Supporting Information

Achieving deep cuts in the carbon intensity of US automobile transportation by 2050: Complementary roles for electricity and biofuels

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Summary

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Figures

Tables

Equations

County-level datasets are too large to display. They are available by request from the corresponding author.

Methods

PHEV Deployment Scenario

EIA Annual Energy Outlook geographic regions:
New England, Mid-Atlantic, East North Central, West North Central, South Atlantic, East South Central, West South Central, Mountain, and Pacific

EIA Annual Energy Outlook vehicle types:
Conventional gasoline, conventional diesel, flex-fuel, CNG, CNG bi-fuel, hybrid-electric vehicle (HEV) gasoline, HEV diesel, PHEV 10-mi range, PHEV 40-mi range, electric vehicle (EV) 100 mi-range, EV 200-mi range, HFCV, liquefied petroleum gas, and liquefied petroleum gas bi-fuel

Equation S1 is used to approximate the proportion of US passenger car sales that are PHEVs between 2012 and 2050. To avoid allowing small fractions of vehicles to survive indefinitely on the road, all cars from a particular model year are assumed to have retired after 36 years. This assumption also prevents the scenario from requiring sales data from years too early for reliable data collection. With a 36-year maximum lifetime, sales data incorporated into the scenario begins in 1976. Numerical sales penetration results from the scenario are shown in Table S1.

Equation S1: PHEV penetration P of total US auto sales, where t = years elapsed since 2012

$$P(t) = \frac{1}{1.41(1 + e^{-0.25t+5})}$$

As vehicles are retired due to age, collisions, or other failures, new vehicles enter the passenger car fleet. Equation S2 presents our model of the fraction of new vehicles purchased during a particular year that remain on the road after a years. This model is based on conventional passenger cars, but is applied to all cars in the scenario, including PHEVs and FFVs. The functional life of Li-ion batteries that are used in PHEVs is not well understood. We assume that battery replacement will be more cost-effective than full vehicle replacement. Replacement batteries are expected to be comparable to the vehicle's original battery, and, aside from the possible need for battery replacement, PHEVs are not expected to have substantially different lifetimes than conventional vehicles. We do not account for regional variation in vehicle retirement rates.

Equation S2: Fraction of vehicles remaining, FVR, on the road where a = vehicle age in years [1]

$$FVR(a) = \frac{1}{1 + e^{-0.28(16.9-a)}}$$

Table S1: PHEV scenario results

Year	Total sales penetration	Total fleet penetration	Early adopter MSAs	Counties in top 20% by income	Early adopter states	Counties in top 50% by income	Counties in bottom 50% by income
2012	0%	0.05%	2.7%	0%	0%	0%	0%
2013	1%	0.09%	3.8%	0%	0%	0%	0%
2014	1%	0.14%	1.4%	0%	0%	0%	0%
2015	1%	0.20%	2.2%	0%	0%	0%	0%
2016	1%	0.29%	4.3%	0%	0%	0%	0%
2017	2%	0.39%	3.6%	0%	0%	0%	0%
2018	2%	0.53%	5.4%	0%	0%	0%	0%
2019	3%	0.70%	12.0%	0%	0%	0%	0%
2020	3%	0.92%	13.4%	1.5%	0%	0%	0%
2021	4%	1.2%	17.5%	5.6%	0%	0%	0%
2022	5%	1.5%	20.8%	8.8%	3.3%	0%	0%
2023	7%	2.0%	23.9%	11.9%	6.4%	0%	0%
2024	8%	2.5%	27.8%	15.8%	10.3%	0%	0%
2025	10%	3.1%	31.6%	19.7%	14.1%	3.8%	0%
2026	13%	3.9%	35.6%	23.6%	18.0%	7.7%	0%
2027	16%	4.9%	40.2%	28.2%	22.7%	12.4%	0%
2028	19%	6.0%	45.6%	33.6%	28.1%	17.8%	0%
2029	23%	7.3%	51.6%	39.6%	34.1%	23.8%	0%
2030	27%	8.8%	58.1%	46.2%	40.6%	30.3%	0%
2031	31%	10.6%	65.1%	53.2%	47.6%	37.3%	0%
2032	35%	12.5%	72.4%	60.4%	54.8%	44.5%	0%
2033	40%	14.7%	79.5%	67.5%	61.9%	51.6%	0%
2034	44%	17.0%	80%	75.8%	70.3%	60.0%	0%
2035	48%	19.6%	80%	80%	77.3%	67.0%	7.1%
2036	51%	22.2%	80%	80%	80%	72.7%	12.7%
2037	55%	25.0%	80%	80%	80%	78.3%	18.4%
2038	58%	27.9%	80%	80%	80%	80%	24.6%
2039	60%	30.8%	80%	80%	80%	80%	30.5%
2040	62%	33.7%	80%	80%	80%	80%	35.5%
2041	64%	36.6%	80%	80%	80%	80%	39.6%
2042	65%	39.5%	80%	80%	80%	80%	43.0%
2043	66%	42.3%	80%	80%	80%	80%	45.7%
2044	67%	44.9%	80%	80%	80%	80%	47.9%
2045	68%	47.5%	80%	80%	80%	80%	49.6%
2046	68%	49.9%	80%	80%	80%	80%	51.0%
2047	69%	52.2%	80%	80%	80%	80%	52.1%

2048	69%	54.3%	80%	80%	80%	80%	53.0%
2049	69%	56.3%	80%	80%	80%	80%	53.6%
2050	70%	58.1%	80%	80%	80%	80%	54.2%

MSAs in the top 15 based on new hybrids per household in 2009 were categorized as "early adopters MSA" and the top 15 states in terms of new hybrids per person were early adopter states. See http://www.hybridcars.com/hybrid-sales-dashboard/december-2009-dashboard.html.

Vehicle technology:
Recently introduced PHEVs vary widely in their battery ranges. The 2013 Chevrolet Volt is reported to have a 61-km all-electric range, while the Toyota Prius PHEV can run on electricity plus a small amount of gasoline for approximately 18 km before switching to gasoline-only drive. Both models are priced between $32,000 and $40,000. [2] The new Honda Accord PHEV is similar to the Prius, with an all-electric range between 16 and 24 km. [3]

Fuel economy:
Historical fuel economy data extending back to model year 1976 and projections through 2050 are used to estimate current and future automotive energy demand. Historical fuel economy data through 2008 are from the US Bureau of Transportation Statistics. [4] Data for new vehicles purchased between 2009 and 2012, as well as projections out to 2035, are from the 2012 EIA Annual Energy Outlook. [5] Since the EIA fuel economy projections are essentially linear in the long-term, 2036-2050 estimates are based on the slope from the 2025-2035 EIA projections.

Driving behavior

Equation S3 is combined with Equation S2 to estimate total fleet VKT. Both equations are applied consistently throughout the continental United States and across vehicle types.

Equation S3: Vehicle-kilometers traveled per automobile per year, *VKT(a),* by vehicle age where a = vehicle age in years [1]

$$VKT(a) = 25{,}750e^{-0.04a}$$

The National Household Transportation Survey (NHTS) completes additional sampling in some states, which allows for state-specific results. In other states, national averages (excluding the states with additional sampling information) were used to assign typical driving behavior to counties based on Metropolitan Statistical Area (MSA) size and urban/rural categorization. MSA names and breakdown of MSAs into counties are provided by the US Census (2009 data: http://www.census.gov/population/metro/data/def.html). Driving behavior and vehicle occupancy in all non-MSA counties were calculated using a population-weighted combination of urban and rural non-MSA county data from the NHTS. This method includes all counties in the contiguous US.

Data were also incorporated at a state level based on the Transportation Energy Data Book Ed. 30 (2011). The underlying analysis considered the number of state EV incentives, number of HEV/PHEV incentives, and number of EV/PHEV recharging stations.

Battery range impacts on fraction of VKT driven on electricity vs. liquid fuel:
The resulting distribution of the fraction of VKT traveled in all-electric mode by range, using the NHTS data, is shown in Figure S1.

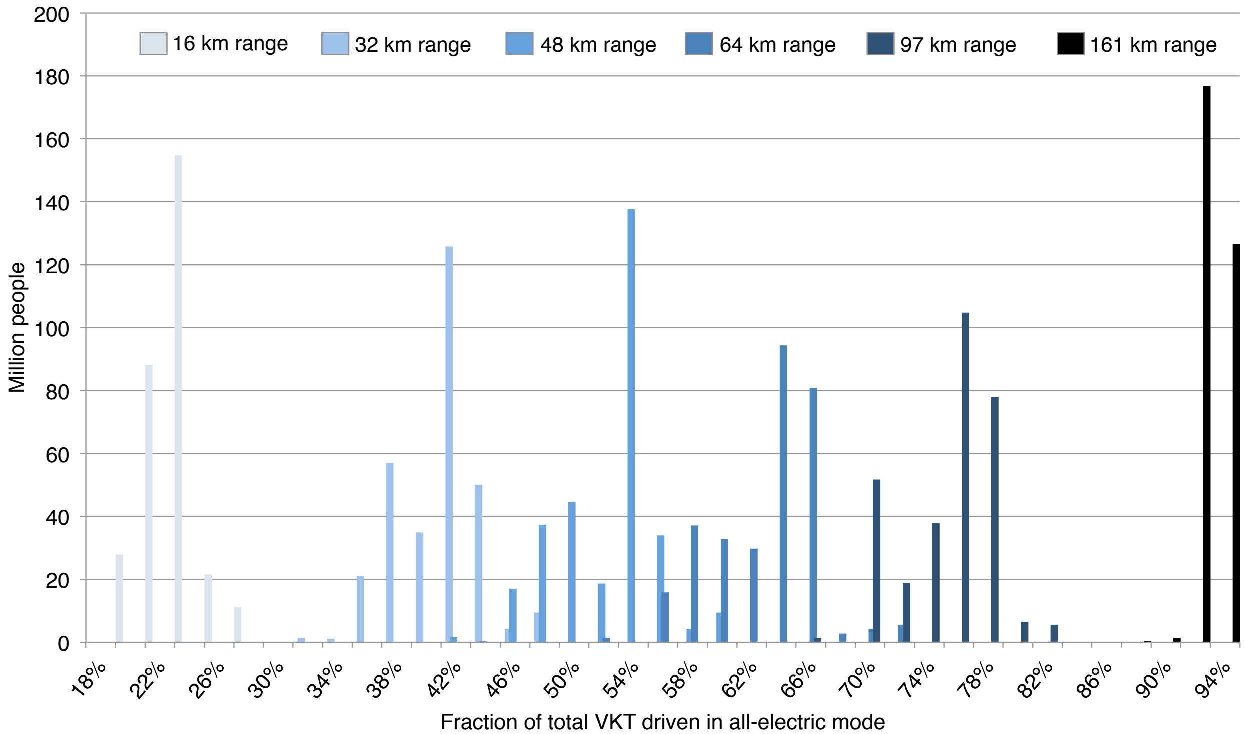

Figure S1: Fraction of VKT driven in all-electric mode in the US, by PHEV battery range and population

Cellulosic ethanol production scenario

The ability to process multiple feedstocks facilitates successful scale-up of cellulosic biofuels. Increased flexibility allows biorefinery operators to reduce transportation costs by drawing from locally available biomass resources, avoid the need for long-term biomass storage by taking advantage of different harvest seasons, and protect themselves against the risk of significant supply disruption owing to crop failure.[6] However, because the composition of each feedstock differs, processing multiple feedstocks is technical more challenging and potentially more expensive than relying on a single biomass type. We have limited this scenario to herbaceous feedstocks only, with the assumption that biorefineries will be capable of processing combinations of the three when necessary.

Biomass production in each county is assumed to have sufficient access to transportation infrastructure if its centroid is located within 25 km of a rail line, the more affordable transportation option on a Mg-km basis.[7] We calculate that, on average, a unit of biomass travels 75 km by rail between farm and biorefinery. Although rail is the focus of the analysis, truck transportation may be more attractive for some biorefineries, which will increase the transportation-related GHG emissions but have a minimal impact on the final results.[8, 9]

Biomass loss factors associated with harvesting, baling, bale transport, and storage are adapted from Shastri et al. [10] According to Shastri et al. [10], storing Miscanthus for a year results in dry matter losses ranging from 1% to 25% depending on the type of storage facility. Each on-farm handling process typically has a biomass loss rate of 5%.[10] For the biomass production scenario presented in this paper, the total field-to-refinery loss rate is estimated by Scown et al.[8] to be 20%.

The minimum commercial cellulosic biorefinery size is set to 136 million liters of ethanol/year, which corresponds to the size of Verenium's first commercial scale cellulosic biorefinery, previously planned for construction in Highlands County, FL. [11] The minimum biorefinery size is smaller than the 231 million liter/year hypothetical plant modeled in Humbird et al. [12] A location is considered a viable biorefinery candidate for further analysis if it is within 100 km of sufficient biomass production to satisfy 100% of its annual needs, or if it lies in a county with one or more existing corn ethanol facilities and is within 25 km of a rail line. Of the 3,141 counties considered as biorefinery sites, 1,491 counties are within 100 km of sufficient biomass production, and 1,446 of those counties have sufficient access to rail infrastructure.

Accounting for regional and seasonal variations in the E85 blend wall, which varies between an annual average of 77 and 81% by region, [13] fuel blending terminals in the United States could be prepared to receive up to 3.0 trillion MJ (130 billion liters) of ethanol annually in 2050, assuming that all gasoline vehicles are flex-fuel.

Calculating biorefinery-to-terminal distances is a large optimization problem that connects all 1254 terminals with 107 biorefineries to minimize system-wide mass distances transported, similar to the analysis completed by Parker et al. [14] for the western US. After being produced at biorefineries, the typical liter of ethanol travels 470 km by rail before reaching a blending terminal. Strogen et al. [9] use a distance more than twice as large (1080 km), but their scenario is based on a 10% blend wall and current corn ethanol production only. If all fuel terminals are ethanol-equipped, the average liter of ethanol is estimated to travel 45 km by highway between terminals and fueling stations.

Most freight transportation also involves a fraction of km traveled during which the train or truck is empty, known as backhaul. For fuel transportation and distribution, the backhaul distance can be approximated as 100% of the original distance; this contribution is accounted for in the emission factors taken from Strogen et al. [15]

Although the E85 label seems to imply a blend of 85% ethanol and 15% gasoline, the true blend varies regionally and seasonally, with lower ethanol content in colder climates and higher ethanol content in warmer climates. Annual average E85 blends are calculated to vary between 77 and 81%. County-level annual average blend data are used to determine the fraction of liquid fuel demand that can be satisfied with ethanol. Data on actual blend wall by county are available for download at cscown.com/supporting-information.

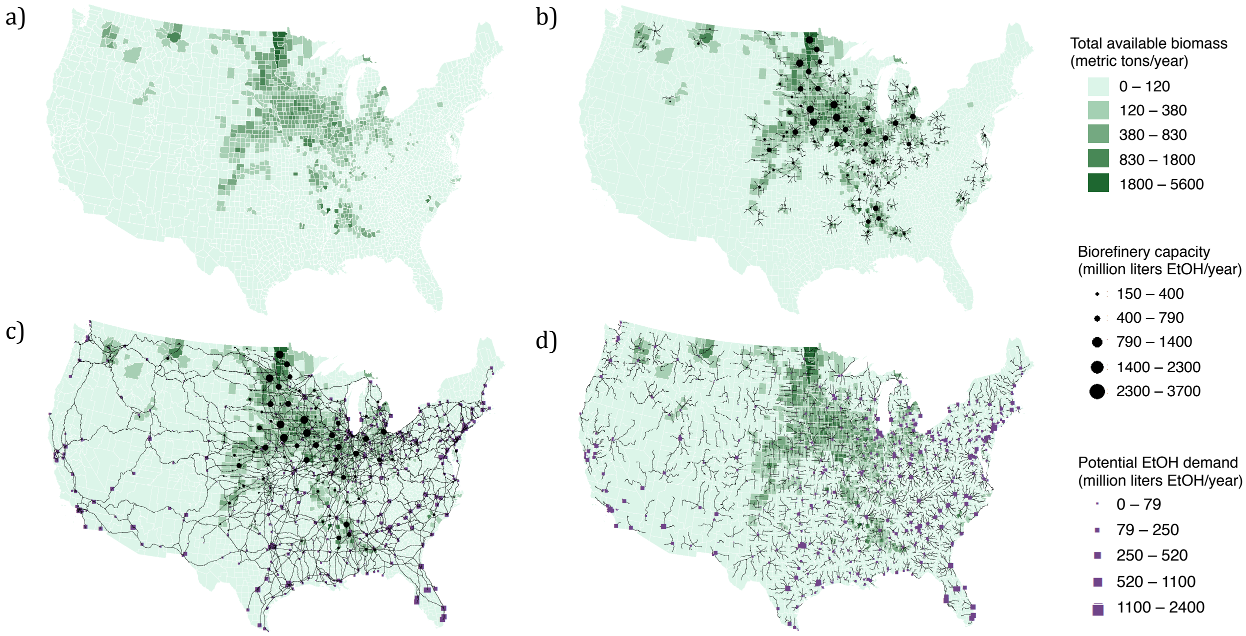

Figure S2: a) Total available Miscanthus, corn stover, and wheat straw at 20% moisture; b) Optimal biorefinery locations and capacities with rail paths for biomass delivery; c) Rail paths connecting the biorefineries to fuel terminals; d) Fuel terminals sized by demand, where 100% of each county demand is allocated to nearest fuel terminal, and highway paths to county centroids

Electricity and liquid fuel demand for PHEVs

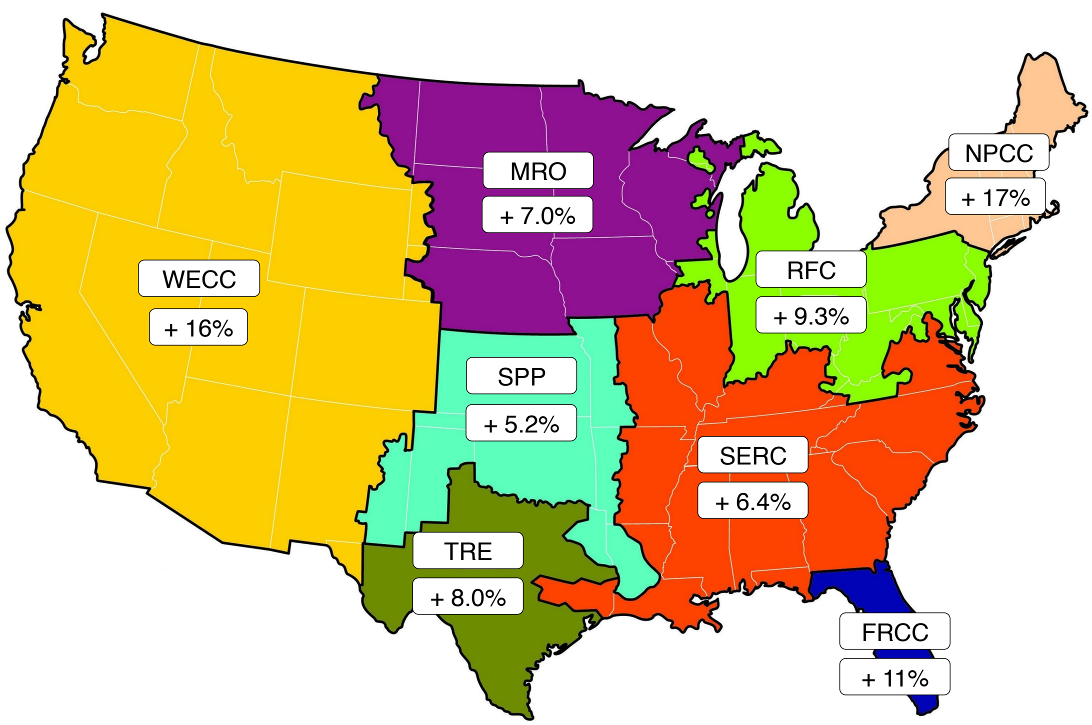

Figure S3: Projected increase in electricity demand by NERC region between 2009 and 2050, based on the PHEV market adoption scenario

Lifecycle greenhouse gas inventory

Notes on other alternative fuels:
The GHG footprint of hydrogen may vary significantly depending on whether it is produced using conventional steam reforming of methane or using electrolysis of water powered by renewables or by nuclear power. We assume that all hydrogen is produced via methane reforming at centralized plants. (Because of its small role in the scenario presented in this paper, hydrogen production assumptions have a negligible effect on the results.) Assumptions related to CNG and LPG also have negligible influence on overall results.

Biorefinery lignin utilization:
Although some biorefineries may choose to send the lignin to be pelletized and sold to coal-fired power plants, we assume that all biorefineries opt to burn their lignin onsite and use electricity exports to offset natural gas-fired power generation.

Table S2: Greenhouse gas emission factors, assumptions, and data sources by fuel type

Energy source	GHG emission factor (gCO_2e/MJ^*)	Assumptions	Data sources
Gasoline	86	• Average US gasoline	GREET[16]
Diesel	89	• Average US diesel	GREET[16]
Electricity	3 - 150	• Wind power represents low end • Current natural gas represents high end	Pacca and Horvath, eGRID2012[17, 18]
Corn grain ethanol	81	• Average US corn grain ethanol • iLUC impacts not included	GREET1_2012, Farrell et al.[16, 19]
Crop residue ethanol	8	• Corn stover used to represent herbaceous crop residue • Biorefinery power exports offset natural gas power	Humbird et al., Spatari et al.[12, 20]
Miscanthus ethanol	-9.5 - 5	• Low case: Converted agricultural soil able to sequester carbon • High/average case: Converted agricultural soil in long-term equilibrium • Biorefinery power exports offset natural gas power	Scown et al. [8]
CNG	75	• Average US CNG	GREET[16]
LPG	78	• Average US LPG	GREET[16]
Hydrogen	140	• Hydrogen production via methane reforming occurs at centralized plants	GREET[16]

*Fuel energy contents based on higher heating value (HHV), where applicable.

Results

Electricity and liquid fuel demand for PHEVs

Table S3: US passenger car fleet total energy use scenario results (trillion MJ/y)

Year	Gasoline	Corn ethanol	Cellulosic ethanol	Diesel	Electricity	CNG	H	LPG
2012	6.74	0.49	0.0	0.08	7.8×10^{-4}	2.1×10^{-3}	2.1×10^{-10}	1.3×10^{-3}
2013	6.63	0.49	3.6×10^{-2}	0.10	1.2×10^{-3}	2.8×10^{-3}	5.1×10^{-9}	1.7×10^{-3}
2014	6.55	0.49	7.1×10^{-2}	0.13	2.3×10^{-3}	3.4×10^{-3}	1.5×10^{-8}	2.2×10^{-3}
2015	6.47	0.49	0.11	0.16	3.7×10^{-3}	4.1×10^{-3}	1.0×10^{-4}	2.6×10^{-3}
2016	6.39	0.49	0.14	0.19	5.6×10^{-3}	4.7×10^{-3}	2.1×10^{-4}	3.1×10^{-3}
2017	6.32	0.49	0.18	0.22	8.1×10^{-3}	5.3×10^{-3}	3.0×10^{-4}	3.5×10^{-3}
2018	6.23	0.49	0.21	0.24	1.2×10^{-2}	5.8×10^{-3}	5.0×10^{-4}	3.9×10^{-3}
2019	6.16	0.49	0.25	0.27	1.5×10^{-2}	6.3×10^{-3}	7.0×10^{-4}	4.2×10^{-3}
2020	6.10	0.49	0.28	0.29	2.1×10^{-2}	6.8×10^{-3}	8.7×10^{-4}	4.6×10^{-3}
2021	6.04	0.49	0.32	0.32	2.8×10^{-2}	7.2×10^{-3}	1.1×10^{-3}	4.9×10^{-3}
2022	5.99	0.49	0.36	0.34	3.6×10^{-2}	7.7×10^{-3}	1.2×10^{-3}	5.2×10^{-3}
2023	5.95	0.49	0.39	0.36	4.7×10^{-2}	8.1×10^{-3}	1.4×10^{-3}	5.5×10^{-3}
2024	5.91	0.49	0.43	0.38	6.0×10^{-2}	8.4×10^{-3}	1.6×10^{-3}	5.8×10^{-3}
2025	5.86	0.49	0.46	0.40	7.6×10^{-2}	8.8×10^{-3}	1.7×10^{-3}	6.1×10^{-3}
2026	5.82	0.49	0.50	0.42	9.6×10^{-2}	9.1×10^{-3}	1.9×10^{-3}	6.3×10^{-3}
2027	5.76	0.49	0.53	0.44	0.12	9.4×10^{-3}	2.0×10^{-3}	6.6×10^{-3}
2028	5.68	0.49	0.57	0.45	0.15	9.7×10^{-3}	2.3×10^{-3}	6.8×10^{-3}
2029	5.58	0.49	0.60	0.47	0.18	9.9×10^{-3}	2.4×10^{-3}	7.0×10^{-3}
2030	5.46	0.49	0.64	0.48	0.22	1.0×10^{-2}	2.5×10^{-3}	7.2×10^{-3}
2031	5.32	0.49	0.68	0.49	0.27	1.0×10^{-2}	2.6×10^{-3}	7.4×10^{-3}
2032	5.15	0.49	0.71	0.50	0.32	1.1×10^{-2}	2.7×10^{-3}	7.5×10^{-3}
2033	4.95	0.49	0.75	0.51	0.38	1.1×10^{-2}	2.8×10^{-3}	7.7×10^{-3}
2034	4.74	0.49	0.78	0.52	0.45	1.1×10^{-2}	2.8×10^{-3}	7.8×10^{-3}
2035	4.51	0.49	0.82	0.52	0.52	1.1×10^{-2}	2.9×10^{-3}	7.9×10^{-3}
2036	4.27	0.49	0.85	0.53	0.59	1.1×10^{-2}	3.0×10^{-3}	8.0×10^{-3}
2037	4.02	0.49	0.89	0.54	0.67	1.1×10^{-2}	3.0×10^{-3}	8.1×10^{-3}
2038	3.76	0.49	0.92	0.54	0.75	1.1×10^{-2}	3.1×10^{-3}	8.2×10^{-3}
2039	3.49	0.49	0.96	0.55	0.83	1.1×10^{-2}	3.1×10^{-3}	8.3×10^{-3}
2040	3.23	0.49	1.0	0.55	0.91	1.1×10^{-2}	3.2×10^{-3}	8.4×10^{-3}
2041	2.96	0.49	1.0	0.56	0.99	1.1×10^{-2}	3.2×10^{-3}	8.5×10^{-3}
2042	2.71	0.49	1.1	0.56	1.07	1.1×10^{-2}	3.2×10^{-3}	8.5×10^{-3}
2043	2.46	0.49	1.1	0.57	1.15	1.2×10^{-2}	3.3×10^{-3}	8.6×10^{-3}
2044	2.22	0.49	1.1	0.57	1.23	1.2×10^{-2}	3.3×10^{-3}	8.7×10^{-3}
2045	1.99	0.49	1.2	0.58	1.30	1.2×10^{-2}	3.3×10^{-3}	8.7×10^{-3}

2046	1.78	0.47	1.2	0.58	1.38	1.2×10^{-2}	3.3×10^{-3}	8.8×10^{-3}
2047	1.65	0.40	1.2	0.59	1.44	1.2×10^{-2}	3.3×10^{-3}	8.8×10^{-3}
2048	1.53	0.33	1.3	0.59	1.51	1.2×10^{-2}	3.4×10^{-3}	8.9×10^{-3}
2049	1.42	0.26	1.3	0.59	1.57	1.2×10^{-2}	3.7×10^{-3}	9.0×10^{-3}
2050	1.33	0.20	1.4	0.60	1.63	1.2×10^{-2}	3.7×10^{-3}	9.0×10^{-3}

Table S4: Distribution of passenger car-related electricity consumption by NERC region

Year	ASCC	FRCC	HICC	MRO	NPCC	RFC	SERC	SPP	TRE	WECC
2012	0.2%	7.3%	0.5%	4.5%	10.5%	24.0%	18.7%	3.5%	5.6%	25.1%
2013	0.2%	5.0%	0.3%	3.1%	13.1%	16.9%	12.9%	2.4%	5.1%	41.0%
2014	0.2%	3.8%	0.3%	2.3%	14.5%	13.2%	9.8%	1.8%	4.9%	49.2%
2015	0.2%	4.9%	0.3%	3.0%	13.7%	16.7%	12.5%	2.4%	5.1%	41.1%
2016	0.2%	5.4%	0.3%	3.3%	13.4%	18.1%	13.7%	2.6%	5.2%	37.8%
2017	0.2%	5.4%	0.3%	3.2%	13.5%	17.9%	13.5%	2.5%	5.2%	38.3%
2018	0.2%	5.7%	0.4%	3.4%	13.3%	18.8%	14.2%	2.6%	5.3%	36.2%
2019	0.2%	5.9%	0.4%	3.4%	13.2%	19.0%	14.4%	2.7%	5.4%	35.6%
2020	0.2%	5.5%	0.3%	3.1%	13.5%	17.7%	13.4%	2.5%	5.3%	38.4%
2021	0.2%	5.2%	0.4%	3.0%	13.8%	17.4%	12.9%	2.3%	5.3%	39.4%
2022	0.2%	4.6%	0.4%	2.8%	14.5%	17.3%	12.3%	2.1%	5.4%	40.3%
2023	0.2%	4.1%	0.5%	2.8%	14.9%	17.7%	12.0%	1.9%	5.3%	40.5%
2024	0.3%	3.7%	0.5%	2.6%	15.2%	17.9%	11.6%	1.8%	5.2%	41.2%
2025	0.3%	3.2%	0.6%	2.5%	15.3%	18.2%	11.3%	1.6%	5.0%	41.9%
2026	0.3%	2.8%	0.7%	2.5%	15.3%	18.6%	11.2%	1.5%	5.0%	42.2%
2027	0.3%	2.6%	0.7%	2.6%	15.2%	18.9%	11.2%	1.4%	5.0%	42.1%
2028	0.3%	2.4%	0.7%	2.7%	15.0%	19.3%	11.3%	1.4%	5.1%	41.8%
2029	0.3%	2.3%	0.7%	2.8%	14.8%	19.7%	11.5%	1.4%	5.2%	41.3%
2030	0.3%	2.1%	0.8%	2.9%	14.6%	20.0%	11.7%	1.4%	5.3%	40.9%
2031	0.3%	2.0%	0.8%	3.0%	14.4%	20.3%	11.9%	1.4%	5.5%	40.5%
2032	0.3%	2.0%	0.8%	3.1%	14.2%	20.5%	12.0%	1.4%	5.6%	40.2%
2033	0.3%	1.9%	0.8%	3.2%	14.0%	20.6%	12.2%	1.4%	5.7%	39.9%
2034	0.3%	1.8%	0.8%	3.3%	13.8%	20.7%	12.3%	1.4%	5.8%	39.7%
2035	0.3%	1.8%	0.8%	3.3%	13.7%	20.9%	12.5%	1.4%	5.9%	39.4%
2036	0.3%	1.9%	0.8%	3.4%	13.5%	21.0%	12.7%	1.4%	6.0%	39.0%
2037	0.3%	2.0%	0.8%	3.5%	13.3%	21.1%	13.0%	1.5%	6.1%	38.3%
2038	0.3%	2.3%	0.8%	3.6%	13.0%	21.2%	13.4%	1.6%	6.2%	37.5%
2039	0.3%	2.6%	0.7%	3.6%	12.8%	21.3%	13.8%	1.7%	6.3%	36.7%
2040	0.3%	2.9%	0.7%	3.7%	12.6%	21.4%	14.3%	1.8%	6.4%	35.8%
2041	0.3%	3.3%	0.7%	3.7%	12.4%	21.4%	14.7%	2.0%	6.5%	34.9%
2042	0.3%	3.7%	0.7%	3.8%	12.2%	21.5%	15.2%	2.1%	6.6%	34.0%
2043	0.3%	4.0%	0.7%	3.8%	12.0%	21.5%	15.6%	2.2%	6.7%	33.2%
2044	0.3%	4.3%	0.7%	3.8%	11.8%	21.5%	16.0%	2.3%	6.7%	32.5%

2045	0.3%	4.6%	0.7%	3.9%	11.7%	21.5%	16.3%	2.4%	6.8%	31.9%
2046	0.3%	4.9%	0.6%	3.9%	11.5%	21.5%	16.6%	2.5%	6.8%	31.4%
2047	0.3%	5.1%	0.6%	3.9%	11.4%	21.5%	16.8%	2.6%	6.9%	30.8%
2048	0.3%	5.3%	0.6%	3.9%	11.3%	21.5%	17.1%	2.6%	6.9%	30.4%
2049	0.3%	5.5%	0.6%	3.9%	11.2%	21.5%	17.3%	2.7%	6.9%	30.0%
2050	0.3%	5.7%	0.6%	4.0%	11.2%	21.5%	17.5%	2.7%	6.9%	29.6%

Lifecycle greenhouse gas emissions

New natural-gas power plants are assumed to be combined-cycle (NGCC) with an efficiency of 50.8%.[21]

Table S5: Fleet average greenhouse gas intensity for US automobiles (g CO_2e/VKT)

Year	CNG	H	LPG	Diesel	Gasoline	Corn Ethanol	Cellulosic Ethanol	Electricity	Positive Error Bar	Negative Error Bar
2012	0.07	0.00	0.04	2.9	255	17.4	0.00	0.1	0.00	0.1
2013	0.09	0.00	0.06	4.0	245	17.3	0.10	0.1	0.00	0.4
2014	0.11	0.00	0.07	5.1	244	17.1	0.21	0.1	0.00	0.9
2015	0.13	0.01	0.09	6.2	238	16.9	0.31	0.2	0.01	1.3
2016	0.15	0.01	0.10	7.2	231	16.6	0.40	0.3	0.02	1.7
2017	0.16	0.01	0.11	8.0	224	16.3	0.49	0.5	0.04	2.2
2018	0.18	0.03	0.12	8.8	218	16.0	0.58	0.6	0.1	2.6
2019	0.19	0.04	0.13	9.5	211	15.8	0.67	0.8	0.1	3.1
2020	0.20	0.04	0.14	10.2	205	15.5	0.75	1.1	0.2	3.7
2021	0.21	0.05	0.15	10.7	199	15.2	0.82	1.4	0.2	4.3
2022	0.22	0.06	0.15	11.3	194	14.9	0.90	1.8	0.3	4.9
2023	0.22	0.06	0.16	11.7	188	14.6	0.97	2.2	0.5	5.5
2024	0.23	0.07	0.16	12.1	183	14.2	1.03	2.7	0.6	6.2
2025	0.23	0.08	0.17	12.5	178	13.9	1.10	3.3	0.8	7.0
2026	0.24	0.08	0.17	12.8	173	13.7	1.16	4.0	1.1	7.9
2027	0.24	0.09	0.17	13.1	168	13.4	1.21	4.8	1.4	8.9
2028	0.24	0.09	0.18	13.3	162	13.1	1.27	5.7	1.9	10.1
2029	0.24	0.09	0.18	13.5	157	12.9	1.33	6.8	2.4	11.3
2030	0.24	0.10	0.18	13.7	151	12.7	1.38	8.0	3.1	12.7
2031	0.24	0.10	0.18	13.8	145	12.5	1.43	9.3	3.9	14.2
2032	0.24	0.10	0.18	13.8	138	12.3	1.49	10.7	4.8	15.8
2033	0.25	0.10	0.18	13.9	131	12.2	1.54	12.2	5.9	17.5
2034	0.25	0.11	0.19	14.0	124	12.0	1.60	13.8	7.1	19.3
2035	0.25	0.11	0.19	14.0	117	11.9	1.65	15.4	8.5	21.1
2036	0.25	0.11	0.19	14.0	109	11.8	1.70	17.0	10.1	22.8
2037	0.25	0.11	0.19	14.0	102	11.6	1.76	18.6	11.7	24.6
2038	0.25	0.11	0.19	14.1	94.2	11.5	1.81	20.0	13.5	26.2

2039	0.24	0.11	0.19	14.1	86.7	11.4	1.86	21.4	15.4	27.8
2040	0.24	0.11	0.19	14.1	79.5	11.3	1.91	22.7	17.4	29.2
2041	0.24	0.11	0.19	14.1	72.4	11.2	1.97	23.8	19.4	30.5
2042	0.24	0.11	0.19	14.1	65.6	11.1	2.02	24.8	21.6	31.7
2043	0.24	0.11	0.19	14.1	59.1	11.0	2.07	25.7	23.7	32.7
2044	0.24	0.11	0.19	14.1	52.9	11.0	2.12	26.3	25.9	33.6
2045	0.24	0.11	0.19	14.1	47.0	10.9	2.17	26.9	28.1	34.3
2046	0.24	0.11	0.19	14.1	41.9	10.5	2.22	27.2	30.4	34.8
2047	0.24	0.11	0.19	14.1	38.5	8.8	2.27	27.5	32.6	35.2
2048	0.24	0.11	0.19	14.1	35.4	7.2	2.32	27.5	34.8	35.5
2049	0.24	0.11	0.19	14.1	32.7	5.7	2.36	27.5	36.9	35.5
2050	0.24	0.11	0.19	14.1	30.3	4.3	2.41	27.2	39.0	35.5

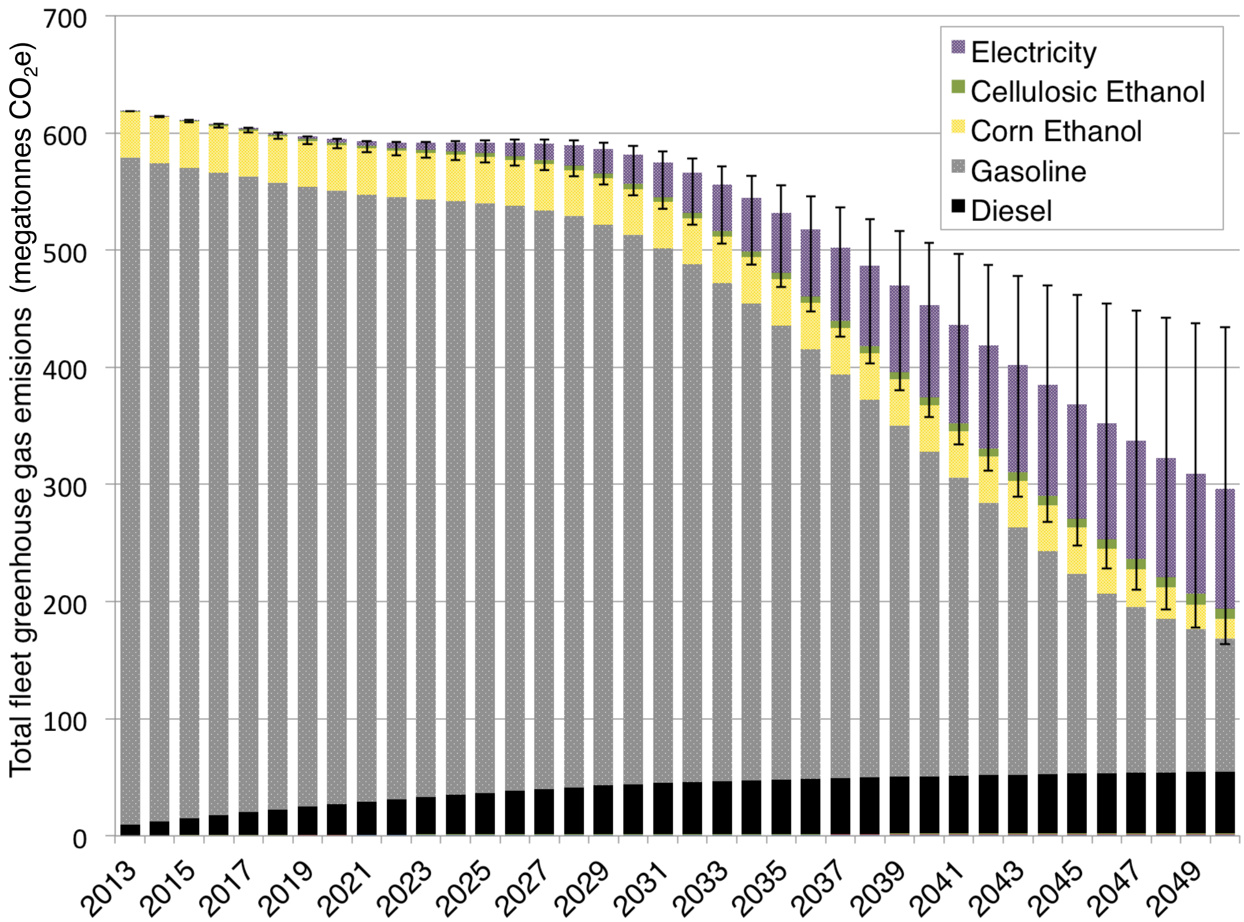

Figure S4: Fleet total greenhouse gas emissions (megatonnes CO_2e per year). Error bars reflect variability in emissions from cellulosic ethanol production and electricity generation.

Table S6: Fleet total greenhouse gas emissions for US automobiles (megatonnes CO_2e per year)

Year	CNG	H	LPG	Diesel	Gasoline	Corn Ethanol	Cellulosic Ethanol	Electricity	Positive Error	Negative Error Bar

									Bar	
2012	0.16	0.00	0.10	6.7	579	39.4	0.0	0.1	0.0	0.1
2013	0.21	0.00	0.13	9.2	569	39.4	0.2	0.2	0.0	1.0
2014	0.26	0.00	0.17	11.8	562	39.4	0.5	0.3	0.0	2.0
2015	0.31	0.01	0.20	14.5	555	39.4	0.7	0.5	0.0	3.0
2016	0.35	0.03	0.24	17.1	549	39.4	1.0	0.8	0.1	4.1
2017	0.39	0.04	0.27	19.4	542	39.4	1.2	1.2	0.1	5.2
2018	0.43	0.06	0.30	21.7	535	39.4	1.4	1.6	0.2	6.5
2019	0.47	0.09	0.33	23.9	529	39.4	1.7	2.1	0.3	7.8
2020	0.51	0.11	0.36	26.0	524	39.4	1.9	2.8	0.4	9.4
2021	0.54	0.13	0.38	27.9	519	39.4	2.1	3.7	0.6	11.1
2022	0.57	0.15	0.40	29.9	514	39.4	2.4	4.8	0.9	12.9
2023	0.60	0.17	0.43	31.8	511	39.4	2.6	6.0	1.2	15.0
2024	0.63	0.20	0.45	33.6	507	39.4	2.9	7.5	1.7	17.3
2025	0.66	0.22	0.47	35.4	503	39.4	3.1	9.3	2.3	19.9
2026	0.68	0.24	0.49	37.0	499	39.4	3.3	11.5	3.2	22.9
2027	0.70	0.25	0.51	38.6	494	39.4	3.6	14.1	4.3	26.3
2028	0.72	0.27	0.53	40.0	487	39.4	3.8	17.2	5.7	30.2
2029	0.74	0.29	0.55	41.3	479	39.4	4.1	20.7	7.4	34.6
2030	0.76	0.30	0.56	42.5	469	39.4	4.3	24.8	9.6	39.5
2031	0.77	0.32	0.58	43.5	456	39.4	4.5	29.3	12.2	44.8
2032	0.78	0.33	0.59	44.3	442	39.4	4.8	34.3	15.4	50.6
2033	0.79	0.34	0.60	45.1	425	39.4	5.0	39.6	19.1	56.7
2034	0.80	0.35	0.61	45.8	407	39.4	5.2	45.3	23.5	63.2
2035	0.81	0.36	0.62	46.4	387	39.4	5.5	51.2	28.3	69.9
2036	0.82	0.37	0.63	47.1	366	39.4	5.7	57.1	33.8	76.6
2037	0.83	0.37	0.63	47.6	345	39.4	6.0	62.9	39.8	83.3
2038	0.84	0.38	0.64	48.1	322	39.4	6.2	68.6	46.3	89.7
2039	0.85	0.38	0.65	48.6	300	39.4	6.4	74.0	53.2	95.9
2040	0.85	0.39	0.65	49.1	277	39.4	6.7	79.0	60.6	101.8
2041	0.86	0.39	0.66	49.5	255	39.4	6.9	83.7	68.3	107.3
2042	0.87	0.40	0.67	49.9	232	39.4	7.1	87.9	76.4	112.3
2043	0.87	0.40	0.67	50.3	211	39.4	7.4	91.6	84.7	116.9
2044	0.88	0.41	0.68	50.7	190	39.4	7.6	94.8	93.3	120.9
2045	0.88	0.41	0.68	51.1	171	39.4	7.9	97.4	102.0	124.3
2046	0.89	0.41	0.69	51.4	153	38.3	8.1	99.5	110.9	127.2
2047	0.90	0.42	0.69	51.8	142	32.3	8.3	101.1	119.8	129.6
2048	0.90	0.42	0.69	52.1	131	26.5	8.6	102.1	128.9	131.4
2049	0.91	0.42	0.70	52.5	122	21.1	8.8	102.5	137.8	132.6
2050	0.91	0.42	0.70	52.8	114	16.3	9.1	102.3	146.6	133.2

References

(1) Bandivadekar, A.; Bodek, K.; Cheah, L.; Evans, C.; Groode, T.; Heywood, J.; Kasseris, E.; Kromer, M.; Weiss, M. *On the road to 2035: Reducing transportation's petroleum consumption and GHG emissions*; LFEE 2008-05 RP; MIT Laboratory for Energy and the Environment: Cambridge, MA, 2008 (accessed March 27, 2013). http://web.mit.edu/sloan-auto-lab/research/beforeh2/otr2035/On%20the%20Road%20in%202035_MIT_July%202008.pdf.

(2) http://www.fueleconomy.gov. U.S. Department of Energy, U.S. Environmental Protection Agency. 2012 (accessed December 17, 2012). http://www.fueleconomy.gov/feg/phevsbs.shtml.

(3) Over 100 MPGe: 2014 Honda Accord PHEV in Photos. 2012 (accessed December 17, 2012). http://wot.motortrend.com/over-100-mpge-2014-honda-accord-phev-in-photos-261751.html - axzz2FM6xEAAS.

(4) *National Transportation Statistics*; US Department of Transportation: Washington, DC, 2011 (accessed March 27, 2013). http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/index.html.

(5) *Annual Energy Outlook 2012*; US Energy Information Administration: Washington, DC, 2012 (accessed December 12, 2012). http://www.eia.gov/forecasts/archive/aeo12/index.cfm.

(6) Zhu, X.; Yao, Q., Logistics system design for biomass-to-bioenergy industry with multiple types of feedstocks. *Bioresour. Technol.* 2011, 102 (23), 10936-10945.

(7) *Strategic Development of Bioenergy in the Western States: Development of Supply Scenarios Linked to Policy Recommendations*; U.S. Department of Energy, U.S. Department of Agriculture: Washington, DC, 2008 (accessed March 27, 2013). http://www.arb.ca.gov/fuels/lcfs/062708wga_ucd.pdf.

(8) Scown, C. D.; Nazaroff, W. W.; Mishra, U.; Strogen, B.; Lobscheid, A. B.; Masanet, E.; Santero, N. J.; Horvath, A.; McKone, T. E., Lifecycle greenhouse gas implications of US national scenarios for cellulosic ethanol production. *Environ. Res. Lett.* **2012,** *7* (1), 014011.

(9) Strogen, B.; Horvath, A.; McKone, T. E., Fuel miles and the blend wall: Costs and emissions from ethanol distribution in the United States. *Environ. Sci. Technol.* **2012,** *46* (10), 5285-5293.

(10) Shastri, Y. N.; Hansen, A. C.; Rodriguez, L. F.; Ting, K. C., Optimization of Miscanthus harvesting and handling as an energy crop: BioFeed Model application. *Biol. Eng.* **2010,** *3* (1), 37-69.

(11) Verenium Corporation announces first commercial cellulosic ethanol project. 2012 (accessed October 10, 2012). http://ir.verenium.com/releasedetail.cfm?ReleaseID=412258.

(12) Humbird, D.; Davis, R.; Tao, L.; Kinchin, C.; Hsu, D.; Aden, A.; Schoen, P.; Lukas, J.; Olthof, B.; Worley, M.; Sexton, D.; Dudgeon, D. *Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol*; NREL/TP-5100-47764; National Renewable Energy Laboratory: Golden, CO, 2011 (accessed March 27, 2013). http://www.nrel.gov/docs/fy11osti/47764.pdf.

(13) *E15 Retailer Handbook*; Renewable Fuels Association: Washington, DC, 2012 (accessed

March 27, 2013). http://ethanolrfa.3cdn.net/11bb6763e853b9e471_izm62udch.pdf.
(14) Parker, N.; Tittmann, P.; Hart, Q.; Nelson, R.; Skog, K.; Schmidt, A.; Gray, E.; Jenkins, B., Development of a biorefinery optimized biofuel supply curve for the Western United States. *Biomass Bioenergy* **2010**, *34* (11), 1597-1607.
(15) Strogen, B.; Horvath, A.; McKone, T. E., Greenhouse gas emissions from construction, manufacturing, and operation of US liquid fuel distribution infrastructure. *ASCE J. Infrastruct. Syst.* **2012** *Available online, in press.*
(16) *GREET1_2012 Fuel Cycle Model*; Argonne National Laboratory: Argonne, IL, 2012 (accessed March 27, 2013). http://greet.es.anl.gov/.
(17) Pacca, S.; Horvath, A., Greenhouse gas emissions from building and operating electric power plants in the Upper Colorado River Basin. *Environ. Sci. Technol.* **2002,** *36* (14), 3194-3200.
(18) *eGRID2012 Version 1.0 Online Database*; US Environmental Protection Agency: Washington, DC, 2012 (accessed March 27, 2013). http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html.
(19) Farrell, A. E.; Plevin, R. J.; Turner, B. T.; Jones, A. D.; O'Hare, M.; Kammen, D. M., Ethanol can contribute to energy and environmental goals. *Science* **2006,** *311* (5760), 506-508.
(20) Spatari, S.; Zhang, Y.; MacLean, H. L., Life cycle assessment of switchgrass-and corn stover-derived ethanol-fueled automobiles. *Environ. Sci. Technol.* **2005,** *39* (24), 9750-9758.
(21) Klara, J. M.; Wimer, J. G. *Natural Gas Combined-Cycle Plants With and Without Carbon Capture & Sequestration*; National Energy Technology Laboratory: Morgantown, WV, 2007 (accessed April 8, 2013). http://www.netl.doe.gov/KMD/cds/disk50/NGCC%20Technology_051507.pdf.