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ACHIEVING 80% REDUCTION IN TRANSPORT GREENHOUSE GAS EMISSIONS, USING THE USA AS A CASE STUDY

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ABSTRACT

This paper investigates the potential for making deep cuts in US transportation greenhouse gas (GHG) emissions in the long term (50-80% below 1990 levels by 2050). Scenarios are used to envision how such a significant decarbonization might be achieved with changes in vehicles, fuels, and vehicle use. A Kaya framework that decomposes GHG emissions into the product of four major drivers is used to analyze emissions and mitigation options. All major transportation activities are included here—cars and trucks, aviation, rail, marine, agriculture, off-road, and construction. We confirm the notion that a portfolio approach is needed to achieve deep cuts in transport. Light duty vehicles offer the greatest potential for emission reductions. Deep reductions in other subsectors are also possible, but are more limited in the types of fuels and propulsion systems that can be used. Deep emission cuts will be greatly aided by reduced travel demand.

1. Background and Introduction

Strategies to achieve a 50 to 80% reduction in greenhouse gas emissions have not been clearly defined. Is it possible to achieve such large reductions in the transport sector? If so, how? Given that transportation accounts for a substantial share of both US and global GHG emissions (29% and 23%, respectively) (EPA, 2006; ITF, 2008), transport clearly must be part of any plan to reduce emissions dramatically. This paper addresses how large reductions might be achieved and what that implies for innovation needs and policy.

The study on which this paper is based is unique in that it examines deep GHG reductions using a detailed disaggregated approach for the entire transport sector. The authors previously conducted a similar scenario analysis of transport sector emissions for California (Yang et al., 2009). A number of studies investigate different aspects of GHG reductions in US transportation, but mostly consider only light duty vehicles (Bandivadekar et al., 2008; Grimes-Casey et al., 2009; Mui et al., 2007; NRC, 2008; Yeh et al., 2008). Some global scenario studies have been conducted for the broader transport sector but national-level detail is lost and deep emission reductions are not examined (e.g., (IEA, 2008; WBCSD, 2004).

This scenario analysis does not explicitly consider costs, though we are currently extending this study using economics models. We do, however, use our deep understanding of future costs of fuels and vehicle technologies and behavioral change in designing these scenarios. Energy-economic models, such as the US Energy Information Administration's (EIA) NEMS model and the US Environmental Protection Agency's (EPA) nine-region MARKet ALlocation (MARKAL) model, are capable of analyzing all transport subsectors simultaneously along with all other components of the energy system, but to the authors' knowledge they have not been used to study in detail how deep emission reductions could be made from all subsectors of US transport in the long term (e.g., see Gallagher and Collantes, 2008).

The problem is that costs of future technologies, including those approaching commercialization such as hydrogen fuel cells, battery electric vehicles, and cellulosic biofuels are highly uncertain. Other more far-off options that are still in the lab are even more uncertain. There is also uncertainty about the ability and likelihood of large socio-technical systems to undergo massive transformations. And there is still additional uncertainty about the willingness of consumers to purchase and use different types of vehicles and fuels. The International Energy Agency estimated in an optimistic case (BLUE Map scenario) that reducing global annual GHG emissions 50% below 2005 levels by 2050 would require the utilization of technologies with marginal abatement costs up to $200/tonne CO_2 (IEA, 2008), but this is little more than informed speculation.

With all the uncertainty about technological innovation and behavior changes, it is clearly impossible to credibly specify economically efficient strategies to achieve large GHG emission reductions. But we can use careful disaggregation of transport activities and informed judgement to make some assessments of what types of changes are needed to achieve large reductions. That is the goal of this paper—to envision how significant decarbonization of the transport sector might be achieved through advanced vehicle technologies and fuels and travel demand reduction.

1.1 Current emissions context

In this paper, *Domestic* GHG emissions include those emissions generated from trips taking place entirely within the US—i.e., from a US origin to a US destination. *Overall* emissions include half of all emissions generated from trips with either an origin or destination in the US, which captures emissions generated as a result of US passenger and goods transport abroad. *Overall* emissions include international aviation and marine travel where an airplane or ship leaves (or arrives from) the U.S. for (or from) points abroad. Thus, the aviation and marine subsectors account for a larger share of overall emissions than they do of domestic emissions.

Table 1 gives a breakdown of transportation energy use and lifecycle GHG emissions by subsector in the US in 1990 for both the *domestic* and *overall* cases. Note that these figures are higher than those reported elsewhere (e.g., EPA (2006)) because our estimates are lifecycle emissions while others tend to only report fuel combustion emissions onboard the vehicle.

Table 1. **Transportation energy use and lifecycle emissions by subsector in the US in 1990 (Based on authors' calculations using data from numerous sources)**

		GHG Emissions*			
Subsector	**Vehicle Type**	**Domestic**		**Overall**	
		MMT CO$_2$e	**%**	**MMT CO$_2$e**	**%**
Light-duty	Cars & Trucks	1,159	60.3%	1,159	55.1%
Heavy-duty	Buses	16	0.8%	16	0.8%
	Heavy Trucks	304	15.8%	304	14.5%
Aviation	Commercial (Passenger)	160	8.3%	210	10.0%
	Freight	33	1.7%	50	2.4%
	General	13	0.7%	13	0.6%
Rail	Passenger	14	0.7%	14	0.6%
	Freight	41	2.1%	41	2.0%
Marine	Large Marine – Intl.	-	0.0%	115	5.5%
	Large Marine – Domestic	31	1.6%	31	1.5%
	Personal Boats	18	0.9%	18	0.9%
Agriculture	Agriculture	40	2.1%	40	1.9%
Off-road	Off-road	92	4.8%	92	4.4%
Total – All subsectors		**1,921**	**100%**	**2,104**	**100%**

* Emissions estimates reported here are higher than those from other published studies because we include the GHGs produced during upstream ("well-to-tank") fuel production processes.

2. Methods

This analysis builds upon previous work completed by UC-Davis researchers, which looked at how the US state of California might reduce its transport sector GHGs (Yang et al., 2009). The analytical framework relies on decomposing total GHG emissions into a handful of key drivers and expressing emissions as a product of those drivers.

Decomposition analysis has become a popular energy and environmental analysis tool in recent years (Ang and Zhang, 2000; Schipper et al., 2001), and several studies have used decomposition analysis to study historical energy use and GHG emissions in US transport by subsector (Lakshmanan and Han, 1997; Mui et al., 2007; Scholl et al., 1996). In this analysis, a transport-variant of the Kaya identity is used (Kaya, 1990), which decomposes transportation

CO_2 emissions into four main drivers: population, travel demand, vehicle fuel consumption, and fuel carbon intensity. This Kaya equation is developed for each transport subsector and vehicle type and is summed over these categories to obtain emissions for the entire transport sector (see Yang et al. (2008) and Yang et al. (2009) for detailed explanations).

In this study, we do not explicitly model the economics (e.g., costs and benefits) and dynamics (e.g., interactions, timing and transition issues) associated with specific mitigation options, although other studies addressing these issues have informed our judgments as to what is plausible in the 2050 timeframe, with respect to technology, economics, consumer acceptance, and structural and behavioral change. The mitigation options described in these numerous studies for the various transport subsectors (e.g., possible changes in vehicle efficiency, low-carbon fuel options and availability and potential for travel demand reduction) were combined using the LEVERS model in order to construct the various scenarios that make up this analysis.

Lifecycle fuel carbon intensity assumptions in our analysis are taken from the Greenhouse gas Regulated Emissions and Energy Use in Transportation (GREET) model developed by Argonne National Laboratory (Wang, 2007).

3. 2050 scenarios and results

Our LEVERS model disaggregates the transport sector and applies the Kaya identity to each subsector and vehicle category individually. Three sets of scenarios are presented and discussed below: (1) a *Reference* scenario to establish a business-as-usual baseline for comparison, (2) *Silver Bullet* scenarios to examine the potential reductions from individual solutions and (3) *50in50* and *80in50* scenarios to illustrate several mixed (i.e., portfolio) strategy approaches for reducing emissions 50-80% below 1990 levels by 2050.

3.1 Reference scenario

The *Reference* scenario describes a future where very little is done specifically to address climate change, and transportation activity and technology development follow historical trends. It is built from assumptions informed by dozens of other studies. In this business-as-usual scenario, population grows 69% from 249 million in 1990 to 420 million in 2050, and across all subsectors transport intensity (travel per person) is expected to increase significantly (doubling, on average), with the aviation subsector seeing the largest relative growth (Table 2). Total travel demand is nearly 3.4 times the 1990 value in the *domestic* case and 4.2 times higher in the *overall* case. These projections are based largely on the Energy Information Administration's (EIA) Annual Energy Outlook (AEO) 2008 Reference Case projections to 2030, which we have extended to 2050 using linear extrapolation (EIA, 2008a). Alternately, using projections from the EIA's High Price Case would bring down the expected growth in travel demand, though these are not used for the *Reference* scenario.

In the *Reference* scenario, conventional vehicles and fuels continue to be employed. In the light-duty vehicle (LDV) subsector, fleet energy intensity is reduced 47% from 1990 levels, achieving just more than the equivalent of 35 mpg (6/7 L/100km), which is slightly better than the federal Corporate Average Fuel Economy (CAFE) standards required for new vehicles in 2020.[1] For most other subsectors, average fleet energy intensities in 2050 are assumed to be slightly

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[1] Note that actual real-world mpg is about 20% worse than official tested mpg in the US, and that President Obama has proposed that the standards be met in 2016 rather than 2020.

lower than they were in 2005, except aviation, where reductions are greater, in line with historical trends.

Table 2 shows that total transport sector-wide energy intensity is reduced 45% between 1990 and 2050, and the average carbon intensity of all transportation fuels is about 2% lower than in 1990. Carbon intensity reductions are small because the use of low-carbon biofuels are largely offset by increased use of oil from higher carbon, unconventional fossil energy sources.

Domestic (lifecycle) emissions reach 3,496 $MMTCO_2e$ in 2050 (+82% from 1990) and o*verall* emissions reach 4,210 $MMTCO_2e$ (+100% from 1990).

Table 2. **Change in transport intensity, energy intensity, carbon intensity and GHG emissions between 1990 and 2050 and GHG share by subsector in the *Reference* scenario**

		LDV	**HDV**	**Aviation**	**Rail**	**Marine/Ag/ Offroad**	**All Subsectors**
T	Domestic	+71%	+99%	+266%	+43%	+92%	+102%
	Overall	+71%	+99%	+415%	+43%	+92%	+148%
E	Domestic	-47%	-20%	-57%	-20%	-50%	-45%
	Overall	-47%	-20%	-57%	-20%	-50%	-44%
C	Domestic	-9%	+6%	+6%	-9%	+6%	-2%
	Overall	-9%	+6%	+6%	-9%	+6%	-1%
GHG	Domestic	+41%	+175%	+183%	+74%	+70%	+82%
	Overall	+41%	+175%	+300%	+74%	+73%	+100%
GHG Share	Domestic	46.6%	25.2%	16.6%	2.7%	8.8%	---
	Overall	38.7%	20.9%	25.9%	2.3%	12.2%	---

3.2 "Silver bullet" scenarios

Because of the diversity and breadth of vehicle types and functions across the transportation subsectors, individual technology or fuel options alone are unlikely to be sufficient to achieve deep reductions in emissions. The “no silver bullet” notion has become well established in recent years (e.g., Grimes-Casey et al., 2009; WBCSD, 2004). In order to further illustrate this insight and understand the potential reductions from individual options, we developed several *Silver Bullet (SB)* scenarios that describe futures in which one mitigation option (such as an advanced vehicle technology, alternative fuel, or travel demand management) is employed to the maximum feasible extent from a technological, economical, and behavioral perspective in 2050, based upon an extensive literature review.

These scenarios explore individual options such as efficiency, biofuels, hydrogen, electricity, and vehicle miles traveled (VMT) reductions. Not surprisingly, our findings substantiate those of other studies: none of the *Silver Bullet* scenarios, even with very optimistic assumptions, are able to achieve the ambitious 50-80% reduction goal. In fact, none even reduce GHG emissions significantly compared to 1990. These scenarios lend further support to the notion that a portfolio approach is needed to make deep GHG reductions in the transportation sector, especially when constraints on technology and resources are properly accounted for.

3.3 Three deep emission reduction "portfolio" scenarios

While there is no one silver bullet strategy for achieving the ambitious 50-80% GHG reduction goal, many of the individual options are complementary and can be combined in a portfolio approach to help reduce total transportation emissions. Three mixed-strategy scenarios were developed to explore these portfolios and understand a range of different transportation futures in which *Domestic* GHG emissions are reduced by 50% (*50in50* scenarios) or 80% (*80in50* scenarios) below 1990 levels by 2050. Our two *50in50* scenarios emphasize biofuels and electric-drive, respectively, but also include increasing vehicle efficiencies and decreasing per-capita VMT. The *80in50* scenario combines these two main options and looks at how emissions might be reduced even further by addressing each subsector to the furthest extent possible.

The three deep emission reduction scenarios have been crafted from a set of optimistic, yet plausible, assumptions about the extent of technological and behavioral change that could be possible out to 2050. A large number of factors (vehicle and fuel technology development, economic context, resource limitations, lifestyle changes, consumer preferences, and policies) will influence what is possible and ultimately plausible in an uncertain world 40 years into the future. While plausibility is inherently a subjective concept, to inform our scenario development, we have relied on a number of other studies, which attempt to estimate plausible penetrations of advanced technology and fuel options over time. Table 3 provides a summary of each of the three deep reduction scenarios.

Table 4 summarizes the three scenarios quantitatively, showing by subsector the breakdown of fuel usage and the normalized values for transport, energy and carbon intensity.

3.3.1 Scenario results and comparison

Figure 1 shows how GHG emissions are reduced compared to the *Reference* scenario for different activity, fuel, and technology options. For each general strategy, reductions are further broken down into improvements in vehicle efficiency and carbon intensity.

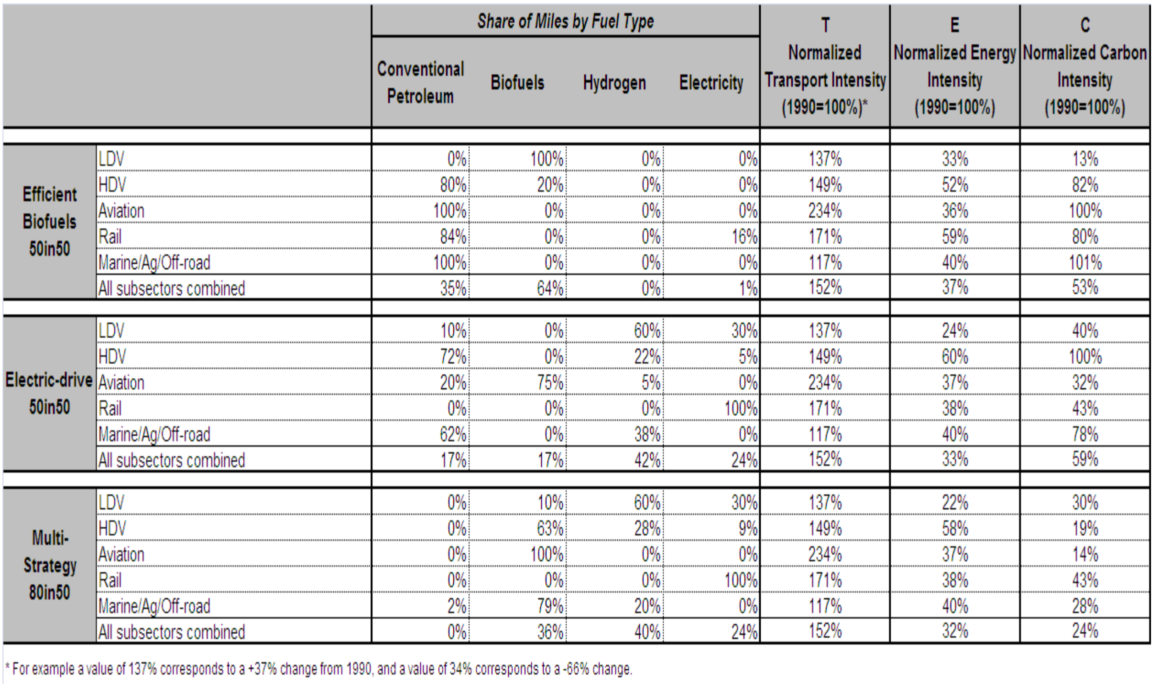
The *Multi-Strategy (portfolio) 80in50* scenario is more successful in making deeper emission reductions because it combines the strategies from the two *50in50* scenarios, which are somewhat complementary, and helps to address their key limitations. Those limitations are resource availability for biofuels and, for electric-drive vehicles, the technical difficulty of serving aviation and heavy duty trucks, as well as the challenges of simultaneously transforming the oil and automotive industries.

In each of the three scenarios, slowing the growth in travel demand with a suite of known transit, land use, and pricing policies leads to important GHG reductions across all subsectors. Per-capita VMT still grows by 52%, and total VMT by 157%, but this is considerably slower growth than in the *Reference* scenario (102% and 241%, respectively).

Table 3. **Overview of the three deep reductions portfolio scenarios**

Scenario Name	**Scenario Summary**
Efficient Biofuels 50in50	**Heavy reliance on advanced biofuels for on-road vehicles.** 25% reduction from *Reference* travel demand. Very low carbon biofuels (12.3 gCO_2e/MJ) and conventional fuels are used in efficient vehicles (63% efficiency improvement). All LDVs and 20% of buses and heavy-trucks are powered by biofuels. All other sectors use conventional fuels since the US is limited to 90 billion GGE of biofuels (Perlack et al., 2005).[2]
Electric-drive 50in50	**Widespread use of electric drive technologies and very low-carbon electricity and hydrogen.** 25% reduction from *Reference* travel demand. LDVs are entirely electric-drive (60% fuel cell and 40% electric vehicles). Buses are similarly electrified while heavy-trucks run on diesel and biofuels. Rail is entirely electrified. Some biofuels are used, primarily in the aviation sector. Energy intensity declines 67% and carbon intensity declines 41%.
Multi-Strategy 80in50	**Combining electric drive with extensive biofuels leads to dramatic GHG reductions.** 25% reduction from *Reference* travel demand. LDVs, buses and rail are primarily electric drive while biofuels are used for heavy trucks, aviation and marine. Energy intensity is reduced 68% and carbon intensity is reduced 76%.

Table 4. **Details of three deep reduction portfolio scenarios, *Domestic* case**



		Share of Miles by Fuel Type				T	E	C
		Conventional Petroleum	Biofuels	Hydrogen	Electricity	Normalized Transport Intensity (1990=100%)*	Normalized Energy Intensity (1990=100%)	Normalized Carbon Intensity (1990=100%)
Efficient Biofuels 50in50	LDV	0%	100%	0%	0%	137%	33%	13%
	HDV	80%	20%	0%	0%	149%	52%	82%
	Aviation	100%	0%	0%	0%	234%	36%	100%
	Rail	84%	0%	0%	16%	171%	59%	80%
	Marine/Ag/Off-road	100%	0%	0%	0%	117%	40%	101%
	All subsectors combined	35%	64%	0%	1%	152%	37%	53%
Electric-drive 50in50	LDV	10%	0%	60%	30%	137%	24%	40%
	HDV	72%	0%	22%	5%	149%	60%	100%
	Aviation	20%	75%	5%	0%	234%	37%	32%
	Rail	0%	0%	0%	100%	171%	38%	43%
	Marine/Ag/Off-road	62%	0%	38%	0%	117%	40%	78%
	All subsectors combined	17%	17%	42%	24%	152%	33%	59%
Multi-Strategy 80in50	LDV	0%	10%	60%	30%	137%	22%	30%
	HDV	0%	63%	28%	9%	149%	58%	19%
	Aviation	0%	100%	0%	0%	234%	37%	14%
	Rail	0%	0%	0%	100%	171%	38%	43%
	Marine/Ag/Off-road	2%	79%	20%	0%	117%	40%	28%
	All subsectors combined	0%	36%	40%	24%	152%	32%	24%

* For example a value of 137% corresponds to a +37% change from 1990, and a value of 34% corresponds to a -66% change.

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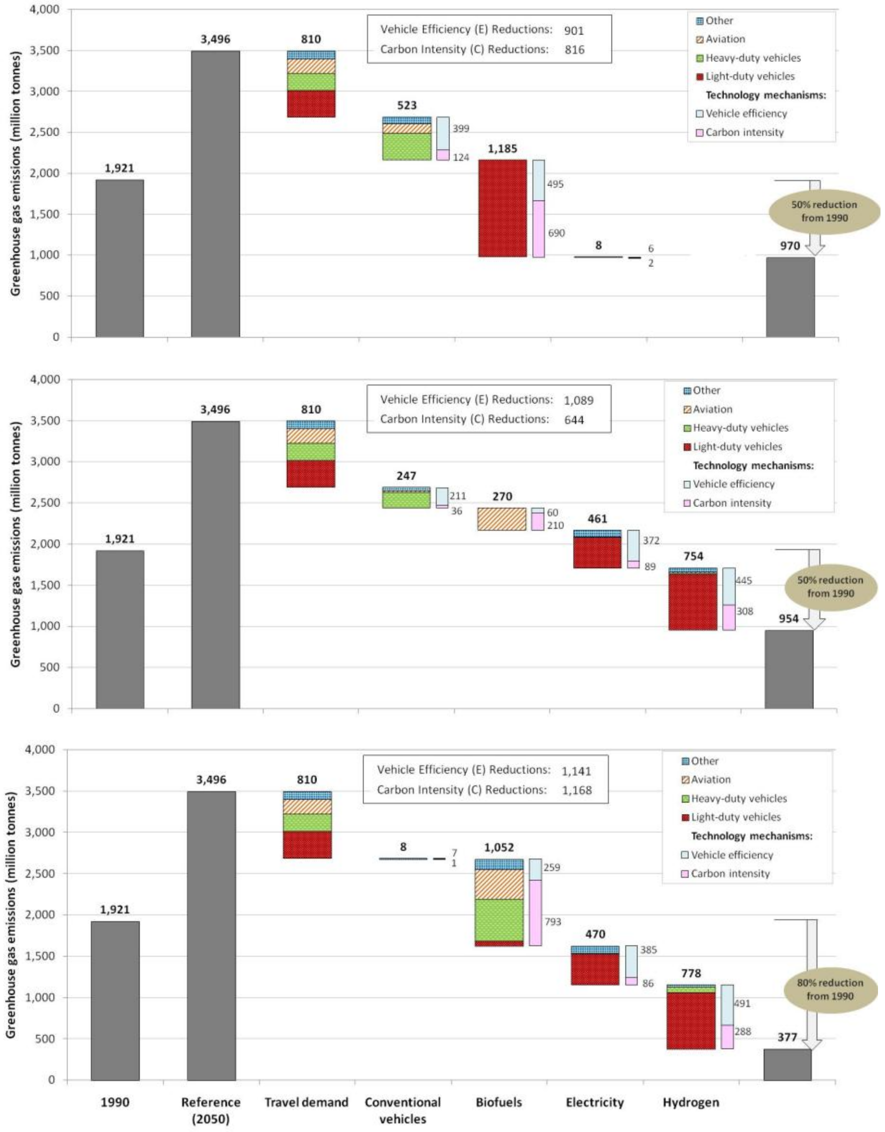
2. The Natural Resources Defense Council (NRDC) puts this estimate at 120 billion gge [(NRDC, 2004. Growing Energy: How Biofuels Can Help End America's Oil Dependence. Natural Resources Defense Council.]. IEA estimates global liquid biofuels potential to be in the range of 443-536 billion gge. [IEA, 2004. Biofuels for Transport: An International Perspective. International Energy Agency, Paris, France.]. US ethanol consumption was just 6 billion gge in 2008 [(EPA, 2008b. Renewable Fuel Standard Program. Environmental Protection Agency.].

Figure 1. ***Domestic* GHG reductions by control strategy for three deep emission reduction scenarios**



Efficient Biofuels 50in50

Electric-drive 50in50

Multi-Strategy 80in50

Each of the three scenarios relies heavily on fuels with very low-carbon intensities to achieve the deep GHG reduction targets. Hence, they are sensitive to assumptions about the fuels production processes. There is a vast range of carbon intensities from different methods for biofuels, hydrogen, or electricity production, and those that result in higher carbon intensity fuels would eliminate much of the emission reductions gained in these scenarios. With biofuels in particular, the scenarios are quite dependent on availability of sustainably grown, low-carbon supply chains. Perlack et al. (2005) estimate that more than 1.3 billion bone dry tons (1.18 billion metric tonnes) of biomass per annum could be "sustainably" supplied (without impacting food, feed, and export demands, or displacing corn croplands) in the US in the long term, if competing demands for biomass are ignored (e.g., electric generation). About two-thirds of this quantity is comprised of residues that would be relatively easy to collect or are already collected for other purposes; the other one-third is comprised of energy crops.[3] If the amount of available biomass resources were constrained to a significantly lower quantity, either because of competing end-use demands or other environmental and economic concerns, then it would be nearly impossible to meet the deep emission reduction goals across the entire transport sector. Similarly, if biomass production cannot achieve such low carbon intensity, because of technology challenges or improved science that finds large associated direct and indirect land use change (LUC) effects, then the deep reduction goals will likewise become much more difficult to attain.

The average lifecycle GHG emissions assumed for the biofuels in our scenarios come almost entirely from biomass feedstock production, collection, and transport, and biofuels distribution (Wang, 2007). These lifecycle emissions could be very low in the future. Future cellulosic biofuels plants, employing either biochemical or thermo-chemical production methods, will likely be energy self-sufficient and, therefore, contribute no additional fossil-derived GHG emissions. And as transport modes used to move biomass and biofuels become more efficient and decarbonized, this will also help to drive down the lifecycle emissions associated with biomass and biofuels production and distribution. We have considered these future changes in our modeling, and is one reason why the value we assume for average US biofuels (12.3 gCO_2e/MJ, excluding indirect LUC impacts) is very low.

To be sure, lifecycle carbon intensities of future advanced biofuels are still uncertain (Farrell et al., 2006; Pimentel and Patzek, 2008). One key reason for this uncertainty is due to potential direct and indirect land use changes associated with biofuels production, the impacts of which are not yet fully known (Sperling and Yeh, 2009). Searchinger et al. (2008) have estimated, for instance, that these land use impacts could, for some biofuel pathways, exceed the lifecycle carbon intensity of gasoline, thus contributing no GHG reduction benefits whatsoever. Biofuels made from waste materials, however, would have little or no land use effect since they require no land for growing. GHG impacts will depend, therefore, in part upon the percentage of available biomass resources that are assumed to be energy crops versus waste biomass. Even a small increase, though, in average biofuel lifecycle carbon intensity due to LUC (e.g. +15 gCO_2e/MJ) would double the carbon intensity assumed in this study, eliminating much of the GHG reduction potential in the scenarios. In sum, if supplies of low-GHG biofuels are significantly constrained for sustainability, technical, economic, or other reasons, then a multi-strategy portfolio approach with considerable penetration of electric-drive vehicles and decarbonized energy carriers (i.e., H_2 and electricity) may be the only real option for making emission reductions across all of transport.

Figure 2 compares fuel consumption and primary resource requirements in the three deep emission reduction scenarios. By aggressively improving vehicle efficiencies across all subsectors, large annual fuel savings can be achieved: 160-185 billion gge in 2050 relative to the *Reference* scenario, or the energy equivalent of 8.7-10 million barrels of oil per day (mbpd). Oil savings are greater in the *Electric-drive 50in50* and *Multi-Strategy 80in50* scenarios, owing to the penetration of higher efficiency electric-drive vehicles. The demand for fossil-based liquid fuels in the three scenarios is low enough to be supplied completely by projected domestic US oil production in 2050, either from conventional or unconventional sources.

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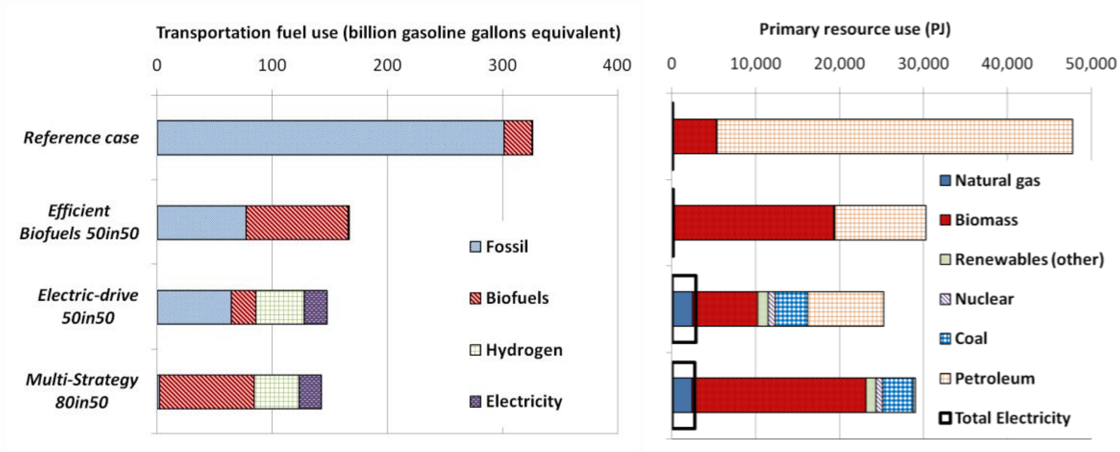
[3] Forestlands in the contiguous US could produce 368 million dry tons annually: fuelwood harvested from forests (52 million); residues from wood processing mills and pulp and paper mills (145 million); urban wood residues including construction and demolition debris (47 million); residues from logging and site clearing operations (64 million); and fuel treatment operations to reduce fire hazards (60 million). Agricultural lands could produce nearly 1 billion tons annually: annual crop residues (428 million); perennial crops (377 million); grains used for biofuels (87 million); and animal manures, process residues, and other miscellaneous feedstocks (106 million).

The results for primary resource requirements are similar to fuel consumption. Resource requirements in *Electric-drive 50in50* are the lowest of all due to higher end-use vehicle efficiencies. In addition, the diversity of primary resource types is much greater in *Electric-drive 50in50* and *Multi-Strategy 80in50* because the use of decarbonized energy carriers such as electricity and hydrogen provides significant resource flexibility and diversification. The exact resource mixes that are chosen for producing these energy carriers will ultimately be determined by policy, economics, and resource constraints, factors that will affect, and also be constrained by, the resulting carbon intensity of the energy carrier. Note that in contrast to the other two scenarios, *Efficient Biofuels 50in50* is heavily reliant on just two primary energy resources, petroleum and biomass.

Figure 2. **Transportation fuel use and primary resource consumption in 2050 by scenario (*Domestic* emissions)**



* Note: "Total Electricity" bar in the Primary resource use figure (right) refers to the total amount of electricity used for transportation purposes in the given scenario. Because electricity is not a primary resource, the bar is superimposed on top of the primary resource bars.

The EIA's business-as-usual projections for future domestic US energy production in 2030 are sufficient to meet the primary resource demands of the *50in50* and *80in50* scenarios (EIA, 2008a).[4] For biomass and renewable electricity generation, the scenario resource demands are well below the *untapped* supply potential using domestic resources (NREL, 2004; Perlack et al., 2005). Note that the total transportation-related electricity consumption estimates shown for each scenario in Figure 2 include electricity used for vehicle recharging and for hydrogen production and distribution. CO_2 capture from hydrogen and electricity production in the scenarios would necessitate storage requirements of at most 430 $MMTCO_2$ per year, well below the roughly 3,600,000 – 12,900,000 $MMTCO_2$ of storage capacity that is potentially available in US oil and gas reservoirs, unmineable coal seams, and deep saline formations (NETL, 2008).

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4. EIA's projections for domestic energy production in 2030 include: crude oil (12,699 PJ), natural gas (21,099 PJ), coal (30,202 PJ), biomass (8,570 PJ), total electric generation (17,599 PJ), nuclear power (10,093 PJ), and renewable power (1,991 PJ).

3.3.2 Overall emissions

The scenarios described here have been designed specifically to meet a goal of 50-80% reduction in *Domestic* emissions. Reducing *Overall* emissions by this amount requires even greater levels of implementation of advanced vehicle technologies, fuels substitution, and/or travel demand reduction. For example, in the *Efficient Biofuels 50in50* scenario, *Domestic* emissions are reduced by 50%, but *Overall* emissions are only reduced by 39%. In *Electric-drive 50in50* and *Multi-Strategy 80in50*, the *Domestic*/*Overall* breakdowns are 50/48% and 80/78%, respectively. If in the *Multi-Strategy 80in50* scenario, the *Overall* case were limited to the same quantity of biofuels and biomass as in the *Domestic* case (82 billion gge, 1.4 billion BDT), then *Overall* emissions would only be reduced by 68%. Achieving an 80% reduction in *Overall* emissions in this scenario by increasing biofuels utilization would require an additional 28 billion gge (+34%) for a total of 110 billion gge of biofuels (or 1.8 billion BDT of biomass, including H_2 production). In light of the surging growth of international passenger and goods movement and constraints on biomass resources, it appears it will be a more significant challenge to reduce *Overall* US transport sector emissions by as much as 80%. Considering the substantial efficiency improvements already assumed for air and marine transport, either a greater quantity of biofuels (perhaps from non-US sources) will be required, especially for aviation, or travel intensity in the international aviation and marine subsectors must be kept to levels not much higher than today's.

4. Study Conclusions

The scenarios presented in the paper illustrate the enormous challenges associated with making deep GHG reductions in the transportation sector. Our findings corroborate the growing understanding that no single strategy can reduce emissions quickly and inexpensively on the scale required. The *Silver Bullet* scenarios confirm results from other studies, showing that no one mitigation option can singlehandedly meet the ambitious GHG goals, especially since total travel demand in each subsector is expected to increase significantly by 2050. This puts a large burden on vehicle and fuel technologies to decarbonize, and by our estimates it is unreasonable to think a single technology approach can shoulder this burden entirely on its own, given the diversity of vehicle types and requirements in the transportation sector.

When multiple technological strategies are combined together in a portfolio approach, however – assuming widespread technical and institutional innovations – the potential for emission reductions could be great, as the *50in50* and *80in50* scenarios highlight. This mixed strategy approach would include (1) restraining the growth in travel demand with strong transport and land use planning policies, and (2) targeting advanced technologies and fuels to the subsectors where they are most feasible. Because multiple options are employed, the portfolio approach reduces the required level of vehicle and fuel technology development and usage for any given mitigation strategy. A portfolio approach also helps to reduce the sensitivity of GHG emissions to any one technology, resource, or behavioral change and the associated risks if the strategy does not flourish.

Though this analysis focuses mainly on *Domestic* emissions, the results of all of the scenarios show that meeting a 50-80% reduction in *Overall* emissions is more challenging. The main issue stems from the greater importance of the aviation and marine subsectors in international travel and the inherent challenge of decarbonizing these two subsectors.

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