GREENHOUSE GAS EMISSION CONTROL OPTIONS: ASSESSING TRANSPORTATION AND ELECTRICITY GENERATION TECHNOLOGIES AND POLICIES TO STABILIZE CLIMATE CHANGE

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ABSTRACT

Prioritizing the numerous technology and policy options is an important step in formulating a cohesive strategy to abate U.S. greenhouse gas (GHG) emissions. This work compares various options across two key sectors of the U.S. economy, electricity generation and transportation, by quantifying the absolute abatement potential of and identifying potential barriers to each. Analyses indicate that diminishing coal's use and associated GHG releases is the primary route to reducing electricity generation impacts. The current grid mix with carbon capture and sequestration in all coal plants could yield a 22-percent savings in U.S. GHG emissions, while shifting to a mix that is 50-percent renewables would yield a 9-percent reduction. In the transportation sector, improving the efficiency of passenger vehicles is imperative, with this sector's long-term potential greatly enhanced by fleet electrification. In the short term, deploying all efficiency-improving technologies available for conventional vehicles could cut U.S. GHG emissions by 10 percent while bringing the average fuel economy of new vehicles above the Corporate Average Fuel Economy's year-2020 target (which is just 35 mpg). In the longer term, plug-in hybrids running on greener electricity and cellulosic ethanol are predicted to provide a 25 percent reduction in current U.S. emissions. Travel mode shifts, while an immediately viable option, are not estimated to provide savings near the levels of emerging electricity generation and vehicular technologies.

INTRODUCTION AND SCOPE

Climate change presents a challenge of unparalleled magnitude and urgency. Advances in scientific knowledge of linkages between anthropogenic greenhouse gas (GHG) emissions and global warming now enable the severity of climate change to be seen through the lens of economic fallout from irrevocable changes in the Earth's physical geography. A 5 to 6°C rise in global average temperature – anticipated by the end of the century, based on the current rate of emissions – is forecast to inflict a 20% loss in global GDP [1], an economic shrinkage matched by the

Great Depression. Attention at all levels of policy making should turn to stabilizing climate change. Accounting for degradation in the Earth's absorptive capacity, current estimates find that 450 ppm atmospheric CO_2e is needed to avoid dangerous consequences; and, after accounting for projected global economic growth, this target will require the U.S. to cut year-2000 emissions by 80% by the year 2050 [2].

Reductions of this scale will require strategies that address the economy's many sectors. Numerous technologies and logistics strategies exist or are near technical maturity; however, none can achieve needed reductions in isolation, and all face obstacles to mass acceptance. Certainly carbon pricing, either through taxation or cap-and-trade schemes, will help to overcome a glaring market externality in which economic actors do not perceive the true costs of their GHG-producing actions. The urgency of climate change in the face of multiple barriers (including up-front costs, imperfect information, risk, market distortions, and organizational and attitudinal inertia) requires thoughtful policy to accelerate market adjustments. To that end, the objective of this work is to quantify the potential of a wide range of technologies and behaviors to reduce U.S. GHG emissions and examine the barriers these will face. While cost is an important consideration, steep GHG targets have been set. Costs are notoriously difficult to estimate in light of new technologies, and most shifts are likely to yield cost savings. Thus, our focus lies in absolute reduction potential and non-cost barriers. To facilitate comparison, reductions (in million metric tons of carbon equivalents [MMTCE]) from the adoption of options to 1% of the total potential market are used here. These estimates can then be scaled to reflect various levels of adoption.

Figure 1 illustrates the various sources of GHG emissions in the U.S. economy. This paper strategically emphasizes emissions from electricity generation and transportation for four reasons: First, over 60 percent of U.S. GHG emissions happen when fossil fuels are combusted at power plants or on vehicles [3]. While electricity generation emissions can be reduced through greater efficiency downstream, especially in the residential and commercial sectors, emissions from these sectors remain largely constrained by the fundamental carbon intensity of fossil fuel-fired power plants. Second, the transportation and electric power sectors are comprised of supply-side entities that are relatively consolidated, have a history of being regulated (in terms of product efficiency and emissions), and whose emissions emerge from relatively homogeneous processes. Third, emissions from these sectors are rapidly growing, a scenario quite different from the industrial sector where emissions are declining as the economy transforms. Finally, as this work will reveal, electricity generation and transportation deserve to be considered side-by-side, due to opportunities for synergistic interaction between the two which could yield even greater reductions in GHG emissions.

ELECTRICITY GENERATION

Electricity generation is responsible for 33% of U.S. GHG emissions [3]. These arise predominantly due to CO_2 emissions when fossil fuel feedstocks are converted to electric power. Theoretically, there are several paths to reducing such CO_2 emissions. As described below, grid dispatch can be managed to minimize utilization of carbon intensive power plants. Retrofitting existing fossil fuel power plants and introducing new fossil fuel technologies can improve conversion efficiency or enable the capture and sequestration of CO_2 emissions. And future capacity additions can be shifted toward less-carbon intensive sources (including renewables). The array of options must be considered in light of several factors, including current consumption patterns and grid composition, expected increase in demand for electricity, and available supplies of fossil fuels. In 2006, Americans consumed 3.8 million GWh of electricity[1], producing 2.7 billion tons of CO_2 [3]. Table 1 summarizes the U.S. grid's composition in 2006.

Annual U.S. demand for electricity is projected to increase 29 percent by 2030, to 4.7 million GWh, driven primarily by increased growth in residential and commercial consumption. The EIA [3] estimates that capacity additions of 263 GW will be needed to meet the added demand. Moreover, coal power is projected to represent a greater share of the grid by 2030 (roughly 54 percent [3]) than it does today, thanks to its relatively low cost. Natural gas's share is expected to fall to just 14 percent, due to rising price volatility. Nuclear's share is not

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[1] Electricity consumed is lower than electric produced due to 7.5 percent transmission and distribution losses, which are assumed throughout this work [63].

expected to grow significantly, due to its uncompetitively high fixed costs.[2] Renewables are projected to reach 13 percent of total electricity supply by 2030, primarily due to growth in wind and geothermal power [3].

Management of Grid Dispatch

Grid capacity and demand for electricity are variable quantities. Grid capacity at a given time is determined by the combination of power available from base-load, intermediate, and variable sources. Base-load sources generate a constant output and cannot be quickly activated and deactivated; these include nuclear, hydroelectric, and some coal plants. Intermediate and variable sources either are easily activated and deactivated or have intermittent generating capacity; these include solar, wind, oil, natural gas, and some coal plants. Demand for electricity peaks both diurnally and seasonally. These peaks can be acute: a daytime peak can be as much as twice of a nighttime trough, while in warm climates a summer peak can be nearly twice a spring peak [4]. Minimum base-load capacity is largely controlled by daily peaks, and nighttime demand typically lies well below base-load capacity, leaving utility companies with much excess generating capacity.

Improved management of grid dispatch could be achieved by shifting existing demand to existing excess capacity, using "smart" dispatch systems, and developing energy storage technologies. Dynamic pricing of electricity could be used to incentivize shifting demand for electricity to times when there is unused capacity reducing overall base-load capacity needed and capturing peaks of some intermittent renewables (notably wind [4]). A "smart" network could use real-time data and automated controllers to level power dispatch to where needs are highest and mitigate concerns about relying upon intermittent renewables for baseload generation. Storage technologies could make renewables with unstable capacities more reasonable investments, by enabling these to be used as base-load sources (collected when capacity is high and dispatched as needed). Energy storage could be implemented either at a decentralized level (batteries used by individuals or companies owning plug-in hybrid electric vehicles, for example) or as bulk storage used by utility companies.

Improving Fossil Fuel Efficiency

Given the nation's continuing reliance on fossil fuel plants for power provision, power-plant efficiency must be addressed. Coal is in a position to remain a part of the U.S. energy equation for generations to come. Absent taxes, subsidies for and technological advances in other generation types, coal will remain, on average, the cheapest and most reliable type of electricity, thanks to its low fixed costs and well distributed reserves (which minimize variable and transmission costs). Estimates of natural gas supplies had been trending down, from a 2001 projection of 35 trillion cubic feet (TCf) supplied in 2020, to a 2008 projection of less than 23 TCF by 2030 [5]. While the success of shale gas has driven recent natural gas production increases, concerns about supply shortages and price volatility as well as use as a transportation fuel will likely diminish its role in the U.S. grid mix. Thus, coal considerations seem key to reducing carbon emissions from power generation. Routes to reduce coal-based CO_2 emissions include improving combustion efficiency and carbon capture and storage (CCS).

The U.S. electric grid contains a substantial number of older, pulverized-fuel (PF) coal-fired power plants[3].The efficiency of PF coal plants can be improved by employing higher temperature and pressure steam conditions to more thoroughly combust fuel inputs. This shift can improve efficiency from 30-35% to 46-48% net efficiency; boiler and turbine technology currently in development could increase this efficiency to 50-55% [6]. Super-critical boilers can be employed as retrofits and are cost-effective as new investments, as compared to sub-critical boilers, due to fuel cost savings [6]. *Integrated Gasification Combined Cycle* (IGCC) technology has been suggested as the next generation of power plant technology which could be widely used for coal. IGCC power plants convert carbon in solid fuel feedstocks into a synthetic gas which is then combusted. The gasification reaction and intermediate conversion steps can be used to yield H_2 and separate out CO_2 (to facilitate CCS) and other impurities. IGCC plants can achieve efficiencies around 40%, and these may reach 50 to 60% by 2020 [7]. Several IGCC plants exist around the world (including three in the U.S.), but cost of electricity from an IGCC is 11-27% higher than from a PF plant, representing a significant near-term barrier [8].

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[2] The outlook for both natural gas and nuclear is unclear. Natural gas production has rebounded from years of decline behind the emergence of shale gas, but price volatility and the extent of domestic reserves remain concerns. Nuclear faces persistent concerns of safety, national security, and lack of a waste disposal plan, but enjoys growing advocacy due to its carbon neutrality and could become cost-effective under scenarios of carbon pricing. (A$100 per ton of GHG price may be needed for competition with natural gas and coal [64].)

[3] 68 percent of coal capacity is from plants that went online in 1978 or earlier and thus employ older, lower efficiency technology [65].

In the longer term, *carbon capture and storage* (CCS) is perhaps the most promising method for reducing carbon emissions from power generation. CCS is the process of separating and compressing CO_2 from industrial or energy sources for long-term storage or use as an input in other industrial processes. CCS is widely used in some industries but application in energy generation will require new methods suited to combustion reactions. A report by the Intergovernmental Panel on Climate Change [9] found that CCS has the potential to reduce CO_2 emissions per kWh by 80 to 90%. While CCS is possible for all types of power plants, some will require more power than others to operate (notably IGCC will require the least power due to more concentrated CO_2 in combustion gases[4]).

Increased demand for power to operate CCS systems and transport and store CO_2, along with higher upfront plant construction costs, will make CCS significantly costlier. The IPCC (2005) estimates that the incremental cost of CCS could be \$0.02-0.05 per kWh for a PF plant and \$0.01-0.03 per kWh for an IGCC plant. The most likely scenario in which CCS will become cost effective thus involves carbon pricing. IPCC (2005) estimates abatement costs using geological storage to be \$30-70 per ton CO_2 for a PF plant and \$20-70 per ton CO_2 for an IGCC plant. A recent MIT study [10] concludes that CO_2 prices greater than \$30 per ton are needed to make CCS cost effective. CCS systems could also include retrofits of existing power plants. Geisbrecht (2008) estimates that retrofitting a typical PF power plant could increase the cost of energy \$0.02-0.07 per kWh and \$0.01-0.03 per kWh at 90% and 30% removal efficiencies, respectively (though abatement cost declines with increasing removal efficiency). Widespread application of CCS will necessitate mature methods of sequestering CO_2. Modes of storage proposed include geological storage, oceanic storage, and storage in mineral carbonates, but more research is needed in this area [9]. Geological storage seems to have garnered the most attention. While geological storage has been successfully demonstrated in select cases (naturally occurring formations, as well as enhanced oil recovery), no large-scale cases have been proven and blowouts pose a major risk (to safety and the GHG reduction success).

Potential for Renewables

Renewable energy sources cause no direct GHG emissions and do not give rise to concerns of safety, national security, byproduct waste management or long-term supply shortages. The U.S. energy resource base is vast (50,000 times current annual energy usage) and the overwhelming majority is renewable: fossil fuels represent only 6.5%, while wind, photoconversion, and geothermal resources represent 27%, 27%, and 39%, respectively [12]. Further, many renewables can be installed at a decentralized level by individuals and businesses, thereby eliminating transmission and distribution losses and simplifying grid administration while yielding energy cost savings.

Hydroelectric power is currently the largest source of renewable electricity in the U.S. While there is estimated to be a potential 30,000 MW of additional capacity[5], this source is not expected to grow much in the future due to complex environmental issues and regulations [3].

Wind power is rapidly expanding in the U.S. In 2007, wind power experienced a boom year as capacity grew by 46% and represented 35% of new capacity additions [13]. Wind power prices are currently \$0.04 per kWh on average, competitive with overall wholesale power prices, though wind power is more economical in regions with higher quality wind resources (in the West and Great Plains) and tax credits and subsidies have caused wind to be more cost-effective overall in many places [13]. Wind power faces significant barriers in terms of transmission infrastructure to connect disparate resources and load centers and low capacity factors (due to variable wind speeds, which diminish transmission investment cost-effectiveness). Improved grid management and battery-based storage could moderate this hurdle. Scale could also make intermittence less of an issue, as more “noise” could mean a more predictable level of generation. One forecast projects wind to be producing 20% of America’s on-grid electricity by 2030, nearly 30 times its current production [14]. Notably, wind power is also a potential power source at a distributed level, and in 2007 the 4.7 MW of off-grid capacity additions nearly matched the 5.7 MW of on-grid additions [13].

Geothermal power plants harness subterranean heat reserves stored in rock and water strata to generate electricity while yielding near negligible GHG emissions (0.6 lbs CO_2e per kWh. The U.S. enjoys a vast geothermal resource, capable of supporting U.S. consumption for 10,000 years [15]. With current technology it is only

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[4] PF power plants with CCS systems would require 24-40% more power, while IGCC power plants would require only 14-25% more power [9].

[5] Total U.S. capacity presently is 1 million MW. [3]

economical to access hydrothermal systems (characterized by high porosity and water contents) at shallow depths (3 km or less), but these represent only 0.1% of U.S. geothermal resources. Accessing further reserves is technically possible, but further development in the areas of drilling, stimulation techniques, exploration, and conversion efficiency is needed for cost-effectiveness. MIT forecasts that a 100,000 MW geothermal capacity is possible within 50 years with modest technology investments [15]. Geothermal resources offer the advantage of being a potential baseload source, but those suitable for electricity generation are largely concentrated in the West and away from major population centers. Unlike wind power, though, geothermal power has a high capacity factor, so investment in transmission infrastructure is more cost-effective.

Like wind, U.S. solar power experienced great recent expansion. U.S. solar resources are substantial enough that less than 2% of the land devoted to agricultural grazing could meet U.S. energy needs [16]. The most prominent solar power technologies are Photovoltaic (PV) and Concentrating Solar Power (CSP). PV systems use semiconductor materials to directly generate electricity from sunlight, are deployable anywhere, and are considered a possible distributed source that could “backfeed” excess power to the grid. According to EERE (2008), PV generated power must fall 50-70% in price to achieve grid parity. This is expected to happen between 2010 and 2015, but could happen even sooner in regions with good solar resources and/or high electricity prices [17]. The U.S. Department of Energy estimates that rooftop PV systems with a 30-year useful life have an energy payback period of just one to four years, depending on subsidies granted and energy prices. Solar resources are intermittent, but the overlap between peak demand and solar availability gives solar a relatively high capacity factor. The most prominent barrier to high penetration of PVs is the difficulty in using a distributed source to generate grid electricity; the U.S. grid was not designed to communicate with small downstream sources, so inverters and grid management systems to enable this must be developed and deployed. CSP systems capture solar heat to power generators and require direct sunlight but can generate significant volumes of power and are a potential centralized source. Renewed interest resulted in 65 MW of capacity going online in 2007, with another 3,600 MW planned [18]. CSPs can be located near existing transmission lines due to the flexibility of solar resources; nevertheless, the need for direct sunlight primarily limits CSP to the Southwest.

Biomass power can be generated from a variety of biomass feedstocks including lumber and mill waste (wood residue), municipal solid waste (MSW), landfill gas, and agricultural waste. Biomass feedstocks sequester carbon prior to being used as a feedstock, thereby offsetting emissions from their combustion. Currently, many industries generate their own electricity from biomass, accounting for 58 percent of the 54 million MW generated in the U.S.; electric utilities contribute the balance, primarily through co-firing with coal to help meet emission regulations [19]. Perlack et al. [20] estimate that the U.S. forestry and agricultural industries are capable of supplying 1.3 billion tons of biomass annually. Using Mann and Spath’s (1997) energy efficiency expectations and assuming an energy content of 15 GJ per ton biomass[6], a 1.3 billion ton supply could yield 2 million GWh of electricity, or about half of 2006’s generation. The use of some agricultural wastes could have the added benefit of reducing emissions from the release of high GWP gases. Nevertheless, expansions of biomass power will likely face competition for biomass inputs from the biofuels and bioproducts sectors. Encouragingly, research to integrate these production processes in a single refinery is ongoing.

Table 1 shows potential GHG reductions from shifts in power generating feedstocks and technologies, both from older generation coal-fired plants and an average grid mix. The grid shows reductions in CO_2 however these are nearly identical to reductions in GHG (grid average is 1.34 lb CO_2e/kWh, for instance). The most significant reductions come from moving away from older generation coal. Notably, IGCC coal plants are competitive with natural gas in the GHG reductions offered, but offer less than half of the savings of a plant equipped with CCS. Shifting the entirety of the U.S. grid to a 50 percent nuclear/renewable mix could reduce U.S. GHG emissions by 10 percent, while introducing CCS in all coal plants could abate 22 percent of U.S. GHG emissions. Assuming current energy demands, this shift would hit the nation’s likely year-2020 targeted reduction of 20 percent; but it remains far the year 2050 target of 80 percent [2, 1], particularly in the face of rising population and economic activity. Transport is another key opportunity, as discussed below.

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[6] The 15 GJ value is a weighted average of mid-point heat contents for wood and agricultural residues.

TRANSPORTATION

The transportation sector accounts for 28% of U.S. GHG emissions and is responsible for 46% of the nation's energy-related GHG emissions growth since 1990, due to increasing vehicle-miles traveled (VMT) and stagnant vehicle fuel economy [3]. A variety of modes contribute to U.S. transportation emissions, including light-duty vehicles, heavy-duty trucks, air, shipping, and rail, which contribute 62%, 19%, 9%, 3%, and 2%, respectively [22]. Transportation GHG reduction paths include lower carbon intensity vehicle fuels, improved fuel economy, and travel demand management to reduce travel and shift travel to more efficient modes.

Vehicle Fuels

Vehicle fuels are responsible for GHG emissions through the energy consumed to recover, process, and transport them (well-to-pump [WTP] emissions) as well as through combustion of the fuels themselves (pump-to-wheel [PTW] emissions). PTW emissions depend on the efficiency of the vehicle itself; for a given fuel, these are largely fixed by the stoichiometry of the fuel combustion reaction (on a per unit energy basis). WTP emissions, in contrast, can vary significantly, depending on efficiencies of the various fuel-pathways. PTW emissions are typically the majority of WTW emissions, though Wang [23] notes that declining tailpipe emissions will make WTP more significant on a per-mile basis. Thus, accurate assessment of vehicle and fuel technologies should consider well-to-wheel (WTW) emissions, as done here.

The high energy content of *fossil fuels* makes them ubiquitous vehicle fuels in spite of their high carbon content. Gasoline and diesel account for 72% and 24%, respectively, of domestic surface transportation motor fuel consumption. Petroleum-based diesel fuel enjoys higher energy content than gasoline and is refined and combusted at a higher efficiency, resulting in a slightly lower GHG emission rate than gasoline per unit of energy. However, diesel fuels have posed air quality problems. The EPA recently implemented new emission standards for lower sulfur fuels and stricter NO_x and PM standards on diesel vehicles, to be fully phased in by 2010, and emission control systems to comply with these are currently in development. While petroleum fuels made from crude oils are relatively uniform in their GHG emission rates, oil shales, oil sands, and heavy crudes could significantly increase emissions from oil and diesel [24]. Thus, as global demand for petroleum increases and high-grade crudes become harder to obtain, gasoline and diesel could become even less desirable from a GHG emissions standpoint.

Excessive reliance upon petroleum based fuels was estimated to cost the U.S. $150 to $250 billion in 2005 (or 1% of GDP), when oil was $40 per barrel. This was due to wealth transfer, economic retardation from oil scarcity, and macroeconomic readjustments [25]. It does not include underwriting of military operations or environmental impacts. Notably, the U.S. demand for petroleum is actually being driven increasingly not by motor gasoline (which only accounts for about half of the products refined from crude oil), but by diesel (which accounts for about a quarter) and other petroleum products. Between now and 2015, demand for diesel is projected to grow about 4 times faster than demand for gasoline; by 2030, the demand for diesel is forecast to grow 14 times as fast [3]. Addressing issues of GHG emissions and economic costs from petroleum based fuels require considering the whole range of products coming from each barrel of crude oil. Diesel fuels can also be made from other feedstocks, including coal, natural gas, and low-value refinery products via Fischer-Tropsch Synthesis; but the more complicated refining processes to produce these result in slightly higher emission rates [26]. *Natural gas* can be used in various forms for motorized transport, with GHG reductions on the order of 20 to 30% per BTU [27] And CNG and LNG combined already meet 15.6% of U.S. bus fuel demands [28]. Natural gas has received much attention as a potential light-duty vehicle fuel because prices are, on average, lower than recent years' petroleum prices, and distribution may be achievable via existing pipe networks to homes (and businesses). Nevertheless, domestic supply uncertainties could make natural gas-based fuels problematic in the long run.

A wide range of *renewable biofuels* made from plant matter, including sugars, starches, and cellulose, also have been proposed as petroleum alternatives. *Fuel ethanols* are a biofuel substitute, and U.S. corn-based ethanol has expanded significantly, from 1,741 million gallons consumed in 2001 to 6,846 million gallons in 2007 [29] over 5 percent of gasoline sales. The WTW GHG emissions of ethanol fuels depend significantly on feedstock type, nitrogen fertilizer production, global warming potential (GWP), farming processes used, energy use in the biofuel plant, and possible co-production of other goods [30]. Corn-based ethanol currently averages a GHG content about 20% lower than gasoline, but this can fall to 55% lower than gasoline if the production plant is fueled by biomass or, alternatively, end up exceeding gasoline carbon intensity if coal-fired power is used in production [31]. Encouragingly, key emissions factors are nitrogen fertilizer demands and plant efficiency, which are improving, leading to a 50% reduction in ethanol plant energy use over the past 20 years [30]. Cellulosic ethanol made from feedstocks including switchgrass, corn stover, crop residues, and farmed trees has been proposed as a less carbon intensive fuel that solves many issues related to corn-based ethanol. Some newer proposed cellulosic feedstocks (in particular fast growing trees) could actually result in a net GHG reduction via the amount of carbon sequestered to soil by the plants [24].

Biodiesels can be made from oils, recycled oils and animal fats yielding a fuel that can substitute for petroleum based diesels. Biodiesel is currently consumed at a rate of 260 million gallons annually, having grown dramatically from 18 million gallons in 2003 [29]. Average U.S. biodiesel carbon intensity is 68% lower than petroleum diesel [31], and can vary greatly depending on co-products [32]. The potential replacement capacity of biodiesel is estimated to a small fraction of U.S. diesel consumption, and fuel quality is often an issue.

Table 2 illustrates properties and potential reductions from shifting 1% of gasoline and diesel consumption to alternative fuels (both neat fuels and blends, on an energy basis). These shifts would be possible with no improvement in engine or driveline efficiency. Shifting all U.S. gasoline consumption to a cellulosic E85 blend could reduce GHG emissions by 5%. Concerns about biofuels persist, however. The dedication of land to farming could impact GHG emissions in the larger scale via land use changes (including induced changes domestically and abroad, due to the profitability of ethanol) and threaten water supplies in regions where heavy irrigation is needed [30]. These issues are generally a larger concern for corn-based ethanol than for cellulosic ethanol. Biodiesels could push cities into non-compliance with air quality regulations due to higher NO_x emissions. Perhaps the largest barrier will be equipping the vehicle fleet and fuel distribution system to handle biofuels. The different fluid properties of biofuels will, in many instances, require new distribution piping and currently only 290,000 vehicles in the light-duty U.S. fleet (0.01%) are capable of running on biofuels, with refilling stations are largely concentrated in the Midwest [19].

Electricity and hydrogen are also potential substitutes for liquid fuels in future generations of vehicles. Unlike biofuels (which tend to be less carbon-intensive than motor gasoline on an energy-basis), electricity and hydrogen are actually more carbon-intensive than gasoline on an energy-basis. However, both fuels emit zero PTW emissions and can be used at a far greater efficiency than motor gasoline is burned, thus yielding significant gains on a WTW basis. For both hydrogen and electricity reductions in WTP emissions are a central challenge: electricity in the U.S., as noted above, largely comes from fossil-fuel intensive production methods while hydrogen currently requires energy inputs far in excess of its usable energy. Non-liquid fuels also require a distribution network and a vehicle fleet that can store the fuel. Electric vehicles appear to lead here: battery technology is progressing rapidly and electric vehicles can largely be charged from the existing electric grid (as discussed below). The problem of safe on-board storage of hydrogen that is central to hydrogen vehicles still lacks a solution.

Light-Duty-Vehicle Efficiency

On a per-mile basis, PTW emissions vary greatly with engine efficiency, transmission efficiency, vehicle design, vehicle operating conditions, and emission treatment systems. The wide suite of options to improve passenger vehicle efficiency includes conventional improvements, many of which are currently cost-effective and are expected to be widely present in vehicles within a 15-year span, as well as advanced powertrain technologies. The latter are more costly and will likely be slower to penetrate the vehicle market (absent policy intervention), but they offer greater potential for long-term fuel economy improvements.

Vehicles powered by spark-ignition (SI) engines and running on gasoline constitute the great majority of the U.S. passenger vehicle fleet. These operate in an efficiency range of only 10-20%: most of the energy in the tank is expended in thermal, frictional, and standby losses in the engine and driveline, while only a fraction of the fuel's energy powers useful accessories and makes it to the wheels [33]. SI engine vehicles are candidates for *conventional improvements*, which increase fuel economy by reducing vehicle loads and improving engine and transmission efficiency. Table 3 presents Jones et al.'s [34] estimates of GHG savings from conventional improvements. These technologies generally already exist in several makes and models currently on the market and others are poised to enter the market, if proper demand for fuel economy exists. One crucial design aspect that has been resisted by vehicle manufacturers on the grounds that it could compromise occupant safety, vehicle mass reductions, is now regarded by many experts [e.g. 35] as an option for improving fuel economy, both because it can potentially be achieved without compromising vehicle size (a more important design parameter from a safety standpoint) and because more massive vehicles actually reduce overall fleet safety by posing threats to other vehicles. Cumulatively, the technologies in Table 3 could offer a new vehicle fuel economy of 31 mpg to 42 mpg, a

17 to 57 percent improvement over an average new U.S. vehicle. The technologies are, however, applicable to different degrees in different vehicles, so midpoints of the potential improvement ranges are used in Table 3.

Compression ignition (CI) engine vehicles running on diesel enjoy a great foothold in the European passenger vehicle market and will likely be a U.S. option, pending improved emission control system technology. *Diesels* combust fuel more thoroughly for an overall fuel economy improvement of 20 to 40 percent [34]. The associated GHG savings are less; however, since diesel fuel is more carbon intensive. Diesel engines could be combined with conventional improvements to transmissions and vehicle design, but the fundamentally different engine type precludes conventional engine technologies. Table 3 shows GHG reductions from a conversion to diesels (without and with conventional transmission and vehicle design improvements). Diesel engines with the relevant conventional improvements do not offer significant savings over an SI engine vehicle including all conventional improvements; both could reduce U.S. GHG emissions by 5 percent compared to baseline 2007 vehicle technology if adopted in all passenger vehicles.

Hybrid electric vehicles (HEVs) have penetrated the U.S. market in recent years. In 2007, about 3% of new vehicle sales were hybrid models, up from 0.5 % in 2004. Hybrids supplement SI engines with electric motors and battery packs. Fuel economy improvements are due to engine downsizing and more efficient engine operating points enabled by the second onboard power source, fuel cutoff during deceleration and idling, and regenerative braking. The U.S. EPA [36] reported fuel economies of four of the most popular hybrid vehicles: the Toyota Prius, Honda Civic Hybrid, Nissan Altima Hybrid, and Ford Escape Hybrid are 46, 42, 34, and 32 mpg. However, these vehicles employ many conventional modifications, so fuel economy improvements are not exclusively attributable to hybridization. Table 3 shows potential GHG emission savings from conversions of the passenger fleet to a hybrid (without and with all conventional transmission and vehicle design improvements). While some hybrids readily pay for themselves in lifetime fuel savings, consumers often demand a shorter payback period of three to five years, which hybrids cannot always deliver. Emerging Li-ion batteries which scale to high production volumes, rely on cheaper commodity inputs, and can offer more power for less metal material (compared to current NiMH batteries) should lower this barrier by decreasing the cost of one of the priciest components [37]. *Plug-in electric vehicles (PEVs)* offer the majority of US VMT from liquid fuels to electricity. Both Nissan and GM have released such vehicles in the U.S. market: the 73-mile all-electric (EPA-rated) battery electric vehicle (BEV) Leaf and the 35-mile all-electric (with extended range) Chevrolet Volt plug-in hybrid EV (PHEV). Toyota will release its PHEV Prius model very soon. In general, a PHEV runs on an initial grid charge for a specified range at which point it switches to, essentially, normal hybrid operation. The GHG emission reduction potential of PHEVs depends on a variety of factors. The type of electricity generation used where the vehicle is charged influences WTW vehicle emissions. Vehicle range determines the fraction of a driver’s VMT that will be electrified. Analysis of daily mileage distributions suggests that vehicles with ranges of 20 and 40 miles could capture 50 and 75 percent of an average drivers’ daily driving [38], assuming the vehicles are charged nightly. Table 3 shows potential GHG emissions reductions from a PHEV 40 and PHEV 60 running off of various electricity scenarios. Notably, the impact of adding additional range to the vehicles is relatively small compared to electricity generation feedstock. At grid average electricity, PHEV 40s and 60s could eliminate 13 and 14 percent of U.S. GHG emissions if employed in the entire passenger vehicle fleet. If charged with coal, HEVs outperform PHEVs, while in the scenario of expanded renewables and CCS the reductions climb to 16 and 18 percent for a full PHEV fleet. In the short term, carbon intensity of electricity will depend on the type of electricity generation used in the local utility company’s intermediate capacity range which varies greatly by region; in the long-term as PHEVs penetrate the market the GHG reductions from the energy pathway will tend towards the average grid mix [37].

Electrifying the vehicle fleet would be a fundamental shift in the nation’s energy use patterns and as such presents numerous policy angles to be explored. Benefits could accrue from centralizing combustive processes from numerous disparate tailpipes to a small number of power plants. This centralization facilitates carbon capture and sequestration (CCS) along with improvements in regional air quality and public health, as emissions shift away from population centers [39]. Accommodating substantial growth in electricity demand could present a barrier, though if grid dispatch is properly managed favorable interaction with the utility industry could be obtained. Pratt et al. (2007) estimate that up to 43 percent of the LDV fleet could be charged overnight with available generation and 73 percent using available daytime and overnight generation (Table 1 illustrates the types of power generation technologies with available capacity). In the long-term overnight charging could represent an overnight base-load that could increase demand for base-load generators and make investments in cleaner base-load generators more cost-effective. In some scenarios, increased demand for currently underutilized overnight generating capacity could even drive down electricity prices [39]. Synergy between overnight peak wind power capacity and expected overnight PHEV charging also has been suggested as a possibility [40]. Dynamic electricity pricing has been suggested as a policy mechanism to induce owners to charge their vehicles overnight.

The biggest hurdle for PHEV technology will be cost. As a benchmark, currently, there are several after-market kits that enable conversion of a Toyota Prius into a limited-range PHEV; these retail for $10,000 to $12,000 [41]. Currently, the biggest factor in PHEVs high cost is the battery price, but as battery technology improves cost should drop. In the longer term (2030 horizon), Kromer and Heywood [37] project incremental costs of $3000 to $6000 for vehicles of 10 to 60 miles of range, a high enough incremental price that most consumers will not perceive PHEVs as cost effective within a reasonable payback period. BEVs face much less of a cost hurdle, thanks to the simpler, all-electric drivetrain design (though range limitations impede user flexibility). Tuttle and Kockelman’s [42] discounted cost comparisons of the Leaf, Volt, and Prius PHEV suggest that these new vehicles are pretty cost competitive, especially for longer driving distances and higher gasoline prices. Uncertainties about production levels are limiting adoption. In the future, uncertainty about battery replacement costs (and range limitations for BEVs, but not PHEVs) may limit adoption. Paul et al.’s [43] simulated adoption and use of PEVs across the U.S. suggest sales may remain low, without significant shifts in U.S. energy prices, buyer preferences, and/or government policies.

Expanded options in terms of vehicle ranges could increase the market for PEVs by better matching vehicle range to individual daily commuting patterns, thereby increasing the vehicle’s cost effectiveness. Vyas et al. [44] examine national daily commuting patterns and conclude that if vehicles of 10 mi, 20 mi, 40 mi, and 60 mi ranges were available, 59% of national VMT could be electrified using the assumption that a person will only buy a PHEV if its range exceeds their daily average driving (so they enjoy the full benefits of its electric abilities). Khan et al. [45]studied the day-to-day driving pattern of GPS-instrumented vehicles in Seattle and found that many (to most) households could swap out a vehicle for a BEV or PHEV, depending on the all-electric range attribute,

Efficient vehicular operation can also reduce fuel consumption immediately, regardless of vehicle type. Vigilant tire pressure maintenance can improve fuel economy and is an opportunity for 36-40 percent of drivers [46]. Consumers can select low rolling resistance tires when they replace tires (every 3 to 5 years, on average), a choice that could impact 80 percent of tires currently on the road and is estimated to pay for itself in fuel savings within the life of the tire [33]. Peak vehicle efficiency is found at speeds between 30 and 55 mph [47] when vehicle engine efficiency and aerodynamic loads are close to their respective maximum and minimum. Table 4 estimates GHG savings from tire improvement scenarios and lowered interstate speed limits. While proposals to lower interstate speed limits have met with considerable disapproval, it should be noted that fuel economy declines at an increasing rate as speed grows; thus savings equal or greater than those shown here could be achieved simply from enforcing speed limits to their posted levels.

Given the numerous technically feasible options to improve fuel efficiency and the demonstrated inability of the market to favor fuel efficiency over other vehicle, fuel economy standards are considered an important part of ensuring a fuel efficient vehicle fleet. *Corporate Average Fuel Economy (CAFE) standards* require that manufacturers’ fleet averaged fuel economies meet a mandated level determined on the basis of technological feasibility, economic practicability, effect of other standards on fuel economy, and the need of the nation to conserve energy. After years of stagnation [48] CAFE standards were raised in 2007 to 27 mpg for passenger car fleets and 22.5 mpg for light duty truck fleets, set to rise to an overall fleet average of 35 mpg by 2020. This standard trails much of the developed world and proposed standards of U.S. states [49]. It also lies below estimates of technically feasible fuel economy: midpoint and maximum estimates of fuel economy in conventional vehicles using the ranges suggested by Jones et al. (2008) are 36.6 mpg and 41.9 mpg. Finally, the new 2020 CAFE target is well below a level of fuel economy that economically rational consumers would find cost effective with gas prices at $3.55 per gallon (43.4 mpg) assuming they discount fuel savings at 3 percent annually . While the timeline on these estimates of technical feasibility is 15 years (to mature by 2023), and while consumers may expect greater return on their investment in fuel economy given that vehicles are depreciable assets, there is reason to manufacturers can achieve more stringent fuel economy standards.

An often raised concern about advanced vehicle technologies is their efficacy from a *full lifecycle perspective*. Moon et al. [50] study the vehicle-cycle and total energy-cycle of special, low-weight (“lightweighted”) vehicles and HEVs compared to conventional vehicles. The advanced vehicles have more CO_2 intensive materials manufacture phase because of the increased use of aluminum (to reduce weights) and more advanced batteries (HEVs).

However, over the total vehicle lifecycle the reductions in GHG emissions from more fuel efficient use phases far outweigh the more energy intensive materials production.

In recent decades the purchase of a new vehicle has not been justified from an energy or CO_2 savings standpoint because the improvement in fuel efficiency in successive model years has been so slow . The appearance of advanced drivetrain vehicles which offer substantially improved fuel economies means accelerated vehicle replacement can reduce GHG emissions. Vehicle ownership durations are, however, increasing as vehicle designs improve. Median vehicle age has increased to 9.0 years for passenger cars and 9.6 years for light trucks (from 7.9 years and 7.7 years in 1996) while scrappage rates have fallen to 4.5% and 4.1% annually for passenger cars and light trucks (from 6.4% and 7.4% in 2000). From a policy standpoint, accelerated vehicle replacement could be encouraged through measures that make consumers value fuel economy more (e.g., higher gas taxes) subsidies and/or tax credits for purchasing more fuel-efficient vehicles, and preference for fuel efficient vehicle lanes (in HOV lanes, for instance).

Passenger Travel Demand Management (TDM)

TDM strategies with potential to abate transportation GHG emissions include shifting travel to more efficient modes, reducing overall passenger travel, and shifting travel to more efficient operating conditions (e.g. non-peak hours). These strategies typically use existing assets thus avoiding the cost or time-lag of new technologies, but institutional and attitudinal factors often work against TDM.

Pricing strategies send market signals which reflect the true costs of driving. *Gas Taxes* in the U.S. contribute, on average, only 40 cents per gallon to the price of gasoline [3]. Gas taxes in the majority of other industrialized countries are significantly higher (e.g. 2.5, 2.6, 1.8, 1.8, and 2.7 times higher in France, Germany, Japan, Norway, and the UK [IEA 2008]). Economists find that gas taxes diminish demand for gasoline either via reduced driving or improved fuel efficiency. A recent estimate places the own-price elasticity of demand for gasoline at -3.4 to -7.7 percent [51]. Table 4 shows the reduction in GHGs expected from various levels of gas taxation increases, using this elasticity. One caveat is that the reductions could be as much as 2-3% smaller and 10-15% smaller in the short and long term via a rebound effect from increases in fuel efficiency [52]. *Pricing Parking* can be an effective travel demand reduction because it overcomes the temporal lapse between costs drivers pay and when they decided to travel. Studies on elasticity of travel demand with respect to parking price find a 10 to 30 percent span, with variation due to numerous factors including trip purpose, location of parking, availability of substitute modes or other free parking, and price and fee structure (e.g. hourly, first hour free, etc.). Other pricing strategies such as congestion pricing, tolls, and HOT lanes can similarly diminish demand for driving and thus reduce GHG emissions, but are not quantified here.

Mode Shifts from private vehicle travel typically reduce GHG emissions by using energy more intensively thus emitting lower GHG per passenger-mile (pax-mi). Streamlining travel into fewer vehicles and transit also enables easier adoption of alternative fuels and technologies to improve vehicle efficiency. The baseline for mode shifts here is private vehicle travel, which accounts for the majority of passenger travel [53]. Tables 5 and 6 show the potential GHG savings from shifting passenger travel from single and average occupancy vehicles with the alternative mode at average and full occupancy.

For daily travel (i.e. intracity trips of less than 50 miles) two passengers make automobiles the most efficient mode. Average automobile occupancy is only 1.63 passengers, and occupancy is even lower for certain crucial trip types (e.g. 1.14 passengers for home to work trips). Clearly opportunities for *carpooling* abound. At average occupancies, rail outperforms driving while buses and driving are competitive (on a Btu/pax-mi basis). Rail savings are often dependent upon the carbon intensity of the electricity they run on and could fall with improvement in electricity generation. Buses, if running at low occupancies, actually result in a GHG emission increase; an occupancy slightly higher than average is needed to make buses less CO_2 intensive than driving, though running buses on alternative fuels can change this. Moreover, to the extent that bus use encourages walking and shorter trips (in order to access bus stops and reduce bus travel times) and more clustered land use patterns (to reduce access costs and trip distances), a one-to-one passenger-mile comparison is imperfect. Of course, much underutilized capacity exists on alternative modes, so a more accurate illustration of the GHG savings from shifting away from single occupant vehicles (SOVs) may simply be the reduction from eliminating one percent of SOV VMT (highlighted in yellow in Table 5). This shift could also be achieved through biking, walking, telecommuting, shorter trip lengths, and other measures aimed at reducing demand for travel altogether.

Intercity travel is similarly dominated by personal vehicle travel which accounts for 90 percent of PMT (air, bus, and train account for 7, 2, and 1 percent); personal vehicles tend to dominate for trips less than 300 round trip miles while air dominates for trips of more than 2,000 roundtrip miles [53]. In intercity travel as in intracity travel, driving becomes competitive at higher occupancies. *Air travel* is presently more efficient than driving solo due to its high average occupancies though occupancy level, vehicle fuel economy, and trip length cause variation in air travel emissions. Occupancies and aircraft fuel economies are both trending upwards: passenger load factor is up from 62.4 in 1990 to 78.8 in 2006 [54] while technological advancements including modern high-bypass turbofans and new, lightweight, high-strength materials have improved energy and aerodynamic efficiency. Improved aircraft fuel economy is limited by turnovers in aircraft (which tend to have 35-40 year useful lives) and capacity additions; fuel economy is forecast to improve 16% compared to a 2001 baseline while 70% of aircraft should be post-2002 additions by 2020 [55]. Air travel GHG emissions also vary with trip length as aircraft take-off and landing are larger energy drains than constant elevation flying. According to the World Resources Institute [56] 0.53 lbs CO2/pax-mi is emitted for a short trip, 0.43 lb/pax-mi for medium trips, and 0.4 lb/pax-mi for long trips[7]. Finally, air travel emissions may be conservatively estimated due to failure to account for indirect emissions from airport access and egress, supportive airport vehicles, and auxiliary power units at airports as well as concerns that emissions at higher altitudes (as 90% of air travel CO_2 emissions are [55]) may have a higher GWP.

High Speed Rail (HSR) is a mode alternative not currently available in the U.S. that has been successfully deployed around the world and proposed for many corridors domestically (in particular, California). Based on per-passenger energy intensities from train technologies existing in other countries (Denmark's IC-3 and France's TGV) or explored by the Army Corps of Engineers and assuming HSR is deployed in corridors where it is competitive with flying (e.g. trips of 200-500 mi.) and nets a similar percent occupancy of 0.7, HSR is very competitive with driving, even with vehicles at high occupancies. The ability to reduce the carbon intensity of HSR via improvements in electricity generation may give it a further edge.

Freight Transportation Efficiency

Freight transport contributes 38% of transportation's GHG emissions, and 11% of all U.S. GHG emissions [22]. The five major freight modes, truck, rail, air, water and pipeline carry 28.5, 38.2, 0.3, 13.0, and 19.9 percent of freight ton-miles and comprise 60, 6, 5, 13, and 16 percent of freight GHG emissions, respectively [57]. Freight transport is growing rapidly as a source of GHG emissions, primarily due to a decline in efficiency (as opposed to increases in shipping activity). Between 1990 and 2005, freight transport emissions increased 69 percent while ton-miles grew less than 30 percent.

Two major trends help to explain efficiency losses which have driven rapid growth in freight GHG emissions. First, trucking's market share has increased at the expense of other, more efficient modes (in particular waterborne and pipeline transport) businesses have come to value the scheduling and routing flexibility of trucking for higher value goods that must be shipped on quicker timelines. Second, the energy efficiency of trucking has dropped markedly (12 percent between 1990 and 2005). While the fuel economy of trucks has not seen much drop off, operational efficiency has declined. Encouragingly, rail's mode share actually outgrew trucking's while energy efficiency increased 23 percent during the same period. Nevertheless, trucking seems to be a baseline against which GHG reduction strategies must be compared. Routes to improve trucking efficiency include fuel economy improving technologies and improved operations.

Trucking fuel economy has, since 1996, improved slightly in single unit trucks (1.9 percent annually) but declined slightly in combination trucks (1.6 percent annually). Nevertheless, a variety of technologies that reduce losses from aerodynamic drag, rolling resistance, accessory loads, and transmission and engine inefficiencies are available that could dramatically improve fuel economy. Table 7 summarizes potential GHG emission reductions

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[7] The average short trip is roughly 200 miles, medium trip is 700 miles, and long trip is 1500 miles; the numbers in Table 5 and 6 correspond to 0.63 lbs CO_2e/pax-mi.

from the deployment of a range of technologies using fuel economy improvement estimates from Vyas et al. (2002). Several of these technologies are potential add-ons which are currently employed in only a small percentage of the fleet, and most are mature technologies or will be by 2010. Hybridization has also been discussed for medium duty trucks, and could be especially beneficial for delivery-type trucks, a growing share of the fleet given growth in Just-in-Time delivery In fact 61 percent of MDTs have a range less than 50 miles [58]. Idling is another significant source of energy loss for trucks which can be readily addressed. A typical truck engine consumes 0.85 gallons of fuel per hour powering air conditioning and electric accessories while at rest stops [59] and an average truck used for long-haul purposes may accumulate 1830 hours of parked idling annually. Technologies with the potential to reduce idling losses include direct-fire heaters and auxiliary power units (APUs). Only 6 percent of heavy trucks had idle-reduction technology in 2002 (U.S. Census Bureau 2004). Truck Stop Electrification (TSE) is another option to reduce fuel use while idling at select truck stops. Table 7 presents potential GHG reductions from these idling reduction strategies.

Improving trucking operational efficiency and using substitute modes with energy efficiency advantages are also classes of strategies that offer great potential for freight GHG emissions abatement. Operational efficiency declines in trucking seem to be the result of an industry that has yet to adjust logistically to new demands. A typical long haul truck may drive 15 percent of its miles empty [60]. Better utilizing existing trucking capacity is achievable by improving routing, improved load matching, and improving loading and unloading procedures. The greatest potential could be through intermodal movements. Rail enjoys a tremendous advantage in energy efficiency over trucking, while waterborne shipping is also more efficient; both are substitutes for some major shipping routes. While numerous factors could limit shifts from trucks to rail or ships such as distance, availability of infrastructure, size of cargo, schedule, durability, and availability of facilities [57]. Improved intermodal facilities could enable rail to take over haul lines with trucking employed for pick-up and delivery (possibly taking advantage of hybridization). Table 8 illustrates possible savings from modal substitutions of one percent of annual trucking activity (1,293,326 ton-miles) and reducing one percent of empty truck miles.

BEYOND THE SCOPE OF THIS WORK

While the emissions of the residential and commercial sectors are largely dictated by the carbon intensity of the electricity they use, improving downstream efficiency can reduce the amount of electricity which must be generated, with all the attendant losses. Residential efficiency can be improved in various ways, by smaller buildings with shared walls and ceilings, wall and ceiling insulation improvements, more efficient building equipment (HVAC systems, water heaters, and heaters), improved building envelopes (to lower heating and cooling loads), appliance efficiency standards, and the introduction of heat pumps (particularly of the geothermal variety) [61]. Commercial efficiency meanwhile should target lighting and opportunities for co-location centered around shared distributed power generation [62]. The industrial sector is not addressed in this work due to the degree of heterogeneity in emissions sources (which precludes abatement via a single widespread technology or behavioral change) as well as the fact that U.S. industrial emissions of GHGs are falling (as the nation transitions to a less manufacturing oriented economy), though clearly this key sector (producing 36% of U.S. GHGs), will also need to cut emissions. In addition to reducing the GHG intensity of specific industrial activities, policies involving carbon taxes, cap-and-trade schemes, and GHG emission offsets are likely to prove key strategies for incentivizing lower energy demand and GHG emissions across all sectors.

CONCLUSIONS

Table 9 compares selected GHG control strategies to top emissions reducing strategies, based on the analyses described above. The list includes combinations of vehicle technologies and alternative fuels, and all strategies are considered in terms of the share they could achieve of the 80 percent reduction in 2000-level emissions estimated to be needed to avoid dangerous effects of climate change. The biggest impacts are felt by changing electricity generation technology and addressing the footprint of older-generation coal technology. Simply increasing the share of renewables in the grid without addressing the high emissions emerging from existing, older coal-fired power plants could result in a dramatic emissions-reduction shortfall.

A "clean grid" with 100% implementation of CCS technology in coal plants and 50% of generation from renewables or nuclear is expected to provide 31 percent of the target reduction; absent CCS only 12 percent of this goal may be achieved. A passenger vehicle fleet of PHEV 60s running on a "clean grid" with CCS electricity and cellulosic E85 is expected to provide 24 percent of the needed reduction; but, notably, the use of cellulosic E85 is only responsible for 2 percent of this (due to the high fraction of electrified miles). In contrast, the use of cellulosic E85 can more than double the contributions of improved conventional vehicles and HEVs. PHEVs running on an average grid electricity mix offer little advantage over an HEV, and an HEV in turn offers little advantage over an improved conventional vehicle. Shifting 10 percent of local passenger miles to a full occupancy HRT could account for another 1.8 percent of the needed reduction, and this could climb to 2 percent if combined with a clean grid with CCS. Shifting to 10 percent of local (intra-urban) passenger miles to 4 person carpools, meanwhile, could meet 1.2 percent of needed GHG savings. Simply employing available technologies for conventional vehicles could equate to 12 percent of the needed reduction. Long-distance passenger travel and freight movement changes do not appeal to be key players.

From a more qualitative perspective, this analysis reveals the needs for concentrated and collaborative investment into various forms of infrastructure and strategies to manage demand for existing assets. All of the technologies discussed here have the potential to be affordable, and in many cases cost-saving, given sufficient research and development and production volumes. The full realization of benefits from many, though, is contingent upon proper supportive infrastructure (e.g., transmission and distribution networks for renewables, refining and refueling infrastructure for alternative fuels, and improvements of the electric grid for PHEVs) and the matching of demand to capacity to ensure more efficient utilization of all resources (particularly with respect to off-peak electric generating capacity and untapped transport supply, in the form of carpooling and existing transit). This work also reveals powerful synergies across sectors and technologies. In a truly ideal scenario, combining a clean grid with CCS with a fleet of PHEVs and the use of cellulosic E85 could account for 56 percent of the required 80 percent reduction (the sum of these two strategies, from Table 9).

Clearly, contributions from other transportation strategies as well as improvements in the residential, commercial, and industrial sectors will still be needed, to hit the overall 80-percent emissions-reduction target. Fortunately, the U.S. has the assets and technical understanding needed to meet the challenge of reducing its GHG emissions by such levels; public engagement, political will, and comprehensive thinking will be key.

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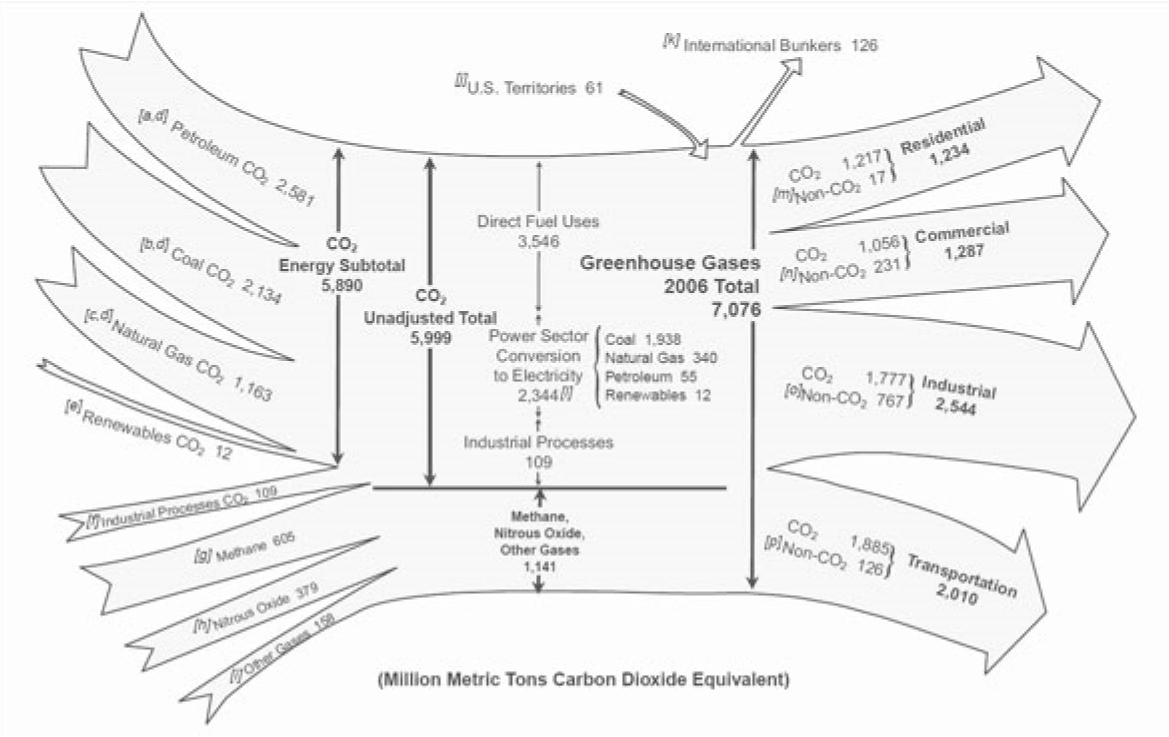

Figure 1: GHG Emissions in the U.S. Economy in 2006 (Source: EIA 2007, Diagram 1)

Table 1: Potential GHG Reduction from Shifts in Electricity Generating Feedstocks and Technologies

Plant Technology	Wholesale Cost (cents/kWh)	Current Share of Capacity (%)	Current Share of Generation (%)	Plant Carbon Intensity (lb CO_2/kWh-Generated)	1 Percent of U.S. Total GHG Emissions (MMTC)	Vs. Coal-Fired Plants		Vs. Grid Average	
						Annual GHG Savings (MMTC)	Percent of U.S. GHG Emissions	Annual GHG Savings (MMTC)	Percent of U.S. GHG Emissions
Coal	4.2	31.97	49.97	2.109	10.17	--		(3.858)	(0.200)
Natural Gas (NG)	3.2-5.6	39.06	20.31	1.182	5.70	4.467	0.231	0.608	0.032
Petroleum	Not Easily Obtained	5.870	1.534	1.749	8.43	1.733	0.090	(2.125)	(0.110)
Geothermal	4.0-6.0 (Hydrothermal) 8.0-28.0 (EGS)	0.237	0.37	0.007	0.03	10.131	0.525	6.273	0.325
Nuclear	6.7	10.38	20.13	0.000	0.00	10.166	0.527	6.308	0.327
Wind	2.0-9.5	1.611	0.802						
Solar (CSP)	12-14	0.051	0.015						
Solar (PV)	13-22								
Biomass	Not Easily Obtained	1.064	0.624						
Hydroelectric	Not Easily Obtained	7.969	6.139						
Coal w/ ICGG	4.6-5.3	Negligible	Negligible	1.294	6.24	3.926	0.203	0.068	0.004
Coal w/ CCS	5.2-9.2 (New) 6.2-11.2 (Retrofit)	N/A	N/A	0.316	1.52	8.641	0.448	4.783	0.248
Grid Average				1.308	6.31	3.858	0.200	--	
Expanded Nuclear and Renewable Sectors (35% Coal, 15% NG, 50% Nuclear & Renewable)				0.915	4.41	5.753	0.298	1.895	0.098
Grid Average with CCS in Coal				0.412	1.99	8.178	0.424	4.320	0.224
Expanded Nuclear & Renewable Sectors, CCS in Coal				0.288	1.39	8.777	0.455	4.919	0.255

Notes: Summer capacity and amount generated values come from EIA's (2008a) Tables 8.2 and 8.11; prices are from MIT (2003), Holt (2005), IPCC (2005), Geisbrecht (2008), and the NREL Energy Analysis Office (2005). The wholesale price of petroleum, hydroelectric and biomass electricity could not be easily obtained. CCS assumed present in coal plants in relevant cases at 90% CO_2 removal efficiency (IPCC 2005). Feedstock carbon intensities and plant heat rates from Aabaken (2006). Annual U.S. electricity generation and GHG emissions from EIA (2008a). IGCC efficiency improvement midpoint of estimates from Tennant (2005). More details can be found in Kockelman et al. (2008).

Table 2: Potential GHG Reductions from Shift in Vehicle Fuels

Fuel	WTW Emissions (lb CO_2e/Mbtu)	HHV Energy Content (Btu/gal fuel)	WTW Emissions (lb CO_2e/gal fuel)	Energy Content Ratio (gal fuel/gal fuel replaced)	1 Percent GHG Emissions (MMTCE)	Annual GHG Savings (MMTCE)	Percent of U.S. GHG Emissions
Gasoline (weighted mix)	219	124,000	27.16	1.00	4.70	Vs. Gasoline	
Corn ethanol neat fuel	171	83,333	14.28	1.49	3.68	1.02	0.014
Corn ethanol (biomass fuel produced) neat fuel	101	83,333	8.38	1.49	2.16	2.54	0.036
Cellulosic ethanol neat fuel	20	83,333	1.66	1.49	0.43	4.27	0.060
E85 (Corn-based) blend	179	94,190	16.82	1.32	3.83	0.87	0.012
E85 (Cellulosic) blend	50	94,190	4.69	1.32	1.07	3.63	0.051
L S Diesel	213	138,700	29.57	1.00	1.72	Vs. Diesel	
Biodiesel neat fuel	69	126,222	8.70	1.10	0.51	1.21	0.017
B20 blend	184	136,444	25.16	1.02	1.46	0.26	0.004

Notes: Ethanols substitute for gasoline (3,300 mbd [EIA 2008a]) and biodiesels substitute for diesel (1,100 mbd [EIA 2008a]). WTW emissions from EPA (2007b). “Fuel replaced” refers to gasoline for ethanols and ethanol blends and diesel for biodiesel and biodiesel blends; energy content ratio reflects the fact that more of alternative fuel must be combusted to liberate an equivalent amount of energy due to lower energy contents in alternative fuels.

Table 3: Potential GHG Reductions from Shift to Vehicle Technologies

	Technology	FE Benefit (%)		Fuel Economy (mpg)	1 Percent GHG Emissions (MMTCE/yr)	Annual Savings (MMTCE)	Percent of U.S. GHG Emissions	Annual Savings (MMTCE)	Percent of U.S. GHG Emissions
		Low	High						
	Base Vehicle (2007 fleet average)	--	--	20.5	4.27	Vs. Average Vehicles		Vs. New Vehicles	
	Base Vehicle (MY 2007 achieved)	--	--	26.7	3.28	0.991	0.051		
Conventional Technologies	*Engine Technology*								
	Cylinder Deactivation	3	8	28.2	3.18	1.087	0.056	0.095	0.005
	Direct Injection	1	3	27.2	3.24	1.024	0.053	0.032	0.002
	Turbocharging	3	7	28.0	3.18	1.087	0.056	0.095	0.005
	Valve Event Manipulation (VEM)	1	7	27.8	3.24	1.024	0.053	0.032	0.002
	Transmission Technology								
	Automatic or Continuously Variable	1	8	27.9	3.24	1.024	0.053	0.032	0.002
	Aggressive Shift Logic	1	5	27.5	3.24	1.024	0.053	0.032	0.002
	Vehicle Design								
	10% Mass Reduction	4	10	28.6	3.15	1.117	0.058	0.126	0.007
	Improved Aerodynamics	1	2	27.1	3.24	1.024	0.053	0.032	0.002
	Accessory Electrification	1	5	27.5	3.24	1.024	0.053	0.032	0.002
	Low RR Tires	1	2	27.1	3.24	1.024	0.053	0.032	0.002
	All Conventional Technologies	17	57	36.6	2.39	1.876	0.097	0.885	0.046
Advanced Drivetrain Technologies	Diesel	20	40	34.7	2.74	1.524	0.079	0.532	0.028
	Diesel w/ Conventional Technologies	29	72	40.2	2.37	1.897	0.098	0.906	0.047
	HEV	17	30	33.0	2.65	1.615	0.084	0.624	0.032
	HEV w/ Conventional Technologies	34	87	42.9	2.04	2.226	0.115	1.235	0.064
	PHEV 40 (Coal-fired)				2.24	2.029	0.105	1.037	0.054
	PHEV 40 (Renewable)				1.02	3.247	0.168	2.256	0.117
	PHEV 40 (Grid Average)				1.78	2.491	0.129	1.500	0.078
	PHEV 40 (Clean Grid)				1.55	2.718	0.141	1.727	0.090
	PHEV 40 (Clean Grid and CCS)				1.19	3.081	0.160	2.090	0.108
	PHEV 60 (Coal-fired)				2.34	1.930	0.100	0.939	0.049
	PHEV 60 (Renewable)				0.51	3.758	0.195	2.767	0.143
	PHEV 60 (Grid Average)				1.64	2.623	0.136	1.632	0.085
	PHEV 60 (Clean Grid)				1.30	2.964	0.154	1.973	0.102
	PHEV 60 (Clean Grid and CCS)				0.76	3.508	0.182	2.517	0.130

Notes: Base vehicle fuel economies from Davis and Diegel (2007), Technology fuel economy benefit estimates from Jones et al. (2008), Fuel economies assume mid-point of fuel economy benefit range, PHEVs improve upon HEV with conventional technologies, PHEV 40 has 50 percent of driving electrified, PHEV 60 has 75 percent of driving electrified, PHEVs operate at electric efficiency of 333 kWh-grid/mi (Gremban 2006), electric carbon intensities from Table 1 with additional 7 percent efficiency loss for transmission and distribution, fuel carbon intensities from Table 2

Table 4: Potential GHG Reductions from Transportation Policies

Speed Limits	**Speed (mph)**	**FE Loss (%)**	**Fuel Economy (mpg)**	**1 Percent GHG Emissions (MMTCE)**	**GHG Emissions Saved (MMTCE)**	**Percent U.S. GHG Emissions**
Base Urban Interstate (65 mph)	65	9.7	18.5	0.865	Vs. Base Urban	
Lowered Urban Interstate (55 mph)	55	--	20.5	0.781	0.084	0.004
Base Rural Interstate (70 mph)	70	17.1	17.0	0.509	Vs. Base Rural	
Lowered Rural 1 (65 mph)	65	9.7	18.5	0.467	0.042	0.002
Lowered Rural 2 (55 mph)	55	--	20.5	0.422	0.087	0.005
Combined Urban and Rural 1				1.248	0.126	0.007
Combined Urban and Rural 2				1.203	0.171	0.009
Tires	**Tire Pressure (psi)**	**FE Change (%)**	**Fuel Economy (mpg)**	**1 Percent GHG Emissions (MMTCE)**	**GHG Emissions Saved (MMTCE)**	**Percent U.S. GHG Emissions**
Underinflated Tire	24	-2.2	20.1	4.639	Vs. Underinflated/Non-RR	
Maintained Tire Pressure	32	--	20.5	4.535	0.104	0.005
Low Rolling Resistance Tires	32	2.5	21.1	4.425	0.111	0.006
Gas taxes	**Price with Tax**	**Percent Price Increase**	**Gasoline Consumption Saved (mbd)**	**1 Percent GHG Emissions (MMTCE)**	**GHG Emissions Saved (MMTCE)**	**Percent U.S. GHG Emissions**
No tax increase	4.00	0.0	0.00	4.677	Vs. Present Tax	
$0.50/gal gas tax increase	4.50	12.5	83.88	4.644	0.032	0.002
$1.00/gal gas tax increase	5.00	25.0	167.77	4.612	0.065	0.003
$1.50/gal gas tax increase	5.50	37.5	251.65	4.579	0.097	0.005
$2.00/gal gas tax increase	6.00	50.0	335.54	4.547	0.130	0.007

Notes: Fuel economy losses from speeds from West et al. (1997). Interstate VMTs from BTS (2008) Table 1-33. Fuel economy loss and gain from tires from NHTSA (2004) and NRC (2006). Gas tax savings based on elasticities from Hughes et al. (2007). Gas tax assumed to apply to motor gasoline only. Annual motor gasoline consumption from EIA (2007).

Table 5: Potential GHG Reductions from Shift from SOV to Carpool or Alternative Mode at Average Occupancies

	Mode Alternative	Average Occupancy (pax)	Average Capacity (pax)	Energy Intensity (Btu/pax-mi)	1 Percent of PMT (MMTCE)	Annual GHG Savings (MMTCE)	% of U.S. GHG Emissions
Intracity Travel	Drive (SOV, gas)	1	4	6049	5.28	--	0.273
	Drive (Avg. HBW occ., gas)	1	4	5306	4.63	0.65	0.034
	Drive (Avg. occ., gas)	2	4	3711	3.24	2.04	0.106
	Drive (2 passengers, gas)	2	4	3024	2.64	2.64	0.137
	Drive (3 passengers, gas)	3	4	2016	1.76	3.52	0.182
	Drive (4 passengers, gas)	4	4	1512	1.32	3.96	0.205
	Bus (Diesel fuel)	9	52	4230	3.59	1.68	0.087
	Bus (B20)	9	52	4230	3.11	2.17	0.112
	HRT (Electric Fuel)	23	82	860	1.45	3.83	0.198
	LRT (Electric Fuel)	25	100	1159	1.95	3.32	0.172
	Commuter Rail (Diesel)	31	114	2996	2.54	2.73	0.142
	Biking/Walking	1	1	0	0.00	5.28	0.273
Intercity Travel	Drive (SOV, gas)	1	4	6049	2.13	--	--
	Drive (Avg. occ., gas)	2	4	3711	1.31	0.82	0.043
	Drive (2 passengers, gas)	2	4	3024	1.07	1.07	0.055
	Drive (3 passengers, gas)	3	4	2016	0.71	1.42	0.074
	Drive (4 passengers, gas)	4	4	1512	0.53	1.60	0.083
	Bus (diesel fuel)	9	52	4230	1.45	0.68	0.035
	Air	99	125	3266	1.01	1.12	0.058
	HSR (IC-3: Diesel 99 mph)	--	138	103	0.04	2.10	0.109
	HSR (TGV: Electric 99 mph)	--	485	487	0.33	1.80	0.093
	HSR (Mag-lev: Electric, 300 mph)	--	156	1187	0.81	1.32	0.069

Notes: Annual Passenger Miles Traveled (Davis and Diegel 2007), Annual Long Distance Passenger Miles Traveled (NHTS 2001), Passenger vehicles get 22.4 mpg (fleet average based on [Davis and Diegel 2007]), HSR Options assumed to have 70% occupancy, HSR modal efficiency from Center for Clean Air Policy and Center for Neighborhood Technology (2006).

Table 6: Potential GHG Reductions from Shift to Alternative Mode at Full Occupancies

	Mode Alternative	Occupancy (pax)	Average Capacity (pax)	Energy Intensity (Btu/pax-mi)	1 Percent of PMT (MMTCE)	Annual GHG Savings (MMTCE)	% of U.S. GHG Emissions	Annual GHG Savings (MMTCE)	% of U.S. GHG Emissions
Intracity Travel	Drive (Avg. occupancy, gas)	1.63	4	3711	3.24	Vs. Avg Occupancy		Vs. 4 Person Carpool	
	Drive (4 passengers, gas)	4	4	1512	1.32	1.92	0.10		
	Bus (Diesel fuel)	9	52	711	0.60	2.63	0.14	0.72	0.04
	Bus (B20)	9	52	711	0.52	2.71	0.14	0.80	0.04
	HRT (Electric fuel)	23	82	237	0.40	2.84	0.15	0.92	0.05
	LRT (Electric fuel)	25	100	291	0.49	2.75	0.14	0.83	0.04
	Commuter Rail (Diesel)	31	114	822	0.70	2.54	0.13	0.62	0.03
	Biking/Walking	1	1	0	0.00	3.24	0.17	1.32	0.07
Intercity Travel	Drive (Avg. occupancy, gas)	2	4	3711	1.31	Vs. Avg Occupancy		Vs. 4 Person Carpool	
	Drive (4 passengers, gas)	4	4	1512	0.53	0.77	0.04		
	Bus (diesel fuel)	9	52	711	0.24	1.06	0.06	0.29	0.01
	Air	99	125	2574	0.80	0.51	0.03	(0.27)	(0.01)
	HSR (IC-3: Diesel 99 mph)	--	138	72	0.02	1.28	0.07	0.51	0.03
	HSR (TGV: Electric 99 mph)	--	485	341	0.23	1.08	0.06	0.30	0.02
	HSR (Mag-lev: Electric, 300 mph)	--	156	831	0.57	0.74	0.04	(0.03)	(0.00)

Notes: Annual Passenger Miles Traveled (Davis and Diegel 2007), Annual Long Distance Passenger Miles Traveled (NHTS 2001), Passenger vehicles get 22.4 mpg (fleet average based on [Davis and Diegel 2007]), HSR Options assumed to have 70% occupancy

Table 7: Potential GHG Reductions from Adoption of Truck Technologies

Technology	FE Benefit (%)	Fuel Economy (mpg)	1 Percent GHG Emissions (MMTCE)	GHG Emissions Saved (MMTCE)	Percent of U.S. GHG Emissions	Potential Add On
All Trucks						
Base Truck	--	9.0	0.750	Vs. Avg. Truck		--
Improved Aerodynamics - Airfoils, baffles, wheel covers, leading edge curvature	4.0	9.4	0.722	0.029	1.50E-03	Yes
Low Rolling Resistance Tires	2.5	9.2	0.732	0.018	9.49E-04	Yes
Advanced Transmission	2.0	9.2	0.736	0.015	7.63E-04	No
Light Medium & Heavy Medium Only						
Base Truck	--	10.4	0.271	Vs. Avg. MDT		
Mass Reduction	5.0	10.9	0.258	0.013	6.69E-04	No
Engine Turbocharging	6.5	11.1	0.255	0.017	8.57E-04	No
Integrated Starter/Alternator, Auxiliary Electrification, & Idle-Off	5.0	10.9	0.258	0.013	6.69E-04	No
Improved Engine - low friction, better injectors, efficient combustion	9.0	11.3	0.249	0.022	1.16E-03	No
Hybridization	40.0	14.6	0.194	0.077	4.01E-03	No
All Improvements w/o Hybridization	34.0	13.9	0.202	0.069	3.56E-03	--
All Improvements w/ Hybridization	74.0	18.1	0.156	0.115	5.97E-03	--
Heavy Duty Only						
Base Truck	--	6.2	0.635	Vs. Avg. HDT		--
Pneumatic Blowing	5.0	6.5	0.604	0.030	1.57E-03	Yes
Single Wide Tires	3.0	6.4	0.616	0.018	9.58E-04	Yes
Mass Reduction	10.0	6.8	0.577	0.058	2.99E-03	No
Auxiliaries Electrified	1.5	6.3	0.625	0.009	4.86E-04	No
Improved Engine - low friction, better injectors, efficient combustion	10.0	6.8	0.577	0.058	2.99E-03	No
Improved Thermal Management	10.0	6.8	0.577	0.058	2.99E-03	No
All Improvements	48.0	9.2	0.429	0.206	1.07E-02	--
Idle Reduction						
Direct-Fired Heating Units	3.4	6.4	0.161	0.005	2.82E-04	Yes
Auxiliary Power Units	9.0	6.8	0.152	0.014	7.10E-04	Yes
Truck Stop Electrification	versus running from engine		0.007	0.044	6.22E-04	N/A

Notes: Fuel Economy benefits adapted from Vyas et al. (2002). Number of trucks in each class from U.S. Census Bureau (2004). Idle Reduction technologies assumed to apply only in sleeper trucks.

Table 8: Potential GHG Reductions from Freight Operational Efficiency Strategies

Mode Shift	**Energy Efficiency (Ton-mi/lb CO_2)**	**1 Percent GHG Emissions (MMTCE)**	**GHG Emissions Saved (MMTCE)**	**Percent of U.S. GHG Emissions**
Trucking	2	1.038	Vs. Trucking	
Rail	18	0.089	0.949	0.049
Waterborne	5	0.294	0.744	0.039
Air	1	2.715	-1.677	-0.087
Logistics	**Annual Empty Miles (mi/truck)**	**1 Percent GHG Emissions (MMTCE)**	**GHG Emissions Saved (MMTCE)**	**Percent of U.S. GHG Emissions**
Base Long Haul Truck	15000	0.229	Vs. Avg. Empty Miles	
Reduced Empty Miles	14850	0.227	0.002	1.19E-04

Modal energy efficiencies from Davies (2007). Annual trucking freight activity from BTS (2008). Annual Average empty miles from EPA (2004). Logistic improvements assumed to apply in heavy duty trucks only.

Table 9: Comparison of Selected GHG Control Options

Strategy	Potential Savings (MMTCE)	Percent of U.S. GHG Emissions	Percent of 80% Reduction
Renewable Electricity Generation (vs. Coal-Fired)	10.166	0.527	0.642
CCS Coal Electricity Generation (vs. Coal-Fired)	8.641	0.448	0.546
Renewable Electricity Generation (vs. Grid Average)	6.308	0.327	0.399
"Clean Grid" w/ CCS Electricity Generation (vs. Grid Average)	4.919	0.255	0.311
CCS Coal Electricity Generation (vs. Grid Average)	4.783	0.248	0.302
PHEV-60, "Clean Grid" w/ CCS & E85 Cellulosic	3.903	0.202	0.247
HEV w/ All Conventional Improvements, E85 Cellulosic	3.804	0.197	0.240
Pass. Car, All Conventional Improvements, E85 Cellulosic	3.725	0.193	0.235
PHEV-60, Clean Grid w/ CCS	3.508	0.182	0.222
PHEV-60, "Clean Grid," E85 Cellulosic	3.359	0.174	0.212
Avg Occupancy Drive to Full Capacity HRT, "Clean Grid" w/ CCS Electric (Local Travel)	3.151	0.269	0.199
PHEV-60, Average Grid, E85 Cellulosic	3.018	0.156	0.191
PHEV-60, Clean Grid	2.964	0.154	0.187
Avg Occupancy Drive to Full Capacity HRT, Electric (Local travel)	2.838	0.147	0.179
Avg Occupancy Drive to Full Capacity Bus, Diesel (Local travel)	2.633	0.136	0.166
PHEV-60, Average Grid	2.623	0.136	0.166
HEV w/ All Conventional Improvements	2.226	0.115	0.141
Avg Occupancy Drive to 4 Person Carpool (Local travel)	1.918	0.099	0.121
"Clean Grid" Electricity Generation (vs. Grid Average)	1.895	0.098	0.120
Pass. Car w/ All Conventional Improvements	1.876	0.097	0.119
Avg Occupancy Drive to HSR, Diesel	1.283	0.066	0.081
Avg Occupancy Drive to 4 Person Carpool (Long Distance Travel)	1.064	0.055	0.067
Heavy Duty Truck to Rail Shift	0.949	0.049	0.060
Avg Occupancy Drive to Full Capacity Bus, Diesel (Long Distance Travel)	0.775	0.040	0.049
Hybrid MDT, All Improvements, B20	0.135	0.002	0.009
Hybrid MDT, All Improvements	0.115	0.006	0.007

NOTES:

[1] Electricity consumed is lower than electric produced due to 7.5 percent transmission and distribution losses, which are assumed throughout this work (US Climate Change Technology Program 2005).

[1] The outlook for both natural gas and nuclear is unclear. Natural gas production has rebounded from years of decline behind the emergence of shale gas, but price volatility and the extent of domestic reserves remain concerns. Nuclear faces persistent concerns of safety, national security, and lack of a waste disposal plan, but enjoys growing advocacy due to its carbon neutrality and could become cost-effective under scenarios of carbon pricing. (A$100 per ton of GHG price may be needed for competition with natural gas and coal [MIT 2003].)

[1] 68 percent of coal capacity is from plants that went online in 1978 or earlier and thus employ older, lower efficiency technology (EIA 2006b).

[1] PF power plants with CCS systems would require 24-40% more power, while IGCC power plants would require only 14-25% more power (IPCC 2005).

[1] Total U.S. capacity presently is 1 million MW. (EIA 2008)

[1] The 15 GJ value is a weighted average of mid-point heat contents for wood and agricultural residues.

[1] The average short trip is roughly 200 miles, medium trip is 700 miles, and long trip is 1500 miles; the numbers in Table 5 and 6 correspond to 0.63 lbs CO_2e/pax-mi.