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Chapter 14:

Potential Reductions of Greenhouse Gas Emissions from Light-Duty Vehicles and Electricity Generation

by Andrew E. Lutz and Jay O. Keller

The objective of this chapter is to consider the potential for reductions in greenhouse gas (GHG) emissions in light of projected growth by mid-century. The analysis focuses on two major energy sectors, light-duty vehicles (LDVs) and electricity generation. These two sectors combine to produce more than half of the total GHG emissions in the United States (U.S.). They are also the sectors of the U.S. energy economy with the fastest growing GHG emissions. While the transportation sector relies almost exclusively on petroleum, new vehicle technologies that move toward eliminating this dependence will involve some degree of coupling to the electricity sector.

The chapter examines the potential for reducing GHG emissions by technological improvements, under the assumption that end-use activity continues to grow at the present rate. A simple linear projection to 2050 suggests that yearly GHG emissions in the U.S. will increase to 60 percent above 1990 emissions without a concerted effort to reduce them. Relatively incremental policy improvements, such as increasing the U.S. Corporate Average Fuel Economy (CAFE) standard to 35 miles per gallon (mpg), are a good start for reducing emissions, but much greater efficiency improvements are needed to have a significant impact. The analysis presented in this chapter shows that after a transition to an LDV fleet at 35 mpg and replacement of coal-fired electricity generation with more efficient natural gas generation, GHG emissions will return to 1990 levels.

The magnitude of the GHG emissions problem requires that research and development be directed toward technologies that both greatly improve end use efficiency and greatly reduce or eliminate carbon from fuels. Policies that incentivize only incremental improvements to efficiency and fuel carbon content will be insufficient to meet GHG reduction targets of 80 percent below 1990 levels. Energy policy needs to be established today to motivate the transition to net-zero carbon technologies.

Background

Calls for more efficient transportation and alternatives to petroleum as a transportation fuel accelerated after the oil crisis of the 1970s. The combination of a peak in domestic U.S. oil production and politically

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motivated restrictions in oil production by the Organization of Petroleum Exporting Countries (OPEC) created sharply rising prices. The initial attempt at controlling prices created the gasoline lines that became the visual image of the decade.

The second problem with transportation was the smog in certain metropolitan regions. The 1970s saw the introduction of catalytic converters on gasoline vehicles to reduce emissions of pollutants, such as carbon monoxide and nitrogen oxides, which are detrimental to local air quality. This required a significant change to the refueling infrastructure. Previously, lead was added to gasoline to prevent engines from knocking at high compression ratios, but lead proved to be a poison to the catalyst. For a period of years, refueling stations provided separate pumps for leaded and unleaded gasoline. The unleaded pump had a smaller nozzle diameter to prevent drivers from accidentally filling the new vehicles with leaded gasoline.

The two problems of the 1970s—limited oil supply and regional smog—motivated regulations that led to the design of cleaner, more efficient vehicles. More stringent regulations and gradually rising oil prices motivated research that resulted in new technologies, such as the hybrid electric drivetrain and advanced diesel technology. The California Zero Emission Vehicle mandate of 1990 attempted to require the introduction of battery electric vehicles, but was ineffective at eliciting a large number of such vehicles because of the limited range and high cost of the initial vehicles. During this brief introduction, there was an attempt to develop a recharging infrastructure. In addition to home recharging, some public parking lots installed recharging facilities. Auto manufacturers also introduced natural gas vehicles, but the refueling infrastructure did not develop beyond a scattered network of sites at government facilities, utilities, and corporate fleets. Research considered hydrogen as a fuel for either internal combustion engines or fuel cells. Problems with pre-ignition—at least for stoichiometric mixtures—limited the use of hydrogen in engines at first, but contemporary engines avoid this problem with either dilution or direct injection. Fuel cells were limited to aerospace applications until the mid-1990s, when breakthroughs in material science made possible the polymer electrolyte membrane (PEM) fuel cells that are now being proven in vehicle demonstrations.

The Greenhouse Gas Problem

Today, concerns about climate change have created a third problem, one that is uniquely global. Carbon dioxide (CO_2) emitted from fossil fuel combustion remains in the atmosphere for decades. Reduction of GHG emissions from the transportation sector requires reducing CO_2 emissions from the fleet of LDVs, either by societal changes to reduce miles traveled or technological changes to the vehicles. Leaving the issue of societal change to social scientists, this chapter considers the potential of technological improvements, under the assumption that end-use activity continues to grow.

CO_2 emissions from LDVs can be reduced technologically by lowering the carbon content of the fuel, increasing the fuel economy of the vehicles, or some combination of the two. Increasing fuel economy is the logical first step, since it does not require changes to the fueling infrastructure. However, vehicle efficiency improvements alone cannot meet GHG reduction targets.

Considering the carbon content of the fuel, biofuels offer the potential of reduced net CO_2 emissions over the entire fuel cycle. Biofuels provide energy storage densities similar to gasoline and diesel. As liquid fuels, their use requires relatively minor changes to the refueling infrastructure, and when produced with attributes similar to gasoline and diesel, they require no change at all to the distribution infrastructure. While corn ethanol may offer only marginal CO_2 reductions, cellulosic ethanol and biodiesel may provide significant reductions. However, even optimistic estimates of biofuel production do not suggest that all of America's current and future transportation needs can be met (Perlack et al 2005; West et al 2010).

Other low-carbon fuel alternatives are electricity, hydrogen, and natural gas. Natural gas contains about 25 percent less carbon per unit of chemical energy than gasoline. While electricity and hydrogen carry no carbon, they are energy carriers that must be produced from other sources, so their life-cycle carbon content depends on the source.

The best solutions may come from combinations of alternative fuels and advanced vehicle technologies. For example, the use of some alternative fuels enables vehicle technologies that allow for better efficiency in converting stored energy to motion. Electric propulsion, supplied either by batteries or fuel cells, offers improved efficiency, in addition to the potential of a fuel that can be produced from noncarbon sources. However, providing refueling facilities for either battery or hydrogen vehicles will require far more extensive investment in the infrastructure than the transition to a separate liquid fuel, such as ethanol or unleaded gasoline.

Vehicle electrification will have impacts on the markets for electricity and natural gas. About 20 percent of the electricity in the U.S. is generated from natural gas. Larger fractions are contributed by natural gas in some regions, and recent installations of new generating capacity are dominated by natural gas. If hydrogen vehicles are adopted anytime soon, the hydrogen will most likely be produced by reforming natural gas. So these three low-carbon fuel options couple the LDV fleet to the electricity market.

Renewable pathways, such as wind and solar, produce electricity with very low carbon intensities. Hydrogen from these sources requires the extra step of electrolyzing water at the expense of system efficiency, but add little to the carbon intensity of the process. Nuclear power is also a source of noncarbon electricity. A new generation of nuclear power plants may in the future produce hydrogen by a thermochemical cycle that splits water, thereby skipping the electricity as an intermediate to hydrogen and improving efficiency. Existing nuclear plants do not operate at sufficiently high temperatures to produce hydrogen, however, so electrolysis is necessary.

Other potentially large sources of noncarbon hydrogen involve fossil fuels coupled to carbon capture and sequestration (CCS) technologies. Steam methane reforming at large, centralized plants could facilitate carbon sequestration. Coal can be used to produce both hydrogen and electricity from oxygen-blown integrated gasification-combined cycle (IGCC) plants. The air separation up front yields an exhaust mixture without nitrogen, eliminating the need for separation prior to sequestration. Such plants may be demonstrated in the near future, providing combined production of electricity and hydrogen with near-zero carbon emissions. In all these cases, near-zero carbon and noncarbon pathways to hydrogen involve electricity, either as an intermediate step or a co-product.

Recognition of the coupling of hydrogen, electricity, and natural gas suggests the approach in this chapter of considering the potential GHG emissions reductions from the transportation and electricity sectors together. The transportation and electricity sectors will likely interact in a variety of ways in the future (Yang 2008). The two sectors are two of the "wedges" of the growth triangle that Pacala and Socolow (2004) suggested could be part of a carbon-stabilization strategy. These two sectors are natural targets for new CO_2 emission regulations. They are already regulated for many local pollutants, including carbon monoxide and nitrogen oxides. The LDV sector is also already regulated with respect to fuel economy, via the CAFE standards, which affect the CO_2 emissions per mile driven.

The following analysis starts by establishing a baseline for the total future GHG emissions, based on the data for U.S. emissions over the past couple decades. The next two sections estimate the potential reductions of CO_2 emissions from LDVs and electricity separately, but casting the reductions in reference to the total emissions. The combined reductions are then estimated by superposition of the individual contributions. This approach ignores the possible interactions between the sectors, because the intent is to examine limiting cases.

The scope of the analysis is limited to the United States. While the United States did not ratify the Kyoto treaty, which intended to limit emissions to 5 percent below 1990 levels, the U.S. government is working on legislation for a cap-and-trade system to regulate future GHG emissions. In addition, individual states are acting to reduce emissions. California, for example, has enacted a low carbon fuel standard (LCFS) for vehicles and an aggressive renewable portfolio standard for electricity generation. Beyond these regulatory actions, California's Governor A. Schwarzenegger has issued an executive order calling for GHG reductions to 80 percent below 1990 levels by 2050, and President Obama endorsed this target in his campaign. Research is studying the so-called "80 in 50" target for both California (Yang et al 2009) and the nation as a whole (McCollum and Yang 2009).

Baseline Emissions Projection

The analysis starts with the most recent data for the contributions of the various sectors to the national emissions of GHG (EPA 2009). Table 14-1 shows the breakdown of U.S. GHG emissions by sector. The LDV and electricity sectors combined account for one-half of the total GHG emissions. Most of the growth in the past two decades has occurred in these two sectors. Emissions from the LDV and electricity sectors grew at average rates of 1.2 and 1.6 percent per year, respectively. In contrast, the other sectors grew at an average of only 0.4 percent per year. These observations suggest that technological improvements in the LDV and electricity sectors would go far towards combating future growth in GHG emissions.

Table 14.1: U.S. GHG emissions in metric gigatonnes of CO_{2eq} per year

Year	*Electric Generation*	*LDV*	*Other*	*Total*
1990	1.86	0.95	3.29	6.1
2000	2.33	1.11	3.55	7.01
2005	2.43	1.16	3.52	7.11
2007	2.45	1.15	3.55	7.15

Source: EPA 2009

To project a baseline into the future, the emissions data are linearly extrapolated, as shown by the solid line in Figure 14-1. The data appear to follow a linear fit between 1990 and 2007. Extrapolation to 2050 suggests the GHG emissions will reach nearly 10 gigatonnes of CO_2 equivalents per year, which is 60 percent larger than the emissions in 1990. In order to apply a business-as-usual policy, the analysis defines three sectors—LDV, electricity, and other—and assumes that the sectors grow linearly. This simplification allows the analysis to project the impact of various strategies for reducing emissions onto the overall picture for GHG emissions to mid-century.

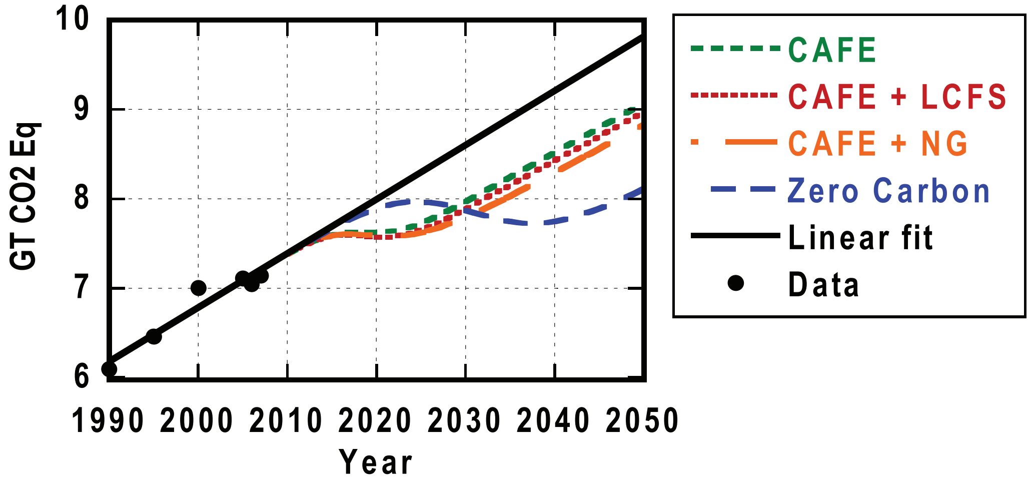
The following sections present estimations of the reduced CO_2 emissions from the LDV and electricity sectors, considering one at a time, and then combining the effects of both sectors.

Reduction Potential of the LDV Fleet

The LDV fleet currently accounts for 16 percent of total U.S. GHG emissions, and its high growth rate means that its contribution is increasing. At present trends, projected LDV emissions are expected to grow to 18 percent of total emissions by 2050.

Except for the recession year of 2009, sales of new vehicles have averaged about 15 million per year (EPA 2007), or about seven percent of the roughly 230 million LDVs in the U.S. fleet (Polk 2009). The average age of vehicles has been growing, due to the fact that the scrap rate is only about 5 percent (Polk 2009). For these sales and scrap rates, a simple uniform replacement of the existing LDV fleet would take about 17 years. The analysis in this chapter captures this replacement period by simulating the transition of the average fuel economy of the vehicles on the road from the existing vehicles to a more efficient fleet. Rather than use dynamic simulation methods to track the vehicle fleet as it evolves with the introduction of new

Figure 14-1: Scenarios of U.S. GHG emissions from LDV fleet



vehicles (Lutz and Reichmuth 2009; Struben and Sterman 2008), we use a simple s-shaped function of time, which can be adjusted by centering the transition at a given year and setting the width of the transition. The s-shaped function varies from zero to one and serves as an adjustment factor in the decomposition of the CO_2 emissions. The convenience of an analytical function means the details of the transition are not captured and the duration of the transition period is not an outcome of the analysis, but an input to be specified. Nevertheless, for the purposes of the study, specification of the transition period provides a picture of the emissions reductions in light of the projected growth.

The first scenario is the proposed new CAFE standard of 35.5 mpg, applied for the combined fleet of cars and trucks, which is to take full effect by 2016 (White House Press Release 2009) and assumed to be held constant to 2050. The projected emissions are scaled from the existing fleet average of 20 mpg (EPA 2007) to the proposed more stringent CAFE value. Actual mpg in 2016 will be lower because the regulations are based on tested fuel economy, not real world fuel economy.

To approximate the new CAFE legislation taking effect in 2016, the transition function is centered at 2020, with a transition from the old, 20 mpg vehicles to the new, 35.5 mpg vehicles that is completed over a period of 16 years. Centering the transition at 2020—not 2016 when the regulation takes effect—puts the halfway mark for the vehicles on the road four years after the regulation. This means that at 2020, half the vehicles on the road are new vehicles that meet the 35.5 mpg CAFE regulation on average, while the remaining vehicles still have an average fuel economy of 20 mpg. The value of the transition function at 2016 is 0.16, meaning that 16 percent of the on-road fleet has been replaced by the newer vehicles. This effectively assumes that manufacturers will be selling a significant number of the more efficient vehicles a couple years early. In fact, the CAFE regulation will require improved mileage in years prior to 2016, but this analysis does not attempt to capture the details of the time schedule in the regulation.

Compared to the black extrapolation line in Figure 14-1, the CAFE proposal, shown in the short dashed line (green), creates a shift to lower emissions. However, after the initial shift downward, the emissions grow in parallel with the extrapolated growth after 2030. The reduction by 2050 is eight percent below the projected GHG emissions.

A modification of this CAFE scenario combines improved mileage with changes to the fuel. Coincident with the new CAFE regulation, California will implement its LCFS that reduces the carbon emissions from the fuel 10 percent by 2020 (Farrell and Sperling 2007). The combined reductions of the CAFE regulation and the extension of the LCFS to the entire U.S., a 10 percent reduction in fuel carbon, is depicted in the dotted line (red) in Figure 14-1.

As another scenario, the long-dashed line in orange in Figure 14-1 shows the influence of switching from gasoline to natural gas, in addition to the vehicles meeting the new CAFE standard. The transition for this scenario is centered at 2025, with a width of approximately 20 years, so it is assumed to occur a bit later than the CAFE scenario and take a little longer to accomplish. These adjustments account for the extra time required to develop the natural gas refueling infrastructure.

Using natural gas instead of gasoline reduces the CO_2 emissions by 25 percent simply because of the lower carbon content per unit of chemical energy. This assumes the vehicle burning natural gas will have the same fuel economy in energy space, which is justified by the comparison of vehicle mileage in Table 14-2. The Honda Civic model is chosen for comparison because it is available as a conventional gasoline vehicle, a hybrid electric vehicle, or a natural gas vehicle. The mileage ratings show that the natural gas vehicle and the conventional gasoline vehicle achieve the same fuel economy rating, measured in energy-equivalent gallons (EPA 2008).

Table 14.2: Vehicle fuel economy comparison

Vehicle	*Composite Mileage*	*CO_2 Emissions*	*Relative CO_2 Emissions*
Civic	28 mpg	0.31 kg / mile	1
Civic-NG	28 mpg-equiv	0.23	0.75
Civic Hybrid	42 mpg	0.21	0.67
Clarity FCX	60 mile / kg H2	0.16	0.5

Note: Comparisons are for for gasoline, natural gas (NG), hybrid and fuel cell vehicles of the same make and approximate size. The CO_2 emissions for the Clarity FCX assume hydrogen is produced from reforming NG without carbon sequestration.

Source: EPA 2008

To put the vehicle fuel consumption rates in perspective, one might ask, what is the best fuel economy that can be expected by future vehicle improvements? The work required to push the vehicle as a glider through standard city and highway drive cycles can be computed to set an expectation for the upper limit on fuel economy. The integration of the velocity time history for the drive cycles depends on the mass, drag coefficient, frontal area, and rolling resistance for the vehicle (Heywood 1988). Using values representative of a Honda Civic and assuming that all of the energy from the gasoline can be converted into motion without any loss, this translates into a maximum test-cycle composite fuel economy of 163 mpg.

Comparing the vehicle mileage ratings to this theoretical maximum mileage suggests that the overall efficiency of converting chemical energy to motion is about 17 percent for the conventional model. The hybrid model achieves 26 percent efficiency measured in this way; however, the hybrid recovers some of the kinetic energy of the vehicle during braking, so the comparison may be artificial. The glider simulation does not include the potential effects of regenerative braking. Since the acceleration term accounts for about 45 percent of the work in the city cycle simulation and 19 percent of the highway cycle work, this limits the amount of energy that could potentially be recovered during braking. The rolling and air resistances will remain and cannot be avoided by drivetrain improvements.

The Honda Clarity has approximately similar glider characteristics to the Civic, but an additional 300 kg, reducing the expected maximum fuel economy to about 131 mpg, so the fuel-to-motion efficiency of the fuel cell vehicle is about 46 percent. While the advancements from conventional to hybrid electric or fuel cell vehicles represent significant improvements, it is likely that the technological evolution is reaching a steeper part of the learning curve.

Glider simulations for a range of vehicle size and mass were performed to suggest a maximum fuel economy for the light-duty fleet. As a representation of the sport utility vehicle segment, repeating the vehicle drive cycle simulations for a Toyota Highlander yields a maximum of 115 mpg. Averaging this with the compact sedan value of 163 mpg, the overall light-duty fleet might be expected to be limited by a value of about 140 mpg, assuming that the vehicle fleet remains apportioned approximately 50/50 between cars/trucks in the future. Some studies (Yang et al. 2009) propose scenarios that assume vehicle mileage as high as 88 to 125 mpg in gasoline equivalents.

While the question of maximum vehicle efficiency provides an interesting perspective on the CAFE requirements, speculations regarding how well the vehicles can eventually do could lead to a number of transition scenarios. However, the ultimate limit on the transition is the case of zero-carbon emissions, which would require that a zero-carbon source of stored energy be supplied to the vehicles.

The last GHG scenario for light-duty vehicles included in Figure 14-1, the medium-dashed blue line, considers a transition to zero-carbon vehicles, ignoring for the moment the question of how this might be accomplished. This transition is centered at 2030, following the suggestion of Greene et al (2008), with a width of nearly 30 years. The maximum reduction achieved by a zero-carbon fleet is about 18 percent lower than the projected growth line by 2050.

The two transitions to more efficient vehicles and zero-emission vehicles would not likely occur independently. More likely is a blended scenario that follows one of the more efficient vehicle curves until it intersects the zero-carbon vehicle curve. This combination would result in a larger decrease in the emissions integrated over the four decades. Nevertheless, the long-term emissions rate per year would be limited by the zero-carbon scenario.

Potential Technologies for Zero-Carbon Vehicles

Potential technologies for vehicles that produce essentially no carbon emissions include biofuels, plug-in hybrid electric vehicles, and hydrogen vehicles. It is important to bear in mind that these vehicle technologies are only zero-carbon if the fuel is produced without emitting carbon dioxide. Electric vehicles that run on grid electricity are not zero-carbon unless all the grid electricity is derived from renewable or nuclear generation. Similarly, the carbon emissions of hydrogen vehicles depend on how the hydrogen is produced.

The most common method of producing hydrogen today is by the steam-methane reforming of natural gas. Comparing the energy content of hydrogen to that of gasoline indicates that one kilogram of hydrogen is roughly equivalent to one gallon of gasoline. For methane-derived hydrogen, a similar rule-of-thumb exists with reference to the carbon emissions. Although natural gas emits 25 percent less CO_2 than gasoline for the same chemical energy, this benefit of the switch between hydrocarbons is offset by the loss in useful energy that is inherent in the reforming process. The most efficient reforming process converts only 70 percent of the chemical energy in the natural gas to hydrogen (Simpson and Lutz 2007). In fact, 70 percent efficiency is the DOE Hydrogen Program goal (DOE 2005). These factors balance, meaning the rule-of-thumb that one kilogram of hydrogen is roughly equivalent to one gallon of gasoline is true both in energy-space and in carbon-space, when the hydrogen is produced by reforming.

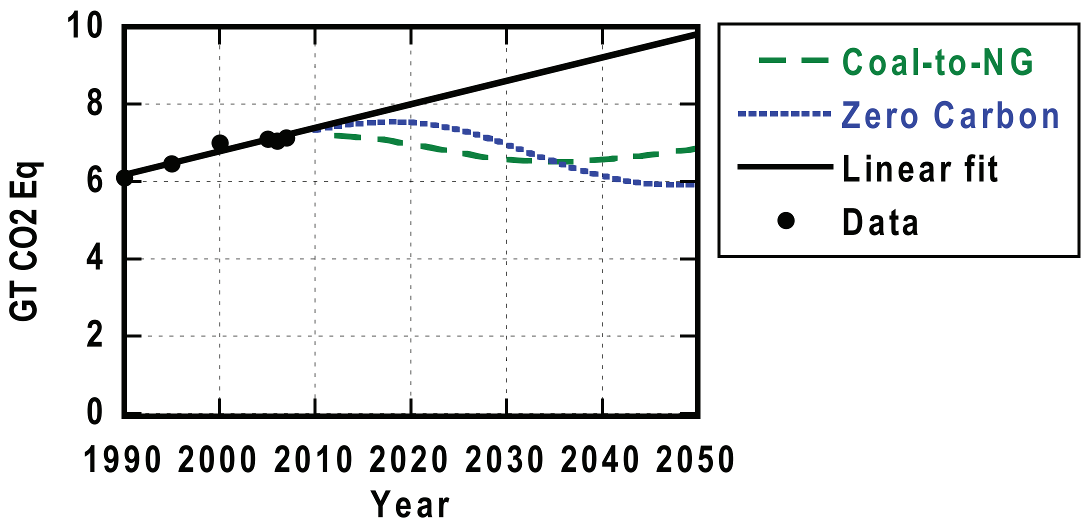
So how do analyses (Lutz and Reichmuth 2009; Greene et al. 2008; Hinkle 2009; Thomas 2008, 2009) obtain reduced carbon emissions with hydrogen vehicles? Most often, the hydrogen vehicle is assumed to be significantly more efficient than the conventional vehicle used for comparison. Comparing the natural gas Civic to the gasoline model using the data shown in Table 14-2 yields a 25 percent reduction in CO_2 emissions. The last row in Table 14-2 compares the CO_2 emissions for the Honda fuel cell vehicle, the Clarity FCX, which is rated at 60 miles per kilogram of hydrogen. Assuming the hydrogen is produced by reforming at 70 percent thermal efficiency, the CO_2 emissions per mile are about half those of the gasoline Civic. This is accomplished by efficiency improvements of the vehicle, not by lower carbon associated with the fuel. The carbon emissions associated with a kilogram of hydrogen are the same as those from a gallon of gasoline.

The approach to zero emissions for a vehicle requires that no carbon be associated with the hydrogen fuel. The present study does not specify the technology to meet the goal of zero-carbon vehicles. This limit in the scope avoids dealing with trade-offs regarding where to apply zero-carbon energy technologies. For example, assertions that renewable or nuclear electricity will be used for producing hydrogen must logically compete with the potential use of the zero-carbon electricity for electric vehicles. Similarly, the carbon emissions associated with electric vehicles depend on assumptions about the future of the electric grid. While some studies are beginning to analyze these interactions for hydrogen vehicles and plug-in hybrid electric vehicles (Yang 2008; Hadley and Tsvetkova 2008; Samaras and Meisterling 2008; Stephen and Sullivan 2008; McCarthy and Yang 2009; Lutz and Reichmuth 2009), this study proceeds to examine the potential reductions in the electricity generation sector on its own.

Reduction Potential of the Electricity Sector

The analysis in this section assumes the LDV and all other sectors grow as projected, but considers reductions in the emissions from the electricity sector alone. The electricity sector currently accounts for roughly one-third of the total U.S. GHG emissions, and coal-fired generation currently emits 80 percent of the GHG emissions from the sector. Since power plants last longer than vehicles, the transition period should be longer, so the analysis uses a width of 40 years. This section presents two scenarios for the electricity sector: replacing coal with natural gas and zero-carbon electricity to replace all fossil fuel generation.

Figure 14-2: GHG emissions projected for the U.S. with reductions due to the electricity sector



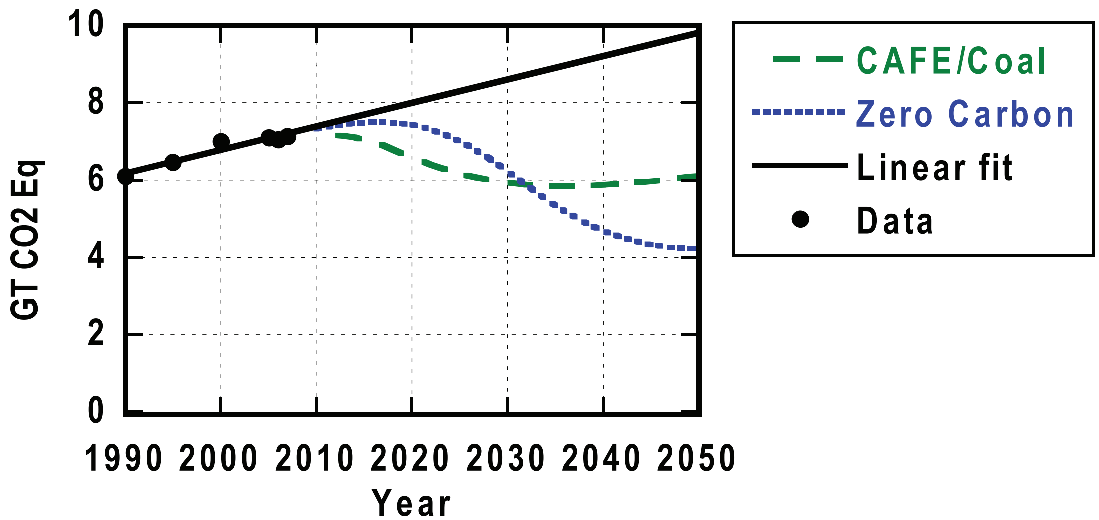
The first scenario uses a "carbon intensity" of 1.4 metric tons of CO_2 per megawatt hour (MWh) to represent typical coal-fired generation. This value is roughly equivalent to pulverized coal generation at 30 percent thermal efficiency. The dashed line (green) in Figure 14-2 shows the transition to natural gas, combined-cycle electricity generation at a thermal efficiency of 60 percent, which has a carbon intensity of 0.3 metric tons of CO_2 per MWh. When the transition is completed, this change reduces the CO_2 emissions from the electricity sector by 74%. Since the transition is centered relatively late (2020) and occurs relatively slowly, it is not entirely completed by 2050. Nevertheless, at this point, the dashed green line in Figure 14-2 shows that replacing coal-fired generation with higher efficiency natural gas generation can reduce overall emissions by 30 percent by 2050.

As a limiting scenario, the dotted blue curve in Figure 14-2 shows the effect of zero-carbon electricity generation, using the same transition width as in the coal replacement scenario, but centered at 2030. Replacing all fossil-fuel generation with zero-carbon electricity leads to an emissions reduction of 40 percent of the total GHG emissions projected at 2050 in the linear fit model.

Combined Potential of the Two Sectors

Figure 14-3 shows combinations of the potential contributions of the LDV fleet and the electricity sector. The dashed green curve represents the combined reduction of efficiency improvements, assuming an LDV fleet at 35.5 mpg and replacement of coal-fired electricity generation with electricity from natural gas at 60 percent thermal efficiency. This combination of efficiency improvements results in total GHG emissions roughly equal to the 1990 rate.

Figure 14-3: GHG emissions projected for the U.S. with combined reductions from the LDV fleet and the electricity sector



For comparison, the limiting combination of carbon-free technologies for both LDV and electricity generation leads to total GHG emissions about 30 percent below the 1990 level. This means that, at current growth rates, reducing total GHG emissions below 1990 levels by changes to the LDV and electricity sectors alone will require the drastic achievement of developing technologies that emit near-zero carbon.

Conclusions

The conclusion of this study is that the potential to reduce CO_2 emissions from both LDVs and electricity generation is limited. Proposed changes to the CAFE regulation and replacing coal-fired power with natural gas will only overcome the estimated growth by the middle of the century. Together, these two sectors currently comprise half of the total U.S. GHG emissions nationwide and represent most of the growth. While any extrapolation 40 years into the future is highly uncertain, a linear extrapolation suggests that growth will offset the potential reductions that are possible from improved efficiency in these sectors. Further reductions below 1990 emissions will require the ultimate of carbon-free technologies in these two important sectors.

Secondly, the approach to defining possible transition periods used in this study suggests that 2050 is not far away. The period for turning over the road fleet of LDVs is about two decades. Unless the relatively long-lived power plants are to be retired before their designed end-of-life, it will be difficult to complete a transition to a new technology by 2050.

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