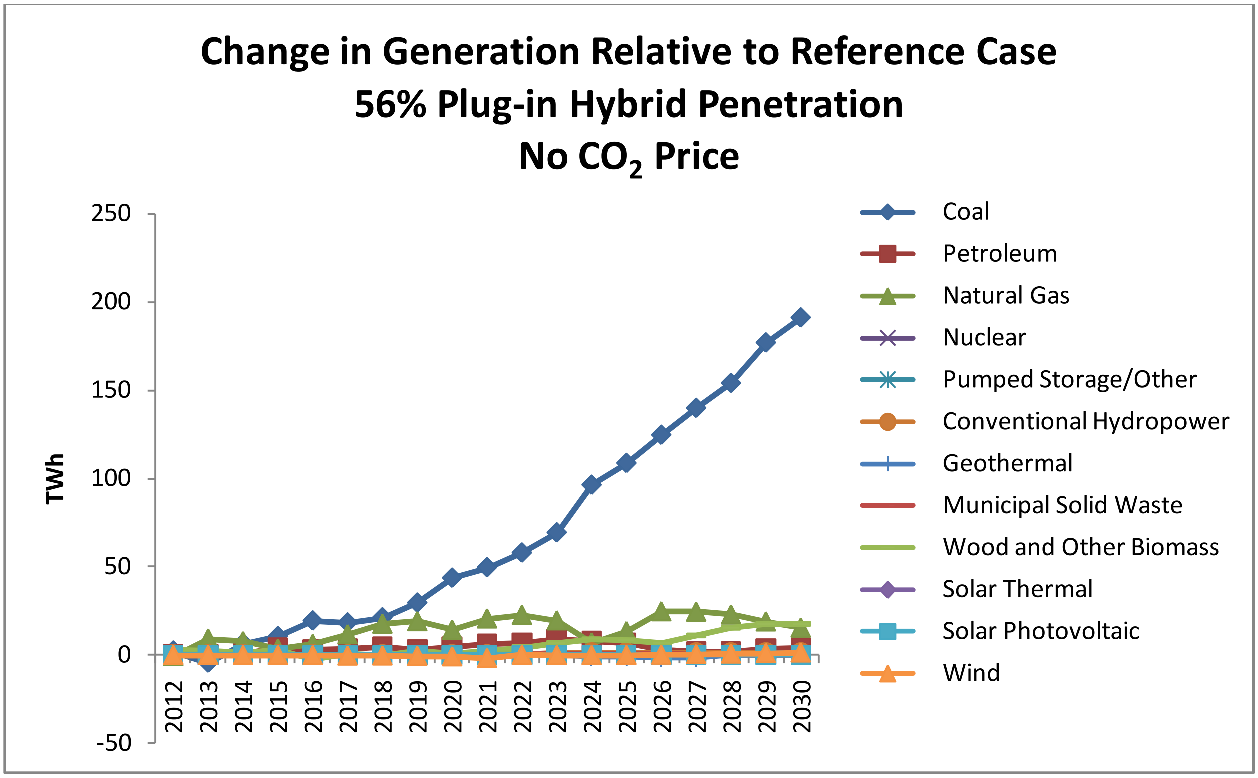


Figure 7. Change in electricity generation over time compared to the reference case, with a 56% plug-in hybrid penetration.

If a \$40-per-ton CO_2 price is present, then a 56% plug-in hybrid penetration results in an additional 132 TWh of coal generation, 75 TWh of nuclear, 14 TWh of wood biomass, and only 5 TWh of natural gas generation by 2030 (Figure 8). Both coal and natural gas generation are lower with a \$40-per-ton CO_2 price than without, and nuclear fills the gap.

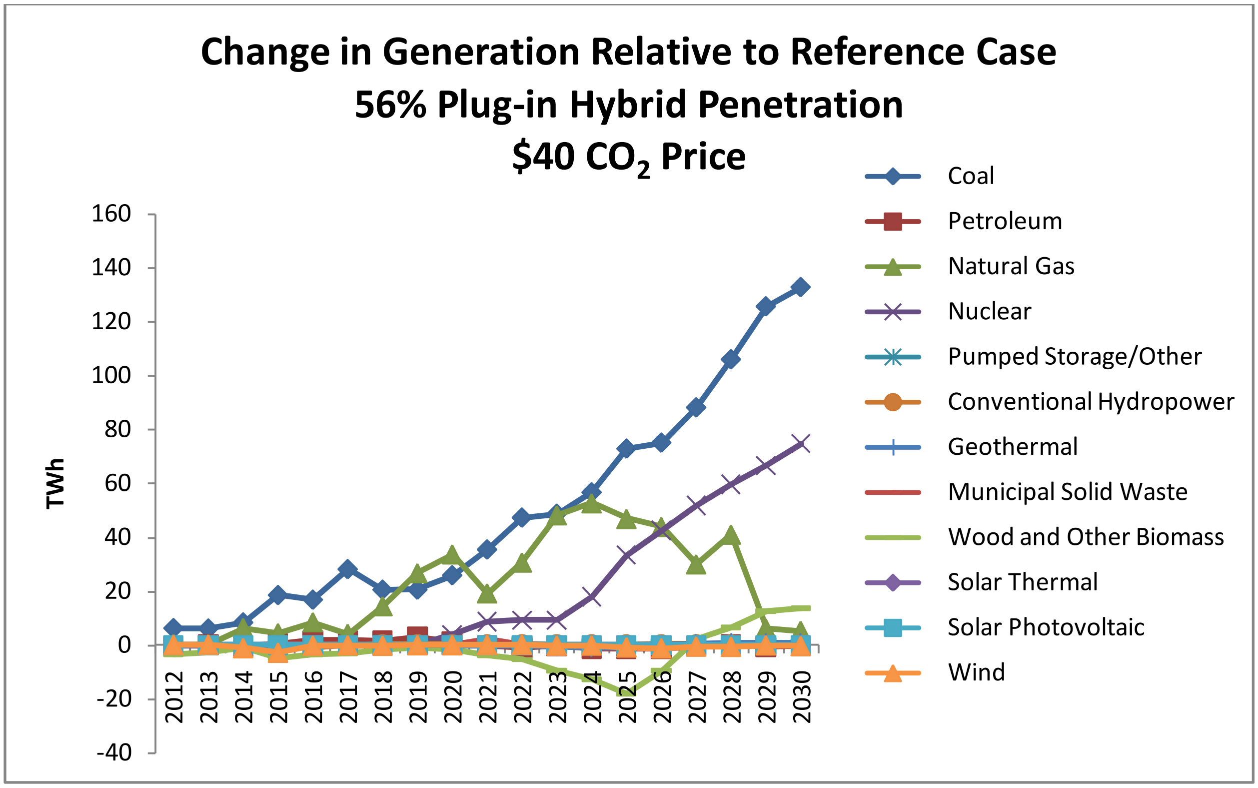
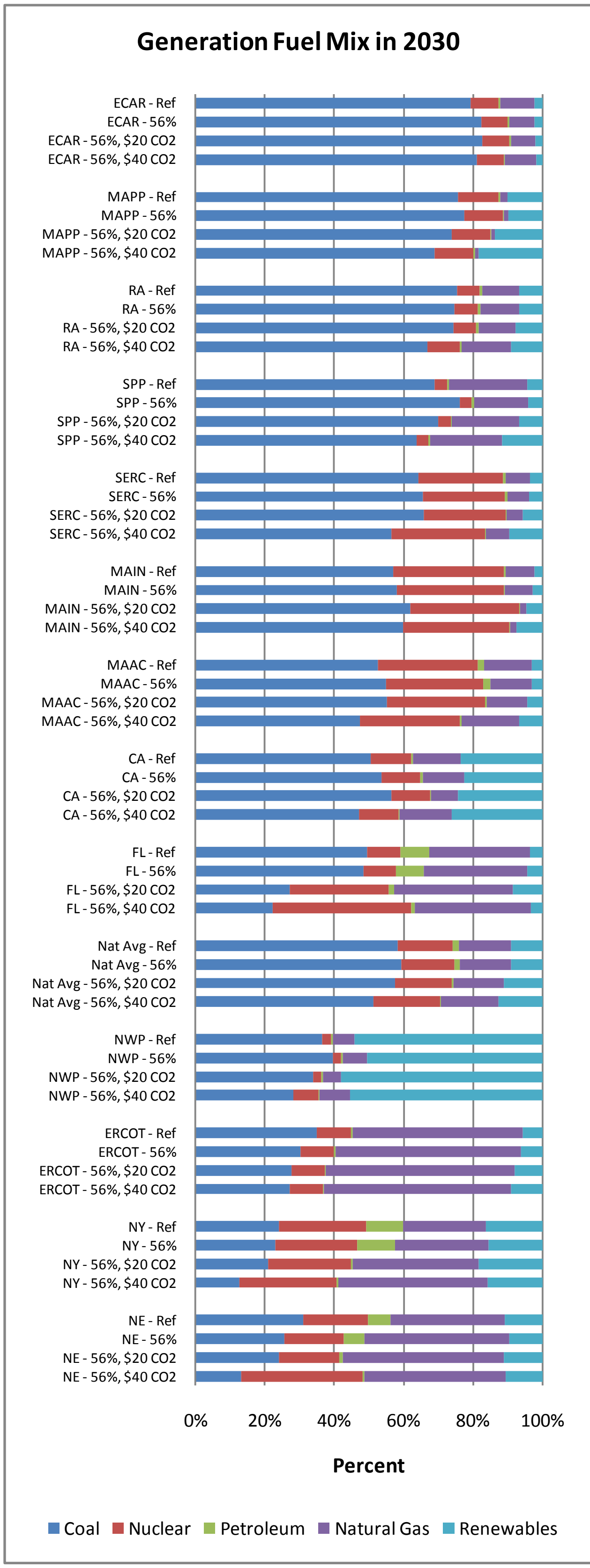


Figure 8. Change in electricity generation over time compared to the reference case, with a 56% plug-in hybrid penetration and a CO_2 price of $40 per ton.

Although the NI-NEMS model predicts that nuclear power will expand in our plug-in hybrid scenarios, other NI-NEMS modeling efforts suggest that when a CO_2 price signal is present, either nuclear or CCS capacity grows. Changes in assumptions about cost and performance between nuclear and carbon capture and storage (CCS) technology can tip the balance toward one or the other in the model. Whether a CO_2 price signal combined with plug-in hybrids would lead to more nuclear or more CCS makes little difference in terms of cost and emissions for plug-in hybrids nationally. Regional results, however, may be affected given that some regions tend toward coal and others toward nuclear (Figure 9). Regions with significant coal capacity will have lower carbon intensity if existing coal plants are retrofitted with CCS technology or if old coal plants are replaced with new coal plants that capture carbon. Therefore, CCS technology can potentially mitigate PHEV-associated CO_2 emissions in coal-intensive regions. See Figure 27 below in the "Regional Integrated Vehicle-Electricity Sector Results" section for a map of the NI-NEMS regions.



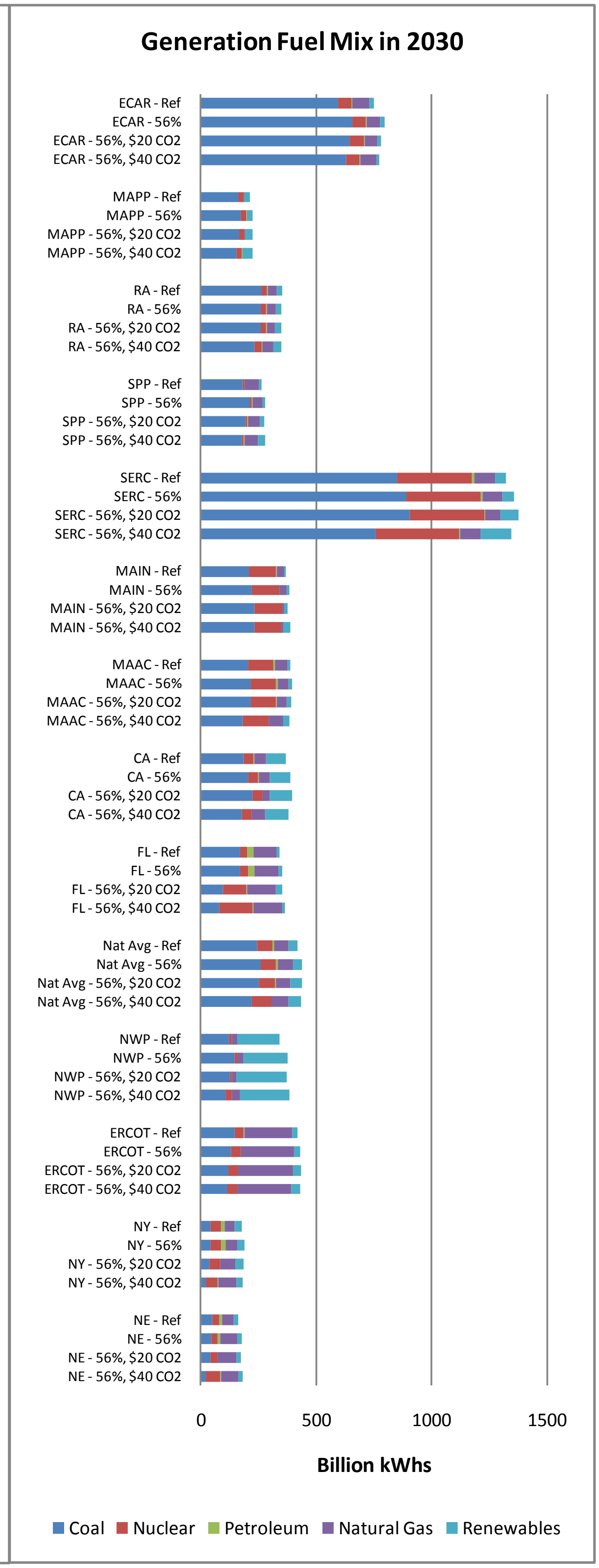


Figure 9. Fuel mix of electricity generation in 2030 by region and by selected scenarios.

Carbon intensity

The carbon intensity of the electricity sector in the reference case starts at 0.601 metric tons per MWh in 2012, then dips to 0.589 metric tons per MWh in 2020, then increases to 0.605 in 2030 (Figure 10). The plug-in hybrid scenarios without a CO_2 price follow a CO_2 intensity trajectory that has the same basic shape as in the reference case, although a 56% penetration leads to a higher CO_2 intensity between 2020 and 2030. This increase reflects the increase in coal generation with a 56% plug-in hybrid penetration. Scenarios with a $40-per-ton CO_2 price results in a consistently downward trajectory of CO_2 intensity.

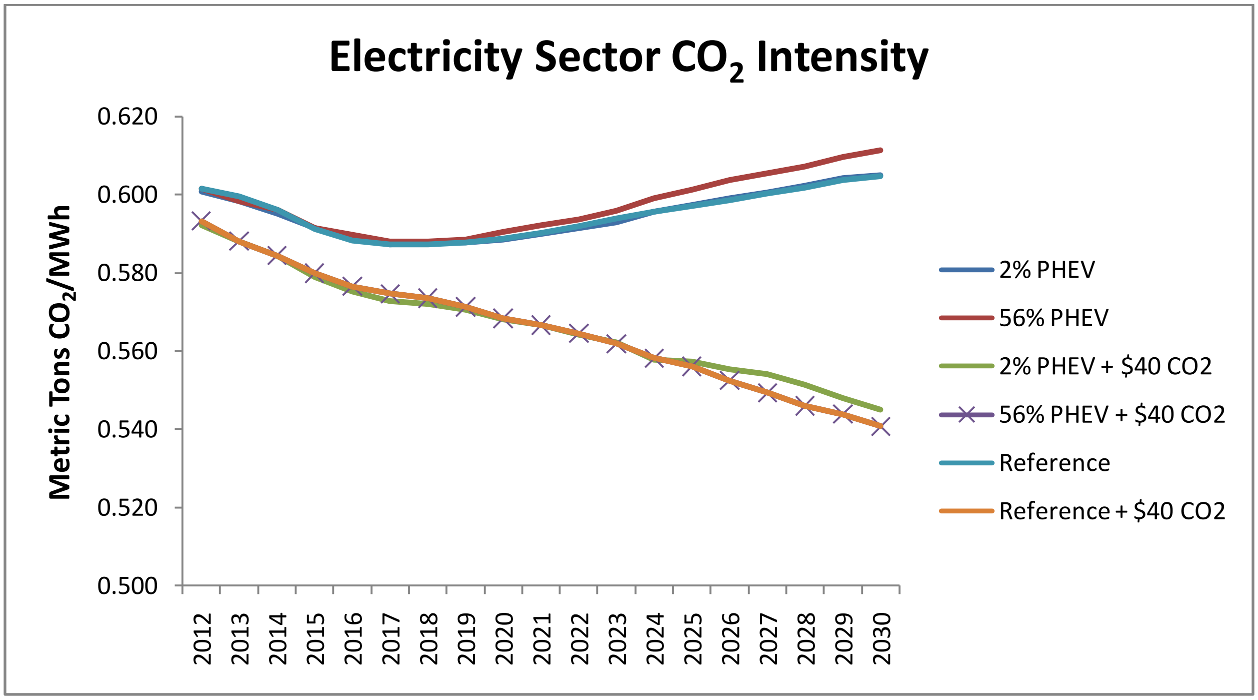


Figure 10. CO_2 intensity of the electricity sector over time for select scenarios.

Electricity prices[4]

National average electricity prices in the reference case *without a CO_2 price* are forecast to increase modestly from 7.2 cents per kWh in 2012 (including generation, transmission and distribution) to 7.6 cents per kWh in 2030 (Figure 11). In reference cases *with CO_2 prices*, the price of electricity grows in 2030 to 7.8 cents per kWh and 8.3 cents per kWh for the $20 and $40 CO_2 cases respectively (Figure 12). Electricity price changes that result from plug-in hybrid penetrations are modest. The largest increase in price—2.2% by 2030—occurs with a 56% penetration of plug-in hybrids when a $40-per-ton CO_2 price is present. A 56% penetration without a CO_2 price results in a 1.4% increase in electricity prices (Figure 13). At a low penetration of 2%, electricity prices decline by 1.1% without a CO_2 price and by 0.3% with a CO_2

[4] National average prices are presented here, but regional electricity prices specific to each scenario from the NI-NEMS model were used in the plug-in hybrid vehicle cost analysis.

price present. Prices decline with small plug-in hybrid penetrations because much of the additional demand can be met with existing capacity, and, at the same time, less peaking capacity is needed. Electricity price changes lie between the numbers cited above for plug-in hybrid penetrations that fall between 2% and 56%.

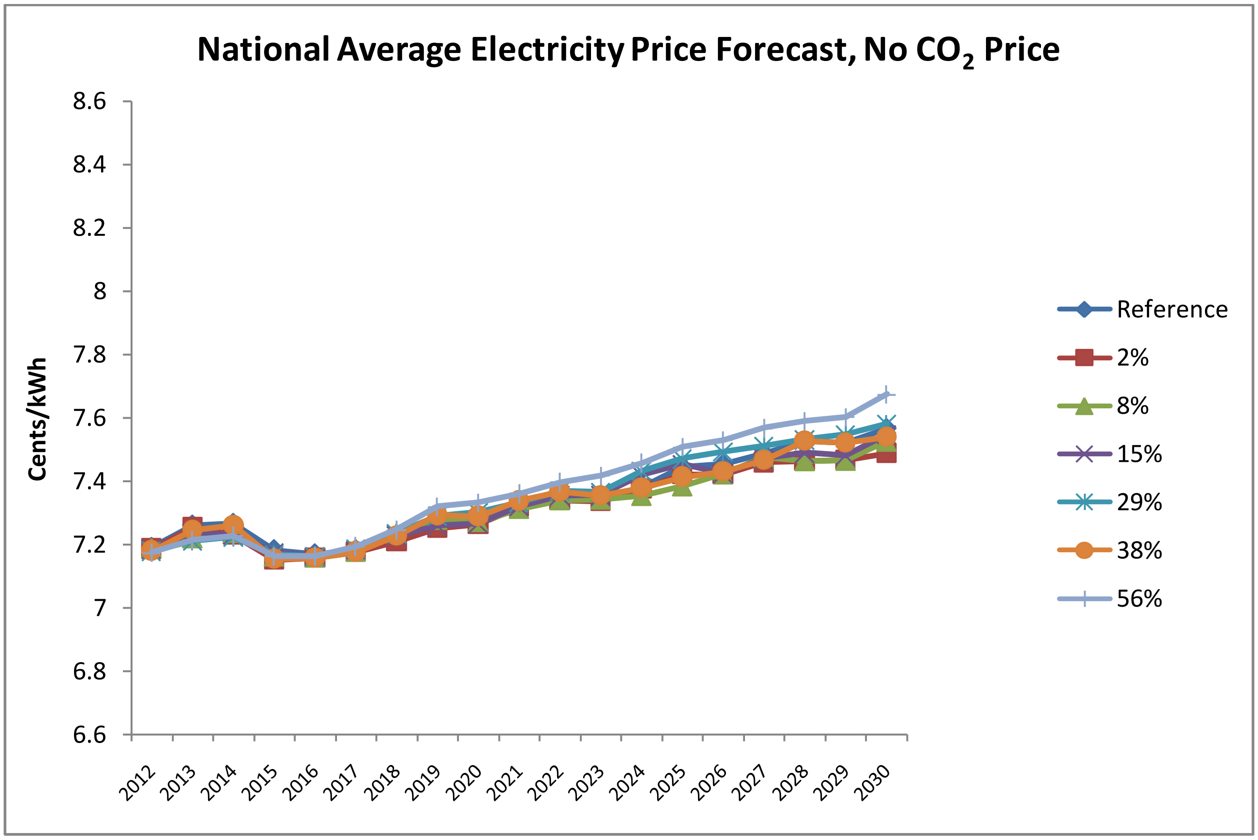


Figure 11. Forecast of national average annual residential electricity prices from 2012 to 2030 for scenarios without a CO_2 price.

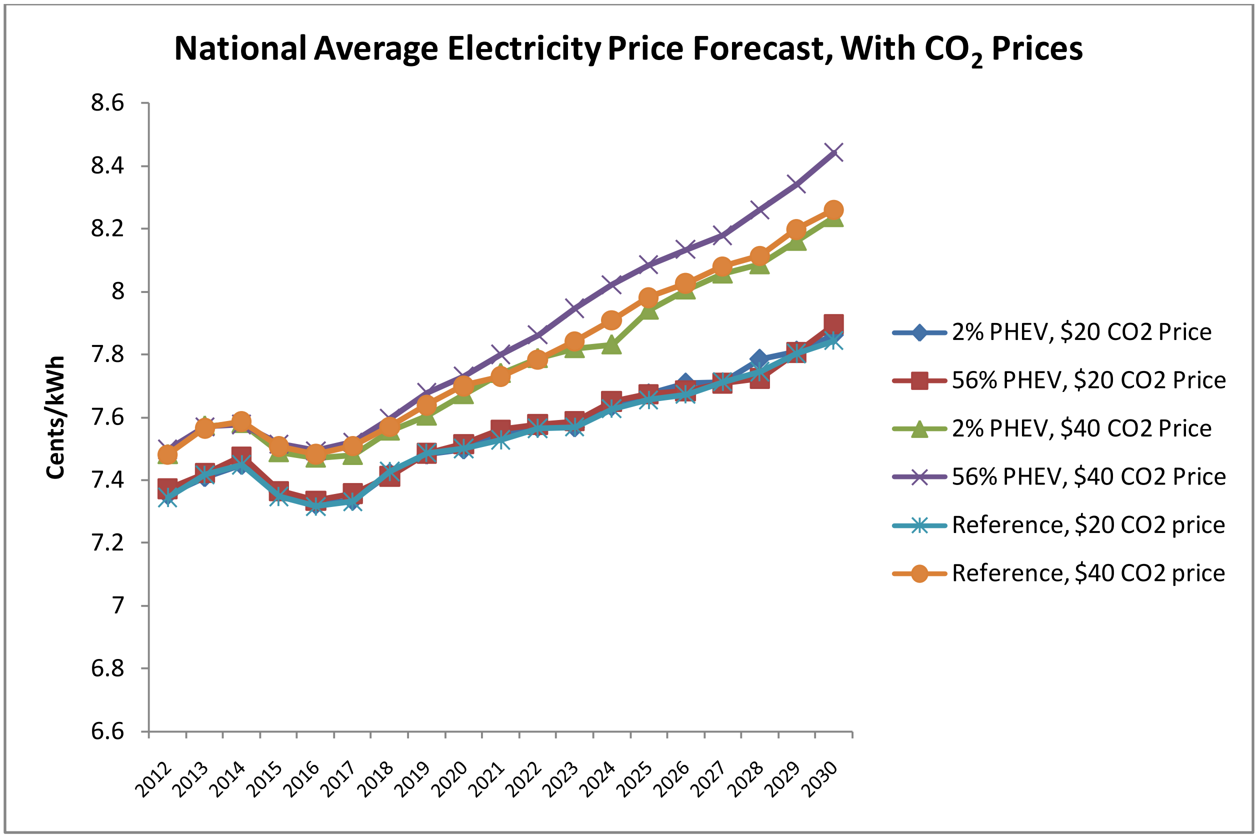


Figure 12. Forecast of national average annual residential electricity prices from 2012 to 2030 for scenarios with a CO_2 price.

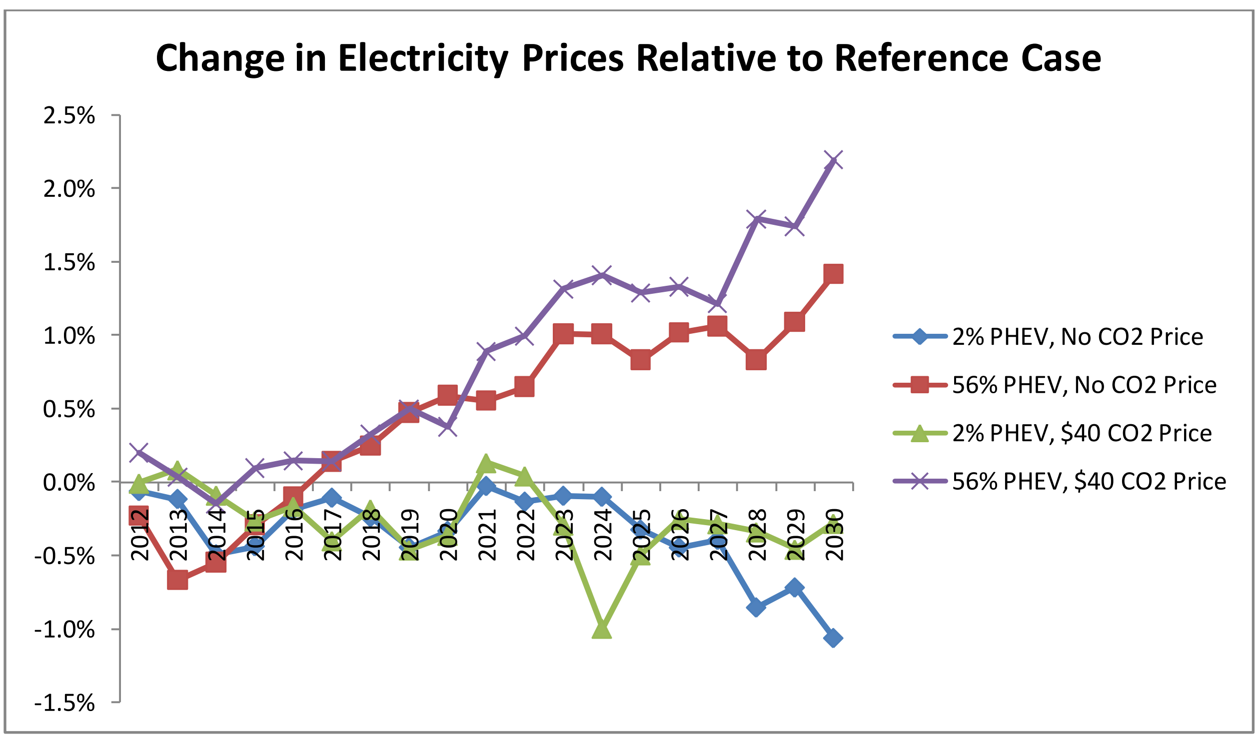


Figure 13. Change in residential electricity prices over time for select scenarios.

National Integrated Vehicle-Electricity Sector Results

Costs

System versus Individual Perspective
This analysis represents a system perspective that takes into account system-wide costs (incremental electricity system costs plus incremental vehicle costs) between 2012 and 2030 on a net present value basis. An analysis of cost from an individual consumer perspective will be much narrower in scope and may come to a different conclusion. In the early years, the cost of purchasing a plug-in hybrid (and to a lesser extent a hybrid) is assumed to be considerably more expensive than a conventional vehicle. This gap narrows over time, and the results presented here reflect this change in relative cost over the entire study period.

Cost depends on a number of assumptions, including the incremental cost of purchasing plug-in hybrid or hybrid vehicles compared with conventional vehicles, whether or not a CO_2 price signal is present (and how strong the signal is), and the cost of gasoline. The incremental cost of purchasing a plug-in hybrid is only speculative now because no major automobile manufacturer sells a plug-in hybrid model. However, because all major components are available and many are already included in regular hybrids, we can reasonably estimate the cost of manufacturing a plug-in hybrid. Obviously, different assumptions about the cost of the vehicles themselves will lead to different conclusions. See the previous section titled "Assumptions" for details on our incremental cost assumptions. Because these cost assumptions are grounded in engineering estimates, we have not included any sensitivity analyses of them in this paper. But we do explore sensitivities to results when the price of CO_2 varies from \$0 to \$20 to \$40 per ton and when the price of gasoline ranges from \$2 to \$8 per gallon.

Assuming the gasoline price to be \$4 per gallon—the default gasoline price assumption in this paper—the overall system cost of plug-in hybrids is significant (Figure 14).[5] The higher cost of manufacturing plug-in hybrid vehicles coupled with the cost of electricity they consume far outweigh the savings in gasoline when compared with conventional vehicles. Regular hybrids, on the other hand, offer modest incremental costs over conventional vehicles. Even though the gap in the cost of manufacturing a plug-in hybrid compared with a regular hybrid is expected to be narrower in the outer years, the difference in gasoline savings is expected to be much narrower by comparison. Once electricity costs are factored in, plug-in hybrids are significantly more expensive than regular hybrids.

[5] Each point in the Figure represents the cumulative results from a single model run from 2012 to 2030. Each line represents a series of model runs with the same assumptions; what varies within a line is the penetration rate of plug-in hybrids. The different lines represent different assumptions, such as whether plug-in hybrids or hybrids displace conventional vehicles or whether or not a CO_2 price is present. This footnote applies to all figures in the paper unless years are shown on the horizontal axis, in which case the information presented is over time and not cumulative, and an entire line represents a single run.

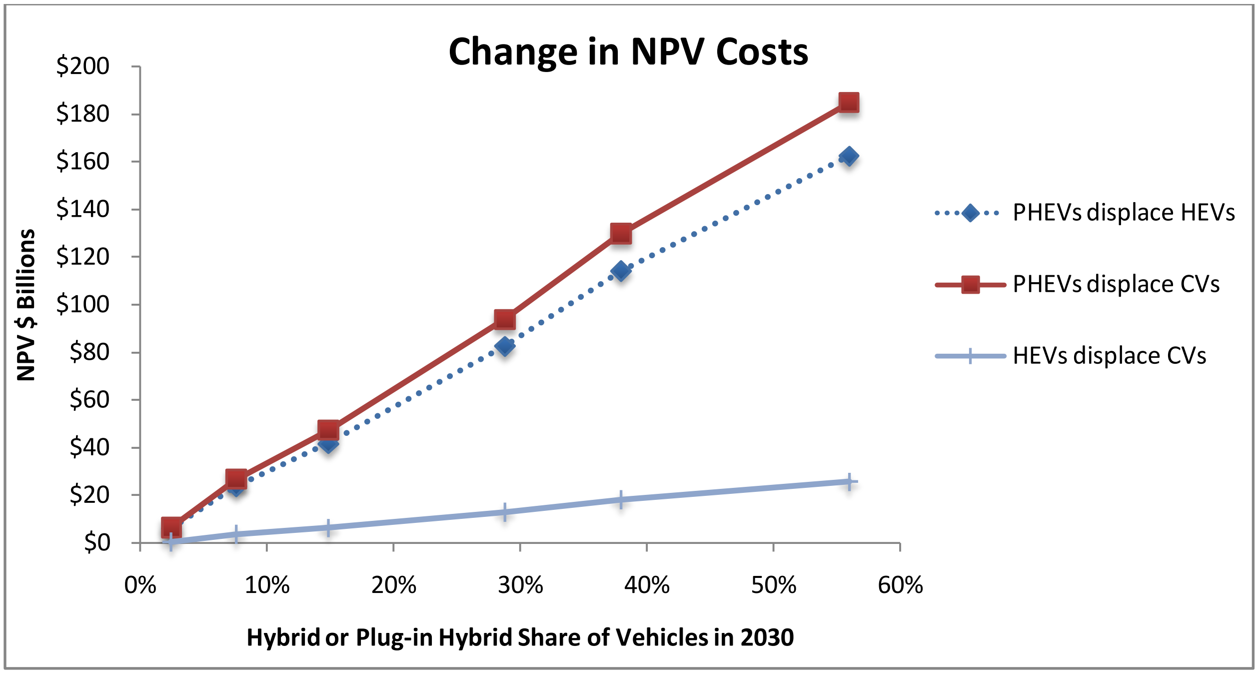


Figure 14. Final penetration of plug-in hybrids (PHEVs) and regular hybrids (HEVs) in 2030 is plotted with corresponding net present value costs over the period 2012 to 2030. Each point represents a complete model run. The dotted line shows the incremental costs of plug-in hybrids compared to regular hybrids.

The story changes somewhat if we assume that a CO_2 price is present and flows through to gasoline prices and through the electricity sector (Figure 15). In this case, the overall cost to society of plug-in hybrids (and regular hybrids) compared with conventional vehicles becomes smaller—the increase in gasoline cost affects conventional vehicles more so than plug-in or regular hybrids.

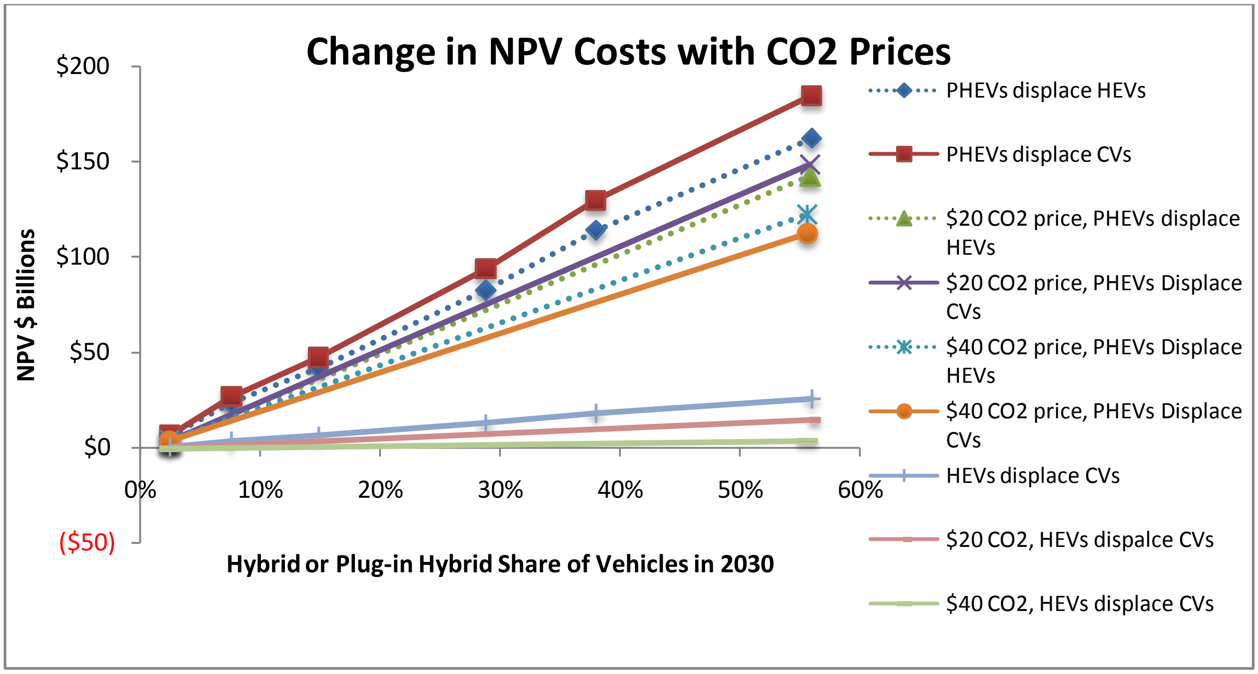


Figure 15. Final penetration of plug-in hybrids (PHEVs) and regular hybrids (HEVs) in 2030 is plotted with corresponding net present value costs over the period 2012 to 2030; results with CO_2 prices are shown. Each point represents a complete model run. The dotted lines show the incremental costs of plug-in hybrids compared to regular hybrids.

With gasoline prices rising and falling so dramatically over the last couple of years, the cost of gasoline is a significant source of uncertainty in our analysis. Our default $4-per-gallon assumption reflects a reasonable price of gasoline as of the writing of this paper, but gasoline prices may continue to increase for some time. The overall cost of both plug-in and regular hybrids is highly sensitive to gasoline prices. If we vary the gasoline price, assume no CO_2 price, and assume a 56% penetration of plug-in or regular hybrids, we find that conventional vehicles are cost-effective at gasoline prices below about $4.75 per gallon. Between $4.75 and $6 per gallon, regular hybrids are the most cost-effective option, and above $6 per gallon, plug-in hybrids become the most cost-effective option (Figure 16). These price points are relevant to a system-wide perspective to inform policy decisions, not for individual consumers in making near-term vehicle purchase decisions.

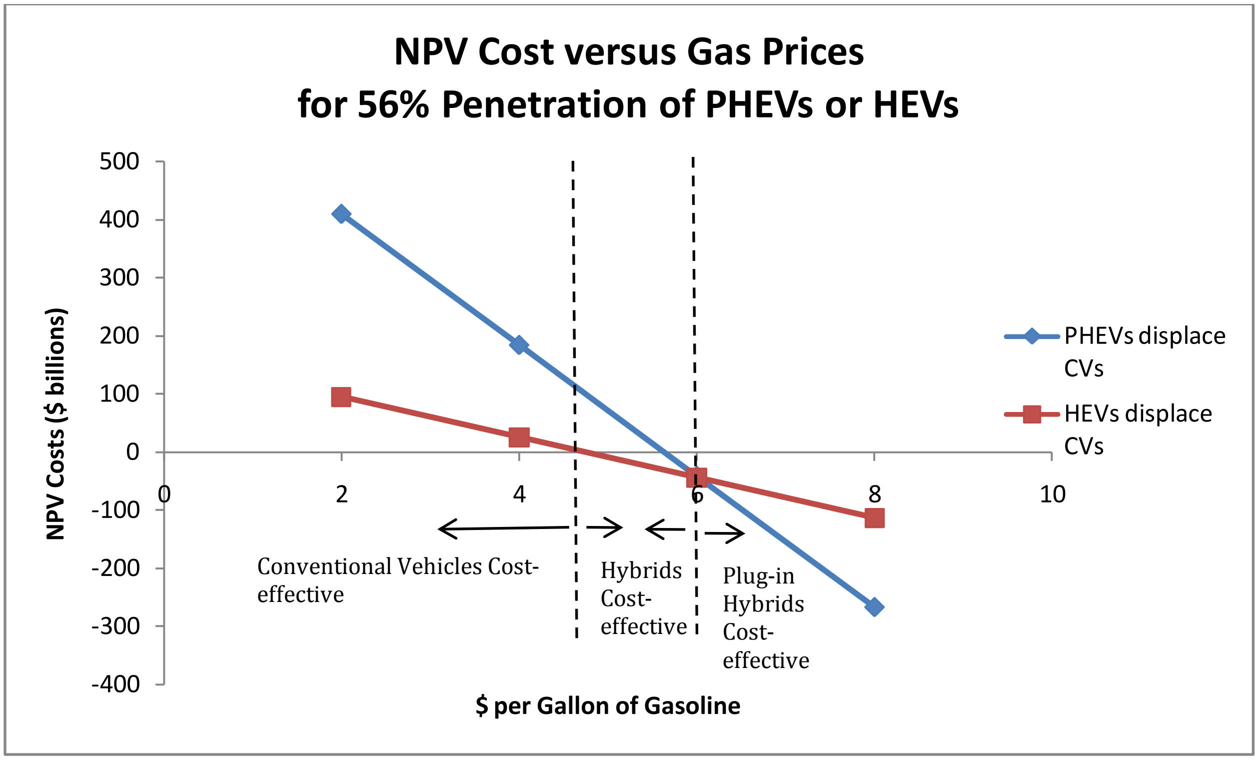


Figure 16. Sensitivity of net present value (NPV) cost of plug-in hybrids and regular hybrids to gasoline prices. NPV cost is calculated over the period from 2012 to 2030.

Combining a $40-per-ton CO_2 price and the same 56% penetration, we find that hybrids and plug-in hybrids become cost-effective at lower gasoline prices (the gasoline prices as presented in the following figure do not reflect the CO_2 price, but the net present value costs do reflect a pass-through of CO_2 prices in the costs of both gasoline and electricity).[6] In this example, conventional vehicles are the most cost-effective below approximately $4 per gallon of gasoline; between $4 and about $5.50 per gallon, regular hybrids are the most cost-effective; and above $5.50 per gallon, plug-in hybrids become the most cost-effective option (Figure 17).

[6] We chose to display gasoline prices without reflecting the CO_2 price so they can be easily compared to current gasoline prices that do not include a CO_2 price. A $20-per-ton CO_2 price translates to 17.6 cents per gallon of gasoline, and a $40-per-ton CO_2 price translates to 35.2 cents per gallon. These additional costs were included in the net present value cost calculations.

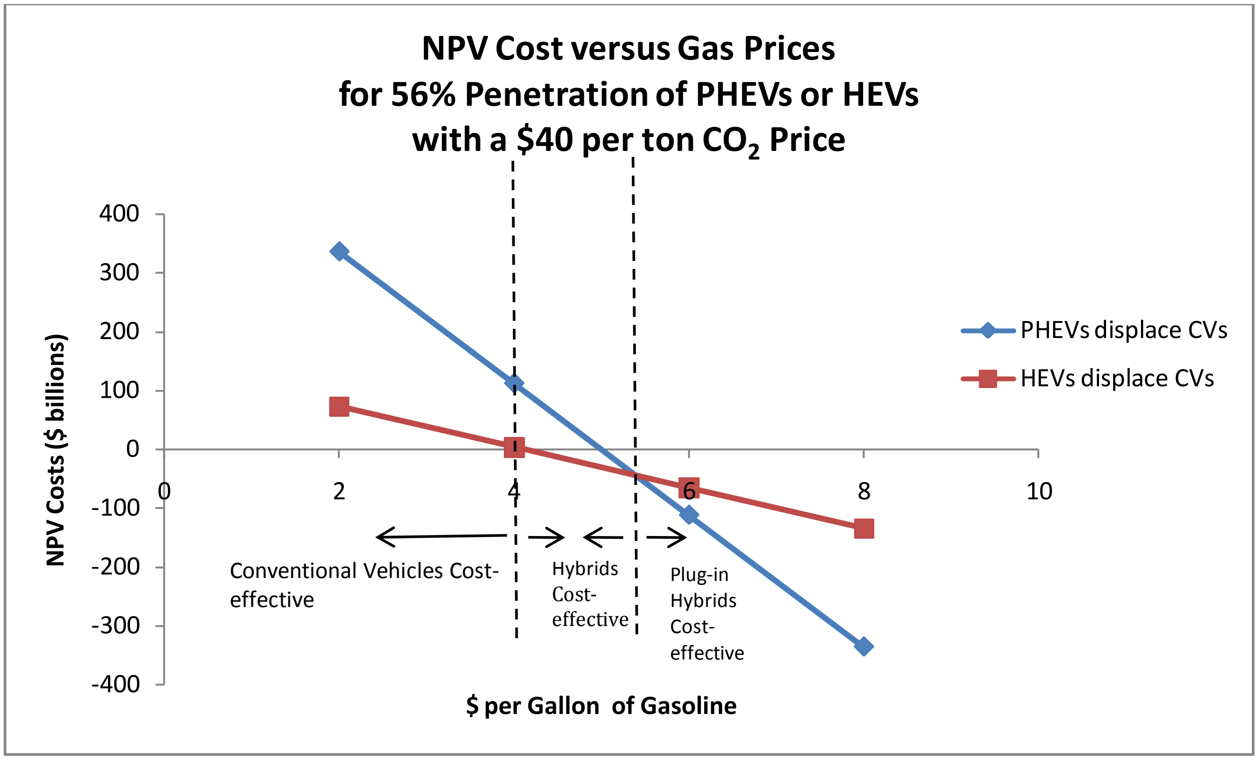


Figure 17. Sensitivity of net present value (NPV) cost of plug-in hybrids and regular hybrids to gasoline prices when a CO_2 price of $40 per ton is present. NPV cost is calculated over the period from 2012 to 2030. The price per gallon displayed is before pass-through of the CO_2 price, though the underlying analysis does include pass-through in the NPV cost calculation.

CO_2 emissions

Compared with conventional vehicles, plug-in hybrids, thanks to much greater energy efficiency, can significantly reduce CO_2 emissions nationally, even when including indirect electricity CO_2 emissions (Figure 18). As more plug-in hybrids displace conventional vehicles, they reduce more CO_2 emissions nationally. Similarly, regular hybrids reduce CO_2 emissions compared with conventional vehicles (Figure 18). In fact, regular hybrids result in almost the same CO_2 reductions as plug-in hybrids, and in some cases, regular hybrids result in even *lower* CO_2 emissions.[7]

With a CO_2 price of $20 or $40 per ton, the electricity sector becomes more efficient and less carbon-intensive, leading to even lower CO_2 emissions for plug-in hybrids (Figure 19). A CO_2 price widens the gap between the emissions of plug-in hybrids and conventional vehicles and establishes a modest gap between plug-in hybrids and regular hybrids. The higher the CO_2 price, the lower the CO_2 emissions resulting from plug-in hybrids relative to hybrids and conventional vehicles.

[7] The electricity system responds to changes in electricity demand stemming from plug-in hybrids. As demand increases, without a CO_2 price, the electricity system may become more or less carbon-intensive depending on the optimal resources at a given demand level. At demands equivalent to 700 and 1,400 million cumulative plug-in hybrids, the electricity sector is more carbon-intensive than at other demand levels. This difference explains why emissions actually increase at these demand levels when plug-in hybrids are compared to regular hybrids.

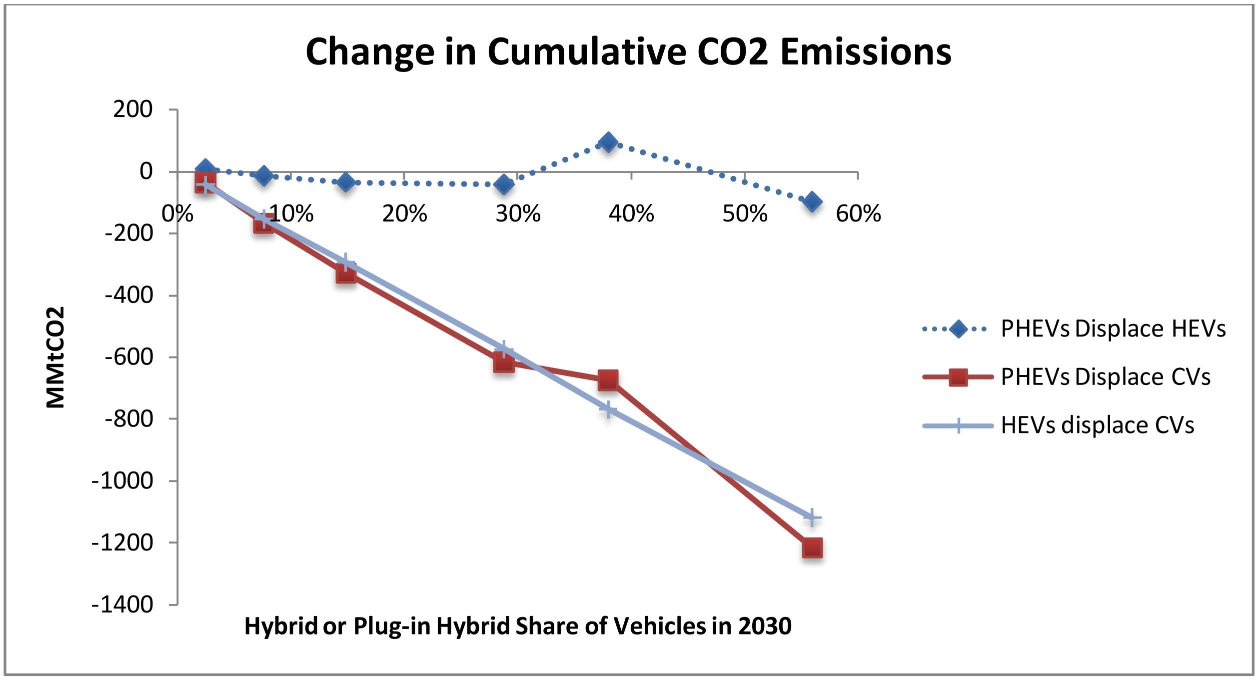


Figure 18. Final penetration of plug-in hybrids and regular hybrids in 2030 is plotted with corresponding changes in cumulative emissions from 2012 to 2030. Each point represents a complete model run. The dotted line shows the incremental emission changes of plug-in hybrids compared to regular hybrids.

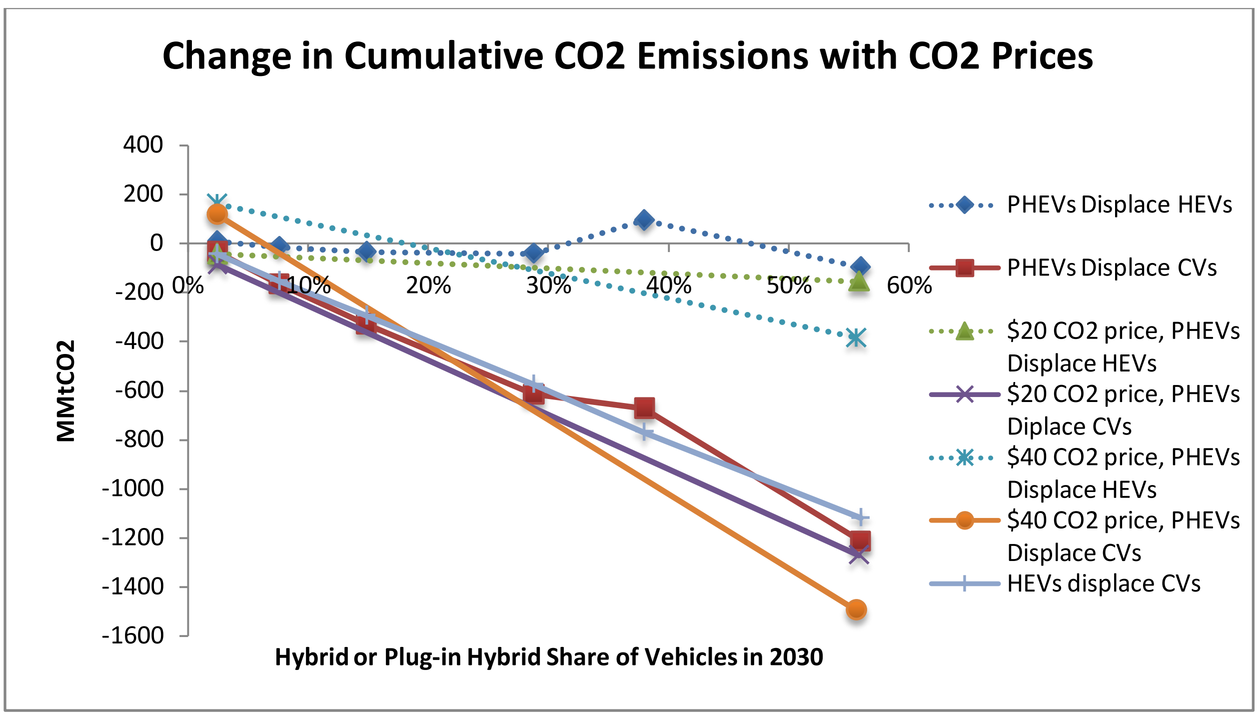


Figure 19. Final penetration of plug-in hybrids and regular hybrids in 2030 is plotted with corresponding changes in cumulative emissions from 2012 to 2030; results with CO_2 prices are shown. Each point represents a complete model run. The dotted lines show the incremental emission changes of plug-in hybrids compared to regular hybrids.

CO_2 emission reduction cost curves

By combining the change in emissions and resulting costs, we can construct CO_2 reduction cost curves for plug-in hybrid or regular hybrid penetrations (Figure 20). Without a CO_2 price present and with the default assumption of $4 per gallon of gasoline, plug-in hybrids cost considerably more per ton of CO_2 reduced than regular hybrids.

CO_2 reduction cost curves are an important tool for policymakers to understand the tradeoffs of pursuing different strategies. When compared with the cost curves of other mitigation strategies, CO_2 reduction cost curves can help policymakers decide whether to devote resources to these alternative vehicles.

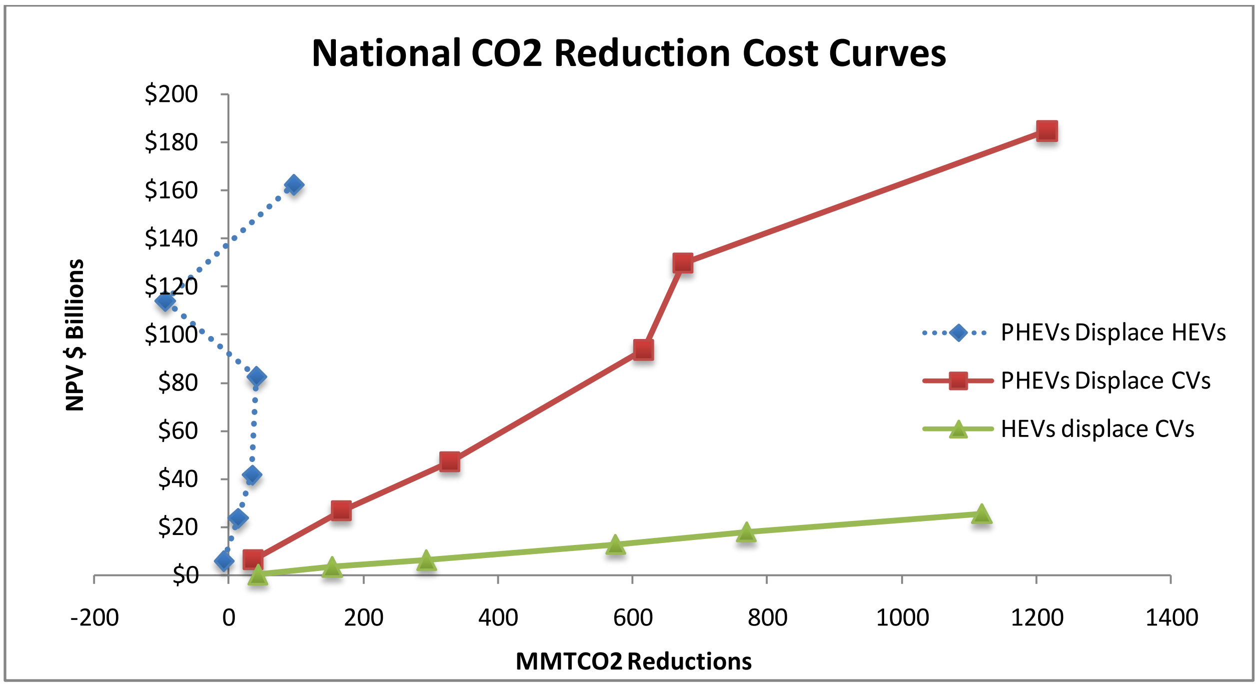


Figure 20. National CO_2 reduction cost curves. The horizontal axis plots emissions reductions, while the vertical axis plots net present value costs. Each point represents a different penetration level of plug-in or regular hybrids and is a complete model run. Results from individual model runs are compiled into cost curves. The dotted line shows the incremental cost of CO_2 reduction for plug-in hybrids compared with regular hybrids.

If we assume that CO_2 prices are present, the slope of the cost curves begins to flatten. Higher CO_2 prices result in flatter cost curves. For example, at a CO_2 price of $40 per ton, regular hybrids achieve virtually zero net cost reductions (Figure 21).

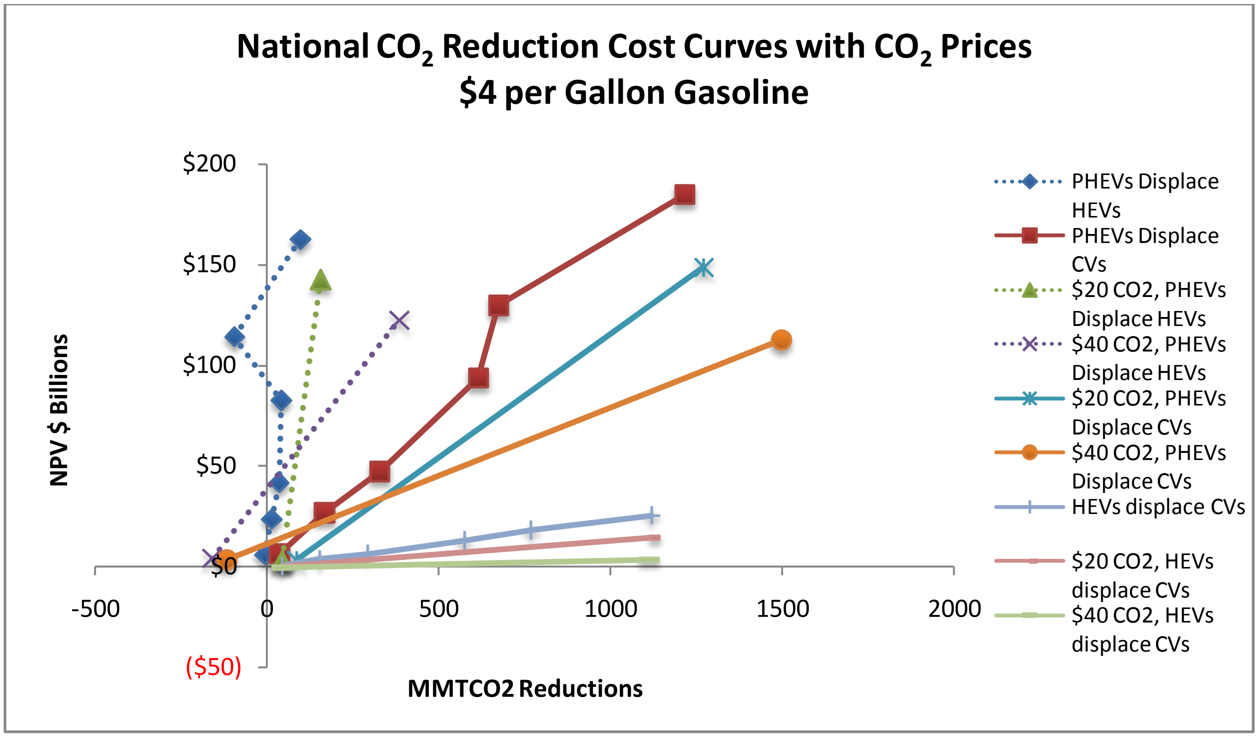


Figure 21. National CO_2 reduction cost curves with CO_2 prices. The horizontal axis plots emissions reductions, while the vertical axis plots net present value costs. Each point represents a different penetration level of plug-in or regular hybrids and is a complete model run. Results from individual model runs are compiled into cost curves. The dotted lines show the incremental cost of CO_2 reduction for plug-in hybrids compared with regular hybrids.

At $6 per gallon of gasoline, the CO_2 cost curves look considerably different (Figure 22). In fact, both plug-in and regular hybrids have negative cost curves: investing in either of the two results in cost savings and emission reductions at a gasoline price of $6 per gallon. The greatest cost savings and emission reductions in this example can be achieved by plug-in hybrids with a CO_2 price of $40 per ton.

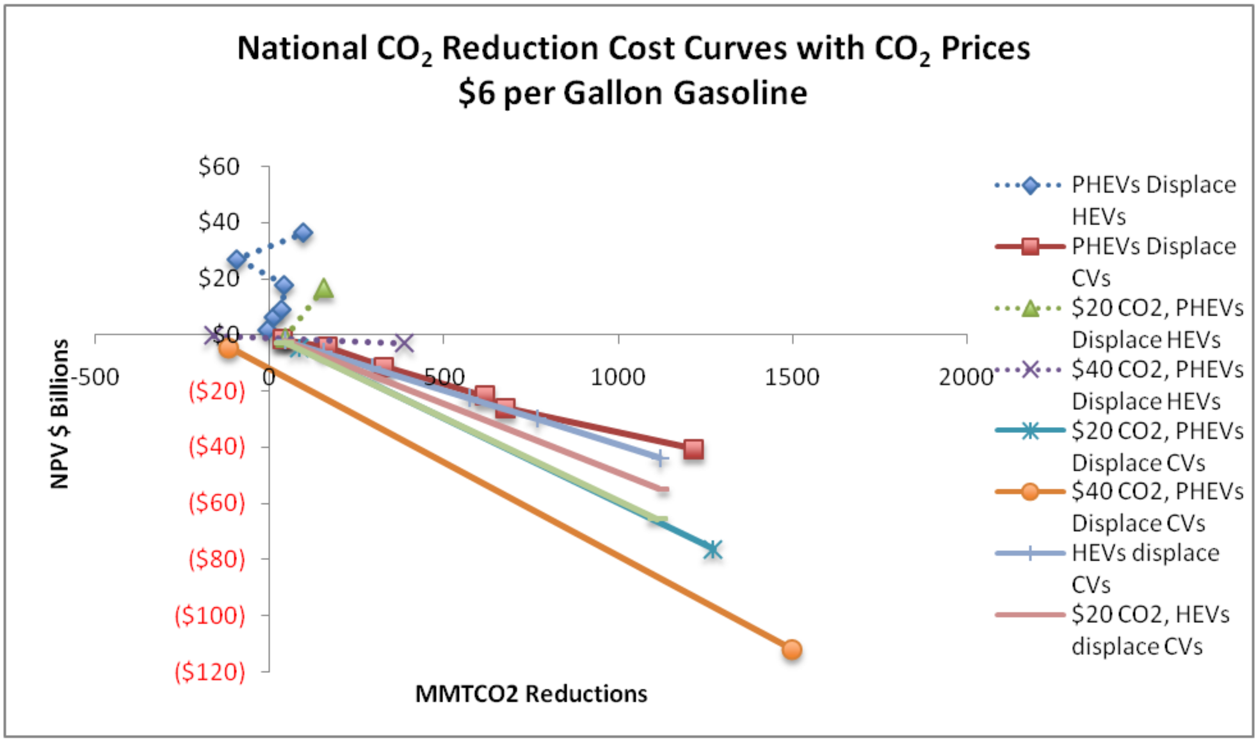


Figure 22. National CO_2 reduction cost curves with CO_2 prices and $6 per gallon gasoline. The horizontal axis plots emissions reductions, while the vertical axis plots net present value costs. Each point represents a different penetration level of plug-in or regular hybrids and is a complete model run. Results from individual model runs are compiled into cost curves. The dotted lines show the incremental cost of CO_2 reduction for plug-in hybrids compared with regular hybrids.

Regional Integrated Vehicle-Electricity Sector Results

Regional results for plug-in hybrids can vary dramatically. In fact, some regions see CO_2 increases with plug-in hybrids unless a significant CO_2 price is present. Regular hybrids consistently result in CO_2 emission reductions in all regions and are therefore better suited than plug-in hybrids in some regions. Policymakers should consider these regional differences when constructing policy regarding plug-in hybrid vehicles. As mentioned in the "Electricity Sector Implications" section, regional results would diverge if carbon capture and storage technology is adopted in the coal-intensive regions in which CO_2 emissions increase with plug-in hybrids.

The NI-NEMS model has 13 electricity market regions, based largely on those of the North American Electric Reliability Council (NERC), as shown in Figure 23. NI-NEMS is intended to be a national model, and results at the regional level presented here are illustrative, not conclusive. Because NI-NEMS can adjust transmission across regions in response to changes in demand resulting from plug-in hybrids, the changes in one region may be influenced by changes in nearby regions. Therefore, if plug-in hybrids were to be adopted in one region and not others, the results might be slightly different than the results shown here in which all regions have plug-in hybrid penetrations.

Regional results are more complicated than national results. Even when compared with conventional vehicles, plug-in hybrids lead to higher CO_2 emissions in some electricity regions (Figure 23).

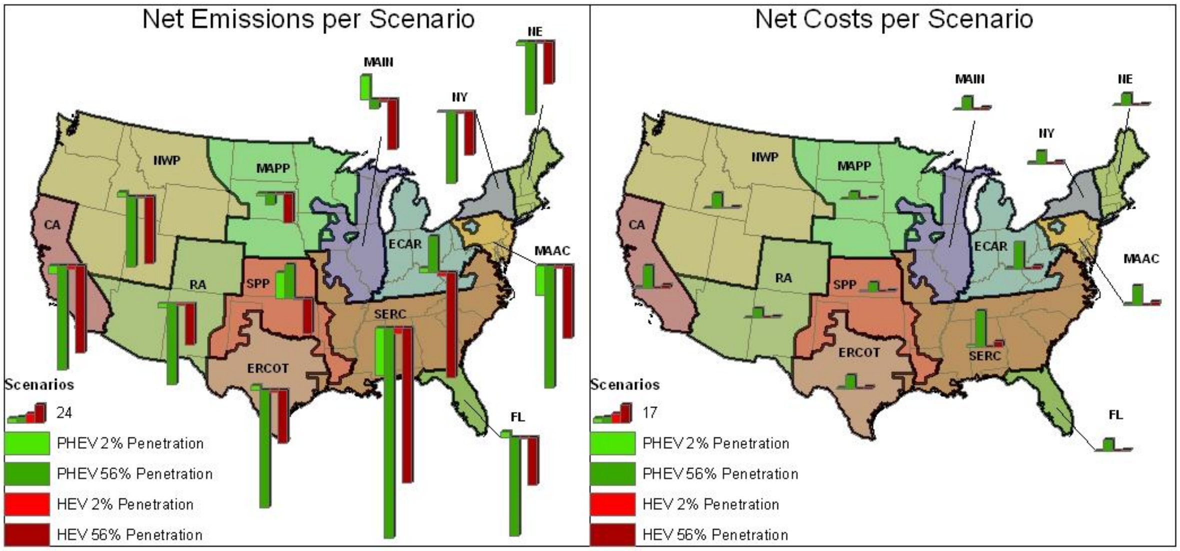


Figure 23. Net emissions of plug-in and regular hybrids (at final penetrations of 2% and 56%) by region on left. Net present value cost of plug-in and regular hybrids (at final penetrations of 2% and 56%) by region on right.

As at the national level, constructing regional CO_2 reduction cost curves is a helpful tool for comparing options (Figure 24). Most regions follow a similar trajectory when plug-in hybrids displace conventional vehicles that is consistent with the aggregate national results. Four regions—SPP, ECAR, MAIN, and MAPP—follow different trajectories, with largely backwards-sloping CO_2 reduction cost curves. For these regions, emissions increase with greater penetrations of plug-in hybrids, largely because of the dominance of carbon-intensive coal-fired generation in these areas. Although plug-in hybrid vehicles are far more efficient than their conventional counterparts, they consume carbon-intensive electric power in these regions that outweighs the gains achieved by reducing gasoline consumption.

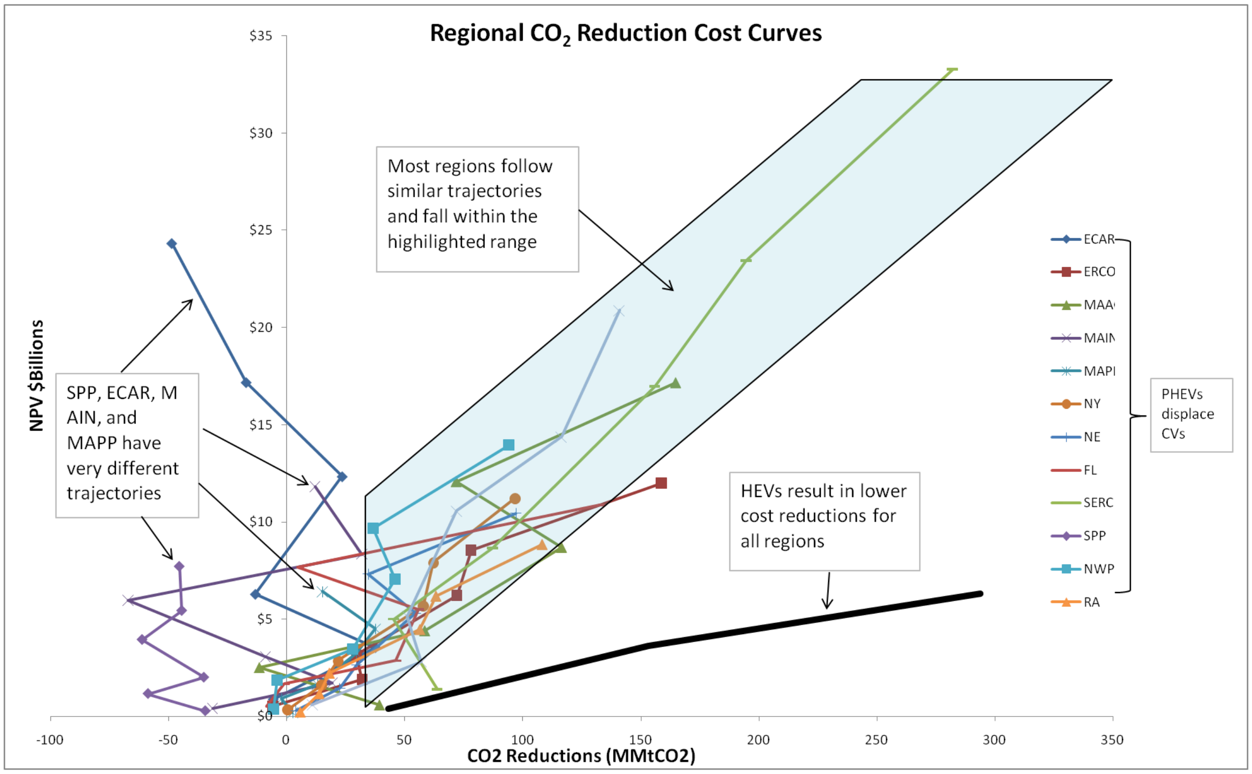


Figure 24. Regional CO_2 reduction cost curves for plug-in hybrids. The horizontal axis plots regional emissions reductions, and the vertical axis plots regional net present value costs. The black line shows a regular hybrid cost curve, which is uniform for all regions.

If gasoline prices are assumed to be $6 rather than $4 per gallon, plug-in hybrids become cost-effective in all regions, although CO_2 emissions remain largely unchanged in MAPP and continue to increase in SPP, ECAR, and MAIN.

On the other hand, if a CO_2 price signal is present, regional cost curves become much more consistent, especially at a CO_2 price of $40 per ton (Figure 25 and Figure 26). Under these scenarios, all regions see CO_2 reductions except at the lowest penetrations of plug-in hybrids. The MAIN region, however, has a nearly vertical cost curve, suggesting that while plug-in hybrids can lead to emission reductions in MAIN with a CO_2 price present, greater penetrations of plug-in hybrids will not lead to greater CO_2 reductions but will lead to higher costs. Nevertheless, in terms of CO_2 emission reductions, regular hybrids perform better in these regions, even with a CO_2 price. To the extent that plug-in hybrids are supported by policy, providing incentives for plug-in hybrids as a carbon mitigation strategy makes most sense in states outside of SPP, ECAR, MAIN, and perhaps MAPP (Figure 27), unless carbon capture and storage technology is also fostered in coal-intensive regions.

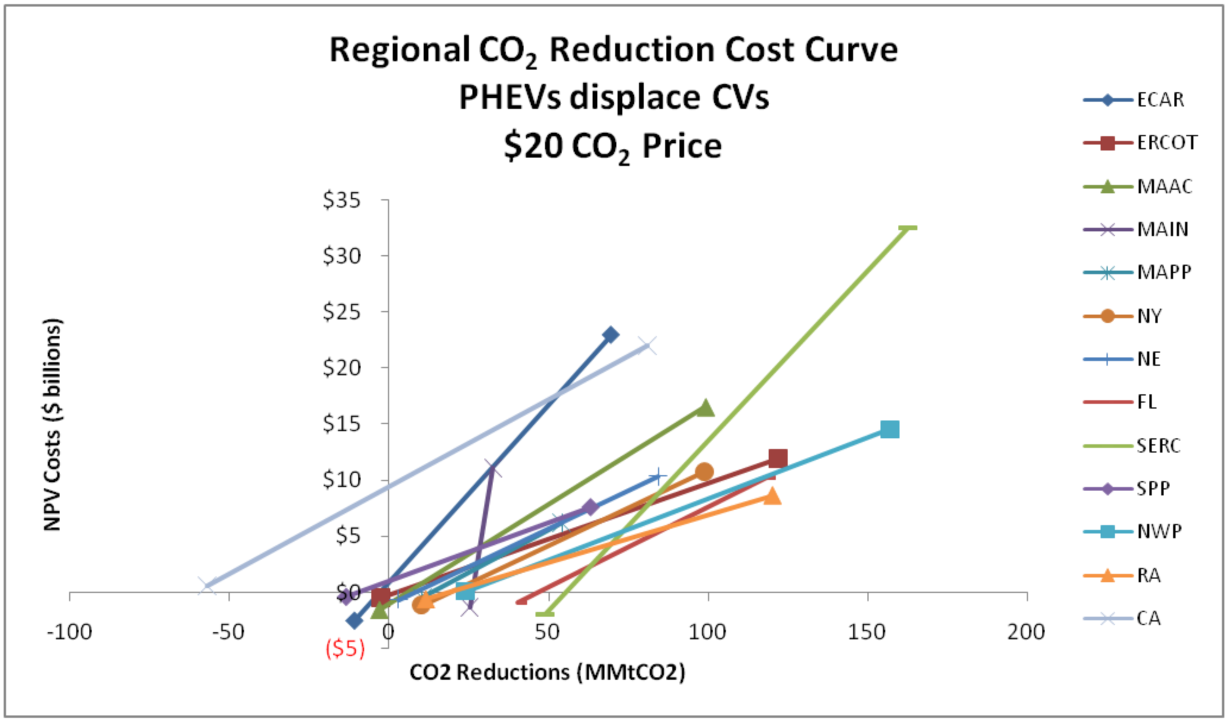


Figure 25. Regional CO_2 reduction cost curves for plug-in hybrids, with a CO_2 price of $20 per ton. The horizontal axis plots regional emissions reductions, and the vertical axis plots regional net present value costs.

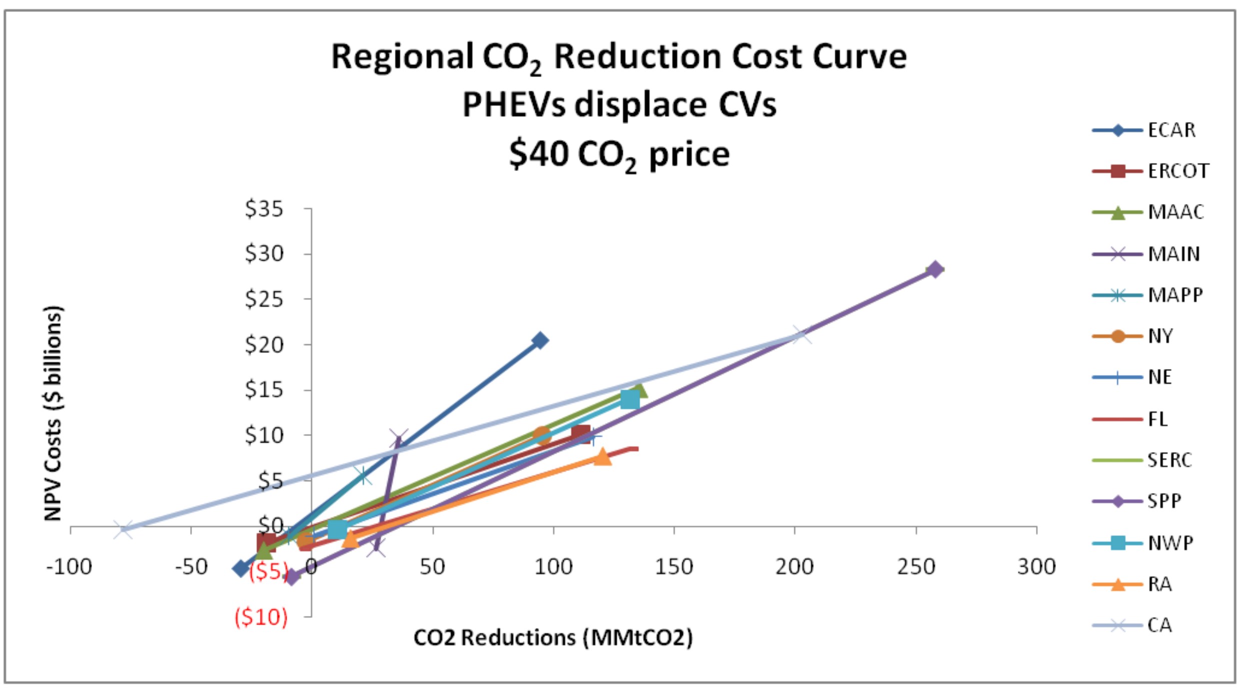


Figure 26. Regional CO_2 reduction cost curves for plug-in hybrids, with a CO_2 price of $40 per ton. The horizontal axis plots regional emissions reductions, and the vertical axis plots regional net present value costs.

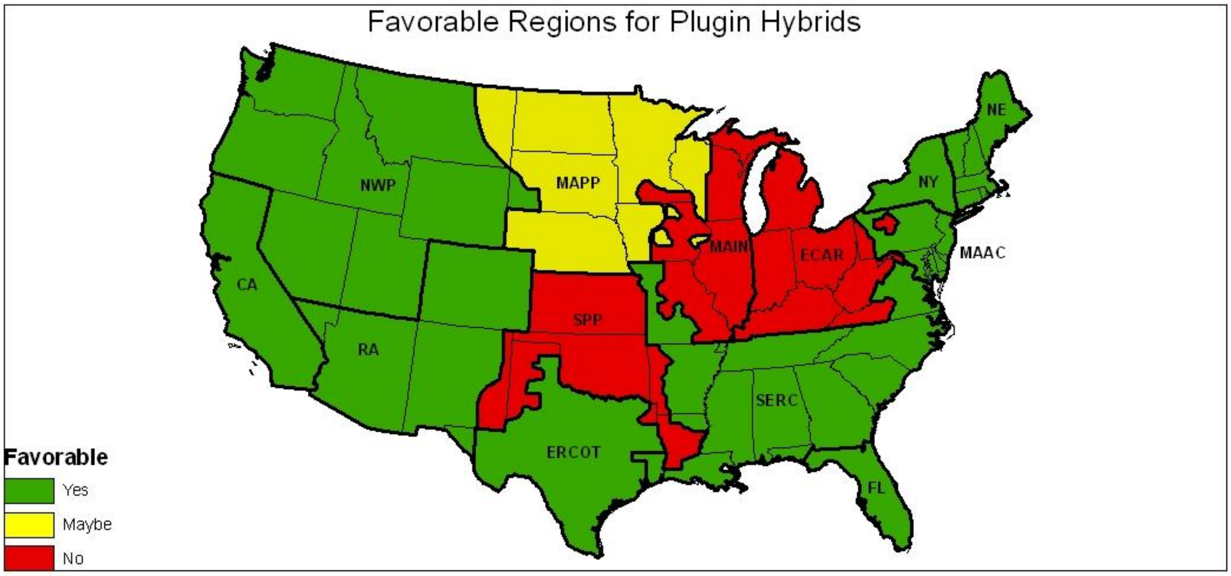


Figure 27. Favorable regions for plug-in hybrids. Regions are displayed as defined in the NEMS model. Green indicates that a region is favorable for plug-in hybrids, yellow indicates a region may be favorable, and red indicates that a region is not favorable for plug-in hybrids.

Energy Security

Although the implications of plug-in hybrid carbon emissions and costs are the focus of this paper, one clear benefit of deploying plug-in hybrids is the fact that they would reduce U.S. gasoline consumption (Figure 28). Plug-in hybrids consume about one-third of the gasoline that conventional vehicles consume and about half of the gasoline that regular hybrids consume.

Reducing gasoline consumption does not necessarily mean that the United States would import less oil or import a smaller percentage of oil. If the cost of oil extraction in the United States is greater than the cost internationally, then a reduction in the demand for oil may very well reduce domestic production more so than imports. Also, about 19.5 gallons out of every barrel of oil (44 gallons) are refined into gasoline. The remainder is refined into other petroleum products. The ratio of refined gasoline to other products from a barrel of oil can vary only somewhat with the current U.S. refining infrastructure. Reducing the consumption of gasoline does not change the demand for the other petroleum products; how significantly lower gasoline consumption affects crude oil imports is uncertain. Issues around reduced consumption of gasoline and oil imports are important but beyond the scope of this paper.

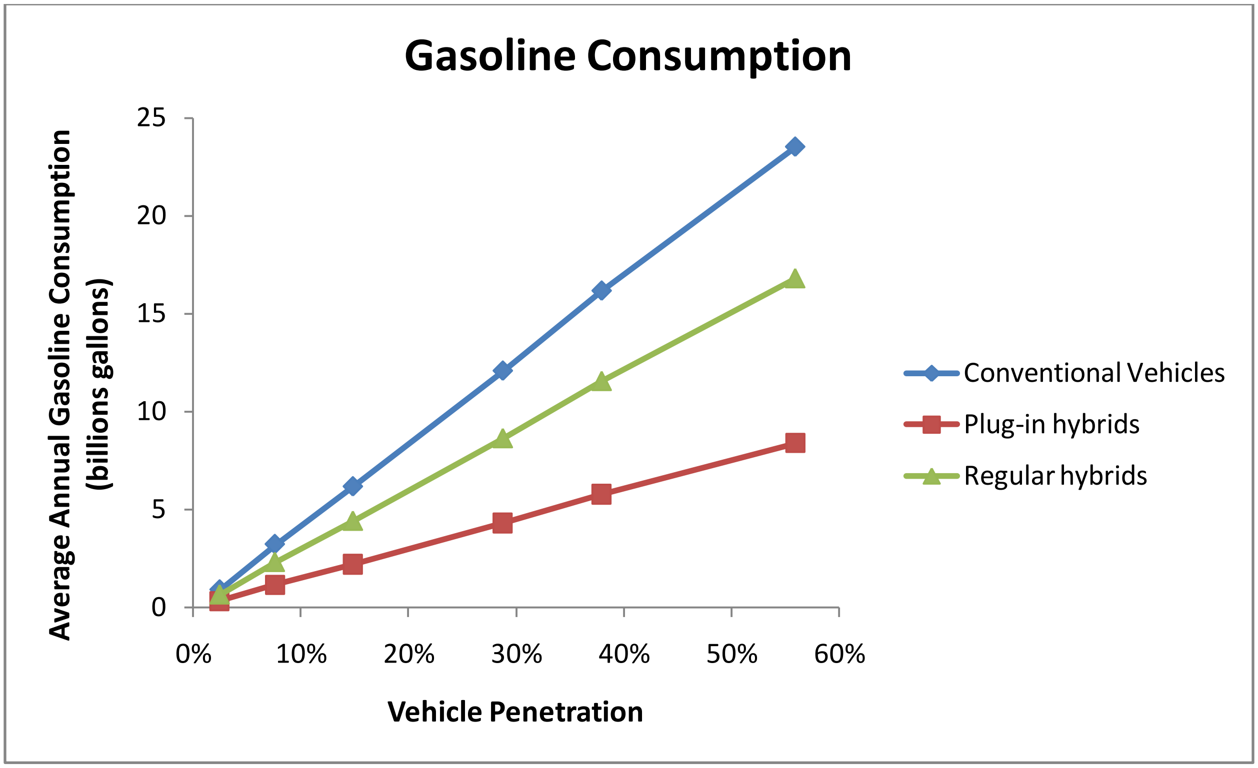


Figure 28. Gasoline consumption, averaged over the period from 2012 to 2030, for conventional vehicles, regular hybrids, and plug-in hybrids.

Conclusions

Plug-in hybrids are, without doubt, good for reducing CO_2 emissions when they displace conventional vehicles. Regular hybrids are also good for reducing CO_2 emissions when they displace conventional vehicles. The question of whether plug-in hybrids or regular hybrids are better in terms of a cost-benefit analysis depends on assumptions. Our analysis suggests that if gasoline prices top $6 per gallon, plug-in hybrids are more cost-effective than regular hybrids. Also, if a substantial CO_2 price (e.g. $40 per ton) is present in the economy, then plug-in hybrids result in more CO_2 reductions than regular hybrids and at a lower cost. If, on the other hand, gasoline prices are below $6 per gallon or CO_2 prices are low or not present, then regular hybrids appear to be a more cost-effective option that leads to more certain emission reductions. These general conclusions break down somewhat in certain regions of the country. In heavily coal-dependent states in the ECAR, SPP, and MAIN regions, regular hybrids are probably a better bet for reducing CO_2 emissions.

Appendix A: Vehicle Model

We developed a vehicle model in Excel that will take outputs from the NI-NEMS model as inputs to forecast the incremental cost and direct CO_2 emissions of building and operating plug-in or regular hybrid vehicles compared to conventional vehicles. Below is a mathematical representation of the vehicle model. We derived the parameters from data reported in a joint Electric Power Research Institute (EPRI)/Natural Resources Defense Council (NRDC) study from 2007 titled "Environmental Assessment of Plug-in Hybrid Electric Vehicles."

Scenario assumption:
PHEVEL = Total annual PHEV electricity consumption

Constant:
$GasCO_2$ = Gasoline CO_2 emission factor

Parameters:
$a = -0.00003$
$b = 0.85$
$c = 3{,}720.4$
$d = 19.707$
$e = -314.29$
$f = 314.78$

Exogenous (from NEMS outputs):
AVMT = Annual average vehicle miles traveled per vehicle
CVMPG = Annual CV efficiency in miles per gallon
SESCO2 = Annual scenario electricity sector CO_2 emissions
RESCO2 = Annual reference case electricity sector CO_2 emissions

Endogenous variables:
UF = Annual utility factor
EIF = Annual efficiency improvement factor
ECpPHEV = Annual electricity consumption per PHEV
GCpPHEV = Annual gasoline consumption per PHEV
PHEVGas = Total annual PHEV gasoline consumption
NPHEV = Annual number of PHEVs
PHEVVMT = Annual PHEV vehicle miles traveled
PHEVDCO2 = Annual PHEV direct CO_2 emissions
PHEVECO2 = Annual PHEV electricity CO_2 emissions
PHEVTCO2 = Annual PHEV total CO_2 emissions

PHEVNCO2 = Annual PHEV net CO_2 emissions
CVVMT = Annual CV vehicle miles traveled
CVDisp = Annual number of CVs displaced
CVGas = Annual CV gasoline consumption
CVCO2 = Annual CV CO_2 emissions

Equations:

$$UF_t = AVMT_t \times (a) + b$$
$$ECpPHEV_t = (c \times UF_t + d) \times EIF_t$$
$$GCpPHEV_t = (e \times UF_t + f) \times EIF_t$$
$$NPHEV_{rt} = \frac{PHEVEL_{rt}}{ECpPHEV_t}$$
$$PHEVVMT_{rt} = NPHEV_{rt} \times AVMT_t$$
$$PHEVGas_{rt} = NPHEV_{rt} \times GCpPHEV_t$$
$$PHEVDCO2_{rt} = PHEVGas_{rt} \times GasCO2$$
$$PHEVECO2_{rt} = SESCO2_{rt} - RESCO2_{rt}$$
$$PHEVTCO2_{rt} = PHEVDCO2_{rt} + PHEVECO2_{rt}$$
$$CVDisp_{rt} = NPHEV_{rt}$$
$$CVVMT_{rt} = PHEVVMT_{rt}$$
$$CVGas_{rt} = \frac{CVVMT_{rt}}{CVMPG_t}$$
$$CVCO2_{rt} = CVGas_{rt} \times GasCO2$$
$$PHEVNCO2_{rt} = PHEVTCO2_{rt} - CVCO2_{rt}$$

—
r = 1 to R, where R = 13 NEMS NERC regions
t = 1 to T, were T = 19 years

the Climate Change Policy Partnership

The Climate Change Policy Partnership (CCPP) researches carbon-mitigating technology, infrastructure, institutions and overall systems in order to inform lawmakers and business leaders as they lay the foundation of a low-carbon economy. Duke University's CCPP is an interdisciplinary research program of the Nicholas Institute for Environmental Policy Solutions, the Nicholas School of the Environment, and the Center on Global Change. Our corporate partners make our research possible and help us bridge the gap between academic research, business expertise, and effective climate change policy application.

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