TECHNOLOGY

LIFECYCLE GREENHOUSE GAS EMISSIONS FROM DIFFERENT LIGHT-DUTY VEHICLE AND FUEL PATHWAYS: A SYNTHESIS OF RECENT RESEARCH

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Transitioning to a cleaner fleet of advanced vehicles powered by electricity, hydrogen, and advanced biofuels or petroleum products can yield a significant reduction in greenhouse gas emissions and petroleum consumption. A meaningful assessment of the comparative merits of these alternate fuel pathways requires a solid understanding of their technological potential to reduce emissions. Available studies evaluating full lifecycle emissions rely on various assumptions of that potential and yield a wide range of results. This brief summarizes and synthesizes the results of several recent studies and presents the full range of greenhouse gas emission estimates for each type of advanced vehicle and fuel. It also explains the reasons these estimates vary so widely and identifies opportunities for future analyses that use a consistent set of scenarios with transparent assumptions in order to compare the greenhouse gas impacts of fuel and vehicle pathways.

INTRODUCTION

The transportation sector is the United States' second-largest source of greenhouse gas (GHG) emissions, accounting for 28 percent of total emissions in 2011.[1] Cars and light-duty trucks emit about 60 percent of transportation's GHG emissions and, correspondingly, consume the most oil in the sector.[2] Considering the threat to the environment from global climate change, there is a clear need for the United States to reduce GHG emissions associated with the light-duty vehicles and fuels.

Advanced vehicles, such as hydrogen fuel cell and electric vehicles, as well as alternative fuels, such as low-carbon biofuels from cellulose, offer the opportunity to significantly reduce GHG emissions. In developing public policy that encourages fuels with the lowest overall GHG emissions, it is important to consider the full lifecycle impacts of different fuel and vehicle combination in order to identify the most viable alternatives. Other factors, like market feasibility are also critical considerations, but are beyond the scope of this paper.

LIFECYCLE ASSESSMENT OVERVIEW AND STUDIES CONSIDERED

Lifecycle assessment accounts for GHG emissions generated from the production, transportation, and consumption of a fuel; often referred to as "well-to-wheel" (WTW). For fossil fuels, the fuel pathway (or lifecycle) assessment accounts for emissions from the extraction and refining process, while for biofuels, it also includes the carbon dioxide absorbed during the plant's growth, and should, but does not always include any indirect land-use changes. Some studies also consider emissions from vehicle manufacturing and disposal.

The following is a list of the studies synthesized in this brief. Only the first two studies listed considered cost as a factor; the remaining studies only considered technological potential. See Table 1 at the end of this brief for more detail.

- *National Research Council: Transitions to Alternative Vehicles and Fuels*, 2013 (NRC)
- *MIT: On the Road in 2035*, 2008 (MIT)
- *Argonne National Laboratory: Well-to-Wheels Analysis of Energy Use and Greenhouse Gas Emissions of Plug-in Hybrid Electric Vehicles*, 2010 (Argonne)
- *California Air Resources Board: California-GREET Model version 1.8b (modified by Life Cycle Associates)*, 2009 (CARB) 3
- *EPRI/NRDC: Environmental Assessment of Plug-in Hybrid Electric Vehicles*, 2007 (EPRI/NRDC)
- *Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles*, 2008 (Samaras and Meisterling)

To establish a baseline providing a consistent basis for comparing the results of the above studies, C2ES used the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model to estimate well-to-wheels emissions for all vehicle types using default parameters.

Because of recent developments in natural gas production involving hydraulic fracturing, C2ES examined the following additional papers focusing on natural gas.

- Argonne National Laboratory's *Life-Cycle Analysis of Shale Gas and Natural Gas* (Clark et al 2011)
- "Greater focus needed on methane leakage from natural gas infrastructure" (Alvarez et al 2012)
- "Life cycle greenhouse gas emissions of Marcellus shale gas" (Jiang et al 2011)[4]

Only the NRC study assessed the WTW emissions for biomass-based fuels that have substantially similar properties to gasoline and diesel, known as drop-in biofuels. As result, C2ES did not evaluate the NRC assessment of these fuels. While drop-in biofuels are still in the research, development, and demonstration phase, there is a clear need for more lifecycle assessments of these fuels from various biomass feedstocks.

STUDY RESULTS SUMMARY AND DISCUSSION

Figure 1 shows the range of well-to-wheel greenhouse gas emissions of key vehicle and fuel combinations from the selected studies and baseline scenario created by C2ES using the GREET model.[5] As seen in the figure, assumptions about vehicle drivetrain efficiency, greenhouse gas emissions from fuel production and distribution, and many other factors led to a wide range of emissions for each vehicle and fuel combination in the present and future. In addition, some studies based their future scenarios on greenhouse gas emission reductions

BOX 1. KEY FINDINGS

- Electricity, hydrogen, and biofuels power the vehicle-fuel combinations with the lowest GHG emissions per mile. When averaging across the studies, the lowest-emitting vehicle-fuel combination is low-carbon biofuels used in hybrid electric vehicles, but hydrogen fuel cell and battery electric vehicles made from very low-carbon sources are the lowest-emitting pathway identified in any study.
- There is a wide range in the estimates among studies for the same vehicle and fuel combination, denoted by the error bars in Figure 1. The variation from the average among the studies (known as the standard deviation) is highest for future gasoline-powered conventional vehicles, reflecting the uncertainty around efficiency improvements for these vehicles.
- Studies project that future lifecycle emissions for all vehicle-fuel combinations will decline, but to varying degrees due to assumptions about vehicle technology and the carbon intensity of fuel feedstocks, especially for biofuels and the electrical grid mix.

while others based them on a combination of fuel and vehicle technologies. A lack of consistency in these scenarios and transparency in the assumptions that defined them made it difficult to meaningfully compare results.

The lowest-emitting vehicle-fuel pathway from any study considered is from low-carbon electricity used to charge battery electric vehicles and low-carbon hydrogen for fuel cell vehicles, including the use of fossil fuel-based feedstocks with carbon capture and sequestration. Averaging among the studies, however, the lowest-emitting vehicles are fueled by 85 percent cellulosic ethanol powering hybrid electric vehicles. This discrepancy between "best" case and "average" case exemplify the importance of transparency in study assumptions.

Across all vehicle types, emissions per mile decline over time, with great variability among all future vehicle and fuel combinations. Notably, all future alternative vehicle technologies represent significant improvements in GHG emissions relative to the GREET 2020 conventional gasoline vehicle (405 grams of carbon dioxide equivalent, CO_2e, per mile).[6] For example, while MIT's analysis assumed that oil sands would make up an increasing share of U.S. gasoline and the U.S. grid would change little in carbon intensity, it also assumed that vehicles would improve in engine efficiency and have their weights reduced by 20 percent. By projecting decreases in vehicle size and improvements in vehicle efficiency, MIT found that conventional vehicles, hybrid vehicles, and plug-in hybrid electric vehicles (PHEVs) can still reduce GHG emissions significantly even when charging from a high-carbon grid or using gasoline.

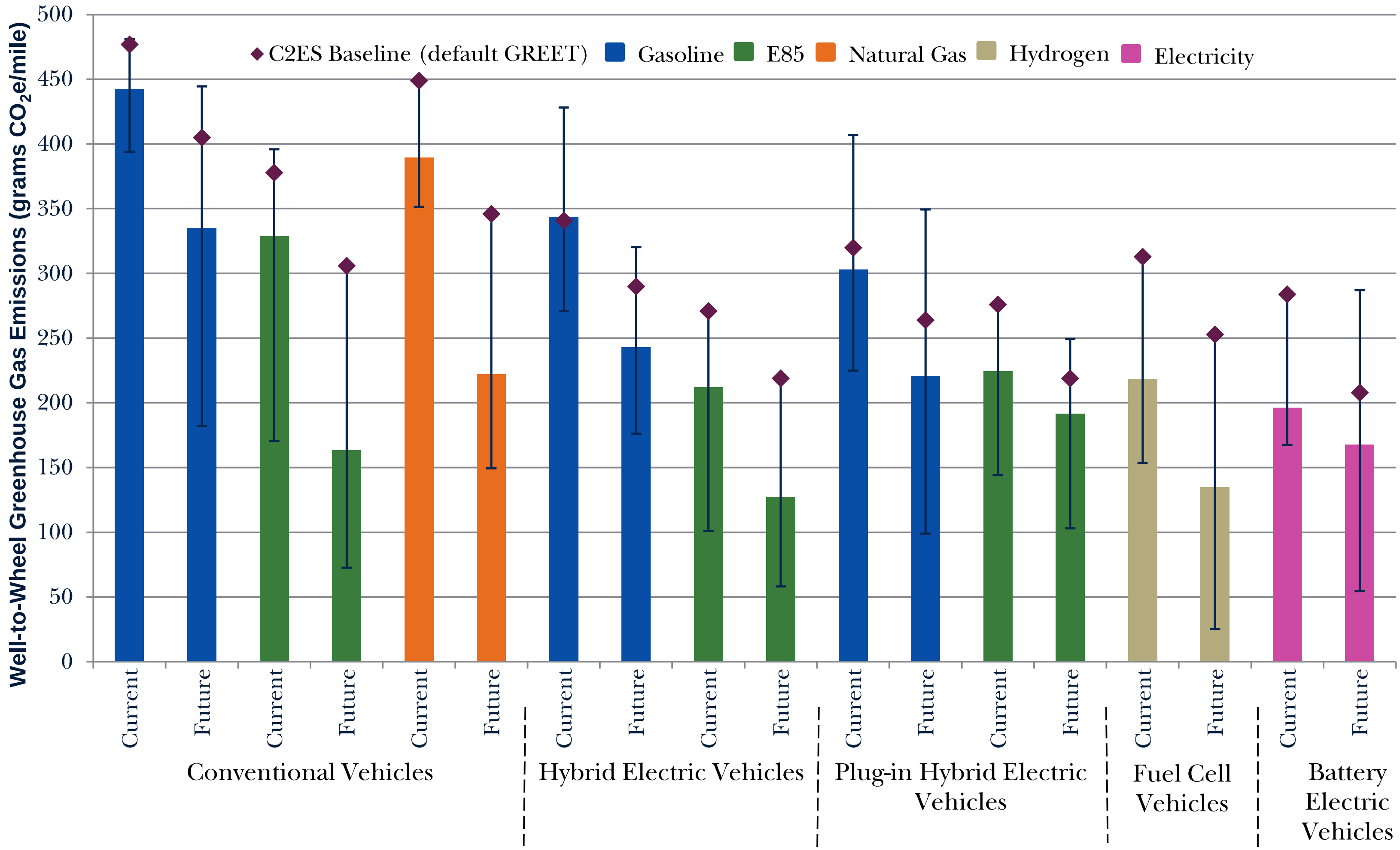
IMPORTANCE OF FUEL CARBON INTENSITY

Lifecycle emissions vary widely depending on the carbon intensity of the fuel, regardless of the vehicle type. For instance, Argonne's hybrid vehicle fueled by corn ethanol emits 17 percent less than its gasoline hybrid, while the same vehicle powered by biomass ethanol from switchgrass emits 63 percent less than the gasoline hybrid. Similarly, the PHEV recharging from the U.S. average grid emits 47 percent less when powered by biomass ethanol instead of gasoline.

For ethanol-fueled vehicles, corn ethanol represents the high end of the range of lifecycle GHG emissions; ethanol from switchgrass or other cellulosic materials are responsible for the low end of the range.[7] Importantly, some of these studies do not include emissions from indirect land use change (e.g., shifting forests into agricultural land to compensate for agricultural land shifting to biofuel production), which is highly uncertain and can be significant. For example, the California Air Resources Board (CARB) estimates that at least 25 percent of emissions from ethanol come from land use change or other indirect effects.

According to Samaras and Meisterling, conventional and hybrid vehicles powered by cellulosic ethanol emit 54 to 68 percent less than when fueled by gasoline. Because of this difference, the same study concludes a gasoline PHEV with an electric range of 30 miles recharging from a low-carbon grid emits 25-54 percent more than a cellulosic ethanol conventional vehicle and 54-100 percent more than a cellulosic ethanol hybrid vehicle.

FIGURE 1: The average well-to-wheel GHG emissions for current and future vehicles (where future is either a specified year, like 2035, or a hypothetical scenario) using the studies considered in this brief along with a baseline scenario created by C2ES using the GREET model. The error bars indicate the minimum and maximum for each fuel type. See TABLE 1 for a complete summary of the data sources in this figure.



BOX 2. PLUG-IN HYBRID ELECTRIC VEHICLES SPOTLIGHT

Among the studies considered, the lowest-emitting PHEV is gasoline-powered and recharged from a very low-carbon grid, with far lower emissions than the lowest-emitting gasoline hybrid vehicle. PHEVs fueled by biomass and cellulosic ethanol are also very low-emitting, despite being partly powered by electricity from a more carbon-intensive grid (e.g., an off-peak U.S. average grid, with about 50 percent coal, 29 percent natural gas, and 20 percent nuclear).

Argonne's research on engine and powertrain efficiency suggests that differences in vehicle operations between driving in electric- and gasoline-powered mode will result in lower overall efficiencies for a PHEV when compared to a hybrid. This is in part based on assumptions about the miles traveled that are powered by electricity and liquid fuel for a PHEV. That is, the more miles traveled that are powered by electricity, the higher the energy efficiency. In addition, the heavier weight of the battery also decreases operational efficiency for PHEVs. Thus, Argonne determined that a hybrid would have lower emissions than a PHEV when powered by the same fuel and relying on the U.S. average electricity mix. For example, Argonne's biomass ethanol hybrid is nearly 30 percent lower in emissions than Argonne's biomass ethanol PHEV. Similarly, in Samaras and Meisterling's low-carbon scenario the ethanol hybrid has slightly lower GHG emissions than the ethanol PHEV.

The PHEV analyzed in the MIT study also has emissions comparable to PHEVs from studies that include a low-carbon scenario, suggesting that gains in engine efficiency and reductions in vehicle weight can help reduce WTW emissions even with little or no change in gasoline and electrical grid carbon intensity.

In a similar vein, the carbon intensity of the grid can have a significant impact on emissions. The same study estimates that a gasoline PHEV powered by electricity from a low-carbon grid has about the same emissions as a cellulosic ethanol PHEV using today's grid.[8]

The most inefficient vehicles, on average, offer the greatest opportunity to lower emissions on a per vehicle per mile basis. As a result, most studies conclude that lowering the carbon intensity of onboard fuel used in hybrid and conventional vehicles would yield more reductions per mile for those vehicles than decarbonizing the grid would for plug-in electric vehicles in part because vehicles that run on electricity have relatively low WTW emissions today. For example, Argonne's 2020 biomass ethanol hybrid is nearly 40 percent lower in emissions than EPRI/NRDC's 2050 low-carbon scenario gasoline PHEV, which is recharging from electricity that is 84 percent lower in carbon intensity than the 2006 baseline. An exception is the NRC report, which says emissions from battery electric vehicles could be reduced by two-thirds between 2010 and 2035, the largest emissions reduction of any vehicle-fuel combination in the report.

The lifecycle emissions of fuel cell and battery-electric vehicles are more uncertain than gasoline vehicles since the fuel (hydrogen and electricity, respectively) can be produced from sources with a wide range of emission profiles. NRC concludes that using low-carbon feedstocks to make hydrogen for fuel cell vehicles and to generate electricity for electric vehicles result in the lowest emissions of any vehicle-fuel combination. In Argonne's model 2020 fuel cell vehicle GHG emissions are lower than gasoline and corn ethanol hybrids and PHEVs, and just slightly higher than the default GREET 2020 battery electric vehicle. Notably, emissions from the Argonne battery electric vehicle in 2020 are 38 percent higher than GREET's default settings for a 2020 battery electric vehicle, showing the wide range of projected emissions from electricity used as transportation fuel.

The uncertainty surrounding hydrogen is reflected in the studies as well. While MIT projects lower emission for fuel cell vehicles in 2035 from natural gas-based hydrogen than from battery electric vehicles, these vehicles do not perform better than gasoline hybrids and PHEVs. Importantly, MIT estimates that it would take 30 years for hydrogen technology to be market-ready. MIT's study shows hydrogen production at central plants would be more efficient and lower in emissions than decentralized hydrogen production at

BOX 3. NATURAL GAS VEHICLES SPOTLIGHT

Natural gas vehicles can offer a notable emission reduction from gasoline conventional vehicles, comparable to many hybrids. However, the main constituent of natural gas is methane, a potent greenhouse gas with about 72 times the global warming potential of carbon dioxide using a 20-year timeframe, or about 21 times over a 100-year timeframe. Consequently, the direct release of methane during production, transmission, and distribution may offset some of the potential climate benefits of its use in vehicles. These methane emissions are an important, yet not well understood, component of overall methane emissions. In recent years greenhouse gas measurement and reporting requirements have drawn attention to the need for more accurate data. This uncertainty can be seen in the revisions that have accompanied methane emission estimates. For example, EPA revised its estimate of the natural gas system methane emissions downward in 2013 to about 1.5 percent from a previous estimate of over 2 percent.[10] Alvarez *et al* (2011) conclude that, because of the short-term warming effects from leaked methane, converting a fleet of gasoline cars to run on natural gas will have greater greenhouse gas emissions than conventional fuels for years before net emission reductions occur.[11] However, Alvarez concludes that a fleet of natural gas vehicles can offer immediate WTW emission reductions as compared to a fleet of conventional gasoline vehicles if methane leakage is below 1.6 percent of natural gas production.[12] This is about the same methane leakage rate used in current EPA estimates, and is well within the range of other studies.[13] Still, accurate methane leakage rates for the entire natural gas value chain are unknown. EPA and others are trying to better understand methane leakage to determine whether there is a net benefit from natural gas combustion compared to gasoline and diesel. The question is how the methane emissions increases compare to the carbon dioxide emission reductions. They are also taking steps to reduce leakage where possible.

refueling facilities, but insufficient demand and the need for an expensive network of transport pipelines mean that distributed hydrogen production at refueling stations is more likely in the short term.[9]

Through 2035, MIT considers hydrogen production through steam methane reforming of natural gas without carbon capture and sequestration as the most likely technology adopted.

CONCLUSIONS, RESEARCH GAPS, AND FUTURE WORK

The results summarized in this brief show that GHG emissions from light-duty vehicles can be reduced in multiple ways. Additional research into transportation fuel pathways is necessary in order to identify cost-effective strategies for reducing petroleum dependence, mitigating global climate change, and enhancing energy security. Technological progress in conventional vehicles provides a short- and medium-term opportunity to reduce emissions. C2ES research concludes, however, that advanced vehicles including, for example, fuel cell and battery electric vehicles fueled from low-carbon feedstocks are needed to reduce GHG emissions to a level that will mitigate the most harmful effects of global climate change.[14]

Because PHEVs operate on both liquid fuel and rechargeable batteries, their fuel's lifecycle emissions are determined by the carbon intensity of both the electrical grid used to recharge the batteries and the onboard fuel. This introduces two sources of variation, in addition to the efficiency of the different vehicle drivetrains, and explains the wide range over which PHEV emissions estimates vary. For PHEVs to be most effective in reducing GHG emissions, they must operate on both clean electricity and a low-carbon liquid fuel. One direction for future research may be a sensitivity analysis of the determinants of PHEVs' GHG performance: at what carbon intensity of the electrical grid and under what use patterns do PHEVs operating on gasoline or biofuels achieve lower emissions than hybrids on the same fuel? At what fuel carbon intensity and under what use patterns does a PHEV recharging from a high-carbon grid attain lower emissions than a PHEV recharging from a low-carbon grid?

These results also support further research into low-carbon fuels, which can benefit all on-road vehicles. Ethanol-fueled vehicles in these studies consistently emit less than vehicles of the same type fueled on gasoline. Wide-scale use of low-carbon biofuels, including drop-in fuels that have similar properties to conventional gasoline, would require overcoming the technological and policy barriers to fuel production at commercial scale. Future biofuel research could focus on direct and indirect land use change, taking into account the sensitivity of different lifecycle emission estimates to the sources of cellulose and agricultural waste, land use patterns, economic and market analysis including infrastructure costs, resource constraints, and accounting methodologies.

It is clear that lowering the carbon intensity of the electrical grid will determine the degree to which PHEVs and battery electric vehicles will reduce GHG emissions from transportation. Research here could shed light on the conditions under which PHEVs and battery electric vehicles contribute most to meeting GHG emission reduction goals based on variables such as electricity dispatch, generation sources for the regional electrical grid, vehicle type including battery-only range, travel patterns, and driver behavior.

As this brief makes clear, the WTW emissions from each vehicle and fuel combination can vary widely depending on assumptions about fuel and vehicle characteristics. Transparency of those assumptions is needed to assess the viability of different fuel pathways since the WTW emissions can vary by geography, vehicle technology, fuel feedstock, and even time of day. Market feasibility of low-carbon fuel pathways is also a vital consideration.

Recent breakthroughs in natural gas production provide further evidence that technological progress is constant and that policymakers ought to incorporate adaptive measures to compensate for changes in technology, information availability, resource constraints, market acceptance, and other factors that could affect lifecycle emissions from transportation fuels. Policy must target all viable options, including advancing low-carbon fuels, efficiency and fuel economy, and low-carbon electricity generation. Progress in these areas will help reduce emissions not only from light-duty vehicles but also from the electric power sector, aviation, and heavy-duty trucks.

The review of existing studies laid out in this brief identifies some critical gaps. There is a clear need for analysis of a fuller range of fuel and vehicle pathways and a consistent set of scenarios with transparent assumptions to compare, including drop-in biofuels, low-carbon hydrogen, unconventional oils, a low-carbon grid, and natural gas using the latest available information.

TABLE 1: Summary of Key Studies and Vehicles Selected

STUDY NAME	ABBREVIATION	YEAR PUBLISHED	TIMEFRAME	SELECTED VEHICLES/ FUELS
Argonne National Laboratory: Well-to-Wheels Analysis of Energy Use and Greenhouse Gas Emissions of Plug-in Hybrid Electric Vehicles	Argonne	2010	2010, 2020	CV (Gasoline) HEV (Gasoline) PHEV 10, 20, 30, 40 (Gasoline, E85) BEV FCV
California Air Resources Board	CARB	2009	Various (year when WTW assessment was completed)	CV (California Reformulated Gasoline, E85, CNG) HEV (California Reformulated Gasoline, E85) PHEV (California Reformulated Gasoline, E85)

				BEV FCV
EPRI/NRDC: Environmental Assessment of Plug-in Hybrid Electric Vehicles	EPRI/NRDC	2007	2010, 2050	CV (Gasoline) HEV (Gasoline) PHEV 10, 20, 40 (Gasoline)
Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation	GREET	2012	2010, 2020	CV (Gasoline, E85, CNG) HEV (Gasoline, E85) PHEV (Gasoline, E85) BEV FCV
Life Cycle Assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles	Samaras and Meisterling	2008	Unspecified	CV (Gasoline, E85) HEV (Gasoline, E85) PHEV 30, 60, 90 (Gasoline, E85)
MIT: On the Road in 2035	MIT	2008	2008, 2035	CV (Gasoline) HEV (Gasoline) PHEV 30 (Gasoline) BEV FCV
Transitions to Alternative Vehicles and Fuels	NRC	2013	2010, 2035	CV (Gasoline, E85, CNG) HEV (Gasoline, E85) PHEV-30 (Gasoline) BEV FCV
C2ES Modeling using default settings in GREET	C2ES	2013	2010, 2020	CV (Gasoline, E85, CNG) HEV (Gasoline, E85) PHEV (Gasoline, E85) BEV FCV

***Vehicles**: CV = conventional vehicle; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle where the number refers to miles powered by rechargeable batteries; BEV = battery electric vehicle; FCV = hydrogen fuel cell vehicle. **Fuels**: E85 = Blended fuel with 85% ethanol and 15% gasoline; CNG = compressed natural gas.*

ENDNOTES

[1] EPA. (2013, April 12). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2011. Retrieved June 6, 2013, from U.S. Environmental Protection Agency: http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2013-Main-Text.pdf

[2] Ibid.

[3] The California Air Resources Board (CARB) conducted its own evaluation of fuel pathways to implement the state's low-carbon fuel standard using a customized version of GREET from 2010. (A low-carbon fuel standard is a performance standard that sets a GHG intensity reduction target for all transportation fuels. Details of California's LCFS program are at http://www.arb.ca.gov/fuels/lcfs/lcfs.htm.) Electric vehicle emissions were about 50 percent lower than those estimated using the 2010 GREET default settings because the state's grid has a lower carbon intensity than the U.S. average. In addition, emissions from corn ethanol-powered vehicles were over 20 percent higher than those estimated using the 2010 GREET default value because of fuel transport distances. The fuel pathways for other fuels in the CARB evaluation are largely similar to the results using 2010 GREET default settings.

[4] The findings in Argonne's Well-to-Wheels Analysis regarding PHEV vehicle efficiency, fuel economy, and electricity usage have also been built into GREET models 1.8c and subsequent versions.

[5] For the GREET model scenarios, C2ES used the years 2010 and 2020 to identify typical (using all default settings) for each fuel-vehicle combination in the figure.

[6] CO_2e is the emissions of a gas, by weight, multiplied by its "global warming potential."

[7] GREET does not take into account indirect land-use change. It only accounts for direct land-use change (decrease in use of farmland due to the byproduct of animal feed from the ethanol production process).

[8] This would represent decreasing electricity carbon intensity from 670g CO_2e per kilowatt-hour to 200g CO_2e per kilowatt-hour, and might be accomplished by supplying generation with a significant share of renewables, nuclear, or coal with carbon-capture and sequestration.

[9] Bandivadekar, A. et al. (2008). On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions. Cambridge: Massachusetts Institute of Technology, Laboratory for Energy and the Environment Report No. LFEE 2008-05 RP.

[10] C2ES. 2013. Leveraging Natural Gas to Reduce Greenhouse Gas Emissions. Arlington, Virginia: Center for Climate and Energy Solutions.

[11] Alvarez, Ramon et a. (April 2012). "Greater focus needed on methane leakage from natural gas infrastructure." *Proceedings of the National Academy of Sciences of the United States of America* 109(17). Retrieved July 8, 2011, from http://www.pnas.org/content/109/17/6435.full

[12] Ibid.

[13] Howarth et al (2012) reviewed the studies on methane leakage and found that they ranged from 63 percent below to 150 percent above the EPA estimate for conventional gas production, and 77 percent below to 100 percent above the EPA's shale gas production. Howarth, R. R. Santoro, A. Ingraffea. (2012). "Venting and leaking of methane from shale gas development: response to Cathles et al." *Climate Change* 113(2), p537-549. doi:10.1007/s10584-012-0401-0.

[14] Greene, David, and Steven Plotkin. 2011. Reducing Greenhouse Gas Emissions from U.S. Transportation. Arlington, Virginia: Center for Climate and Energy Solutions.