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WATER AND GREENHOUSE GAS TRADEOFFS ASSOCIATED WITH A TRANSITION TO A LOW CARBON TRANSPORTATION SYSTEM

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ABSTRACT
Transportation fuels are heavily dominated by the use of petroleum, but concerns over oil depletion (e.g., peak oil), energy security, and greenhouse gas emissions from petroleum combustion are driving the search for alternatives. As we look to shift away from petroleum-based transportation fuels, most options consume and withdraw more water during their life cycle. Thus, shifting to alternative fuel and energy supplies for transportation will likely increase water use for the transportation sector. Previous work suggests that water consumption for transportation could reach 10% of total U.S. water consumption when meeting the Federal Renewable Fuels Standard mandate at modest irrigation levels for feedstock crops (corn, cellulosic grasses) in combination with other alternative fuels and vehicle technologies (electric vehicles, natural gas vehicles, etc.), but more refined analysis is needed. It is important to understand when and where these new water demands for transportation are anticipated to occur. This paper presents results from simulations of the U.S. 9-region (EPAUS9r) MARKAL (MARKet ALlocation) integrated energy systems model for mapping the changes in water withdrawal and consumption during a transition to a low carbon-emitting U.S. transportation fleet. The advantage of using a bottom-up, multi-sector model like MARKAL is the ability to look at consistent scenarios for the full energy system, and endogenously capture interactions between different sectors (e.g. electric power production, biorefineries, and the LDV fleet). MARKAL can simulate a baseline scenario driven by assumptions for biomass feedstock and fossil resource costs and availability, as well as the costs of converting those resources to liquid fuels and electricity. We investigate alternative scenarios both with and without carbon constraints, while varying the pace of vehicle electrification. We compare these scenarios to assess regional differences in water needs as well as aggregate water demand for transportation energy, and how those trade off against greenhouse gas emissions reductions. Our results indicate that the regional water demands and interregional transfers of embodied water could be significant as the light-duty vehicle fleet moves away from petroleum-based fuels, with exports of embodied water on the order of hundreds of billion gallons of water per year for ethanol coming from the Midwest. Interregional transfers of water embodied in electricity may also reach tens of billion gallons of water per year. However, these water requirements will vary substantially based on the light-duty vehicle mix, carbon policy, electric power generation mix, biofuel production levels, and feedstock characteristics.

INTRODUCTION
There are many drivers pushing the United States to search for alternatives to petroleum: global oil depletion, competition for world supply, and energy security. Should regulations mandate the reduction of greenhouse gas (GHG) emissions for the country overall, the United States will need transportation pathways that emit less carbon dioxide (CO_2). Many of these transportation alternatives consume or withdraw more water during their life cycle [1-3]. Much of the increased water use overall is due to biofuels production and the associated water needs for agriculture [4-5]. Adding electricity to the transportation energy mix, brings additional processes into the supply chain for transportation fuels. Therefore, the embodied water for transportation may also include mining and extraction, thermal power plant cooling, and other water uses related to the electric sector [6]. In all, it appears that the share of direct water consumption associated with U.S. light duty vehicle (LDV) transportation could increase to nearly 10% by 2030 compared to only 1-2% in 2000 [7-8].

It is imperative that U.S. stakeholders (fuel and transportation industry, governments at multiple levels, and consumers) understand the water-related impacts associated with future energy options [9]. Here we consider only potential changes in water quantities, and not water quality. While past research has quantified the water footprints for fuels and vehicle use on a technology-specific basis, fewer studies have investigated the relationship between technology options and policies on regional differences. Obviously the areas of production of biofuel feedstocks and locations of fossil fuel mining will bear any localized water impacts, but it is less clear how national priorities might influence the distribution of local and regional energy and water consumption and production. This analysis represents an initial effort intended to discover regional differences in LDV fuel consumption, fuel and electricity production, and associated water consumption. In this manner we describe how vehicle travel and fuel use in one part of the country affects water consumption in another.

DESCRIPTION OF MODELED SCENARIOS

MARKAL Model

The MARKAL (MARKet ALlocation) model is a multi-sector model of the energy system, from primary energy resources supply (e.g., petroleum, coal, biomass) to end-use demand for energy services [e.g., vehicle miles traveled (vmt) in the transportation sector, lumens of lighting, PJ of space heating] [10]. It is a technology-rich, bottom-up optimization model that finds the least-cost system-wide solution over the specific time horizon. Individual sectors within the energy system include highly detailed representation of technologies. This analysis will focus on three primary sectors: (1) light duty transportation, (2) electric power, and (3) biofuels production.

The EPA's U.S. 9-region (EPAUS9r) MARKAL integrated energy systems database models energy supplies, technologies and demands at the regional level using the nine U.S. Census Divisions [11].

1. New England: Maine, New Hampshire, Vermont, Massachusetts, Connecticut, Rhode Island
2. Middle Atlantic: New York, New Jersey, Pennsylvania
3. East North Central: Ohio, Michigan, Indiana, Illinois, Wisconsin
4. West North Central: Missouri, Iowa, Minnesota, Kansas, Nebraska, South Dakota, North Dakota
5. South Atlantic: Maryland, Delaware, District of Columbia, Virginia, West Virginia, North Carolina, South Carolina, Georgia, Florida
6. East South Central: Kentucky, Tennessee, Alabama, Mississippi
7. West South Central: Arkansas, Louisiana, Oklahoma, Texas
8. Mountain: Montana, Wyoming, Colorado, New Mexico, Arizona, Utah, Nevada, Idaho
9. Pacific: Washington, Oregon, California

The use of the Census Divisions provides detail regarding important regional differences in energy supply and demand. However, because of the very local nature of water supply and demand, future work would aim to further disaggregate results with greater spatial resolution.

Using the EPAUS9r MARKAL model, we examine four different scenarios that capture a range of alternatives for the evolution of the energy system. The four scenarios vary across two key dimensions: (1) the rate of vehicle electrification for the light duty transportation fleet, and (2) the targets for CO_2 reduction across the full energy system. Across all four scenarios, minimum volumes of biofuel production are assumed, but the model has the flexibility to produce biofuels above those levels in later time periods (e.g., more than the 36 billion gallons in 2022 specified in the Renewable Fuels Standard). We look at both national and regional results, as well as the interregional trading of fuels and electricity. These are not meant to represent predictions, but rather examples of potential technology/fuel pathways to achieve the scenarios that are described below.

Water Factors

Water factors for energy extraction, production and use were incorporated into the EPAUS9r model for the electric power sector (thermoelectric cooling and upstream resource extraction for coal and uranium), domestic on-shore crude oil extraction, refining of all crude oil, biomass feedstock irrigation, and biofuel production. While this is not an exhaustive representation of all potential water used by the energy sector, it does capture the major consumers of water. EPAUS9r also includes energy use in the industrial, commercial, and residential sectors, but any additional water use beyond the embodied water in the fuel and electricity consumed by these sectors (e.g., process-related water use in the pulp and paper or food processing industry) falls outside of the scope of this analysis.

Water withdrawal and consumption factors for electric power production were taken from a 2011 National Renewable Energy Laboratory (NREL) review of water factors for electricity generation technologies [12], and assigned to the array of electricity generation technology options represented in EPAUS9r. Water usage factors for these options are dependent on the type of technology used, irrespective of location. Regional differences in water requirements for electricity generation are determined based on the mix of technology utilization rates and interregional trading schemes selected by the model as being the most economic solution to satisfy electricity demand requirements for each scenario. Water usage factors were also applied to the suite of resource extraction technologies in EPAUS9r. These factors primarily came from a 2006 U.S. Department of Energy (DOE) Report to Congress [6] and represent the water required for mining and processing of raw fuels such as coal and uranium in preparation for their use by electricity generation facilities.

For electricity generation technologies, water consumption and withdrawal requirements can vary substantially based on the plant type and, most notably, the specific cooling process. For thermoelectric plants, such as those that use steam (e.g., conventional coal, natural gas, and nuclear), the primary water requirement is for a condenser which quenches the high temperature conversion medium exhausted from the power turbine. Many older plants utilize an open-loop cooling system to satisfy this requirement. These systems consume slightly less water per unit of plant output, but demand that far more water is withdrawn from an available source than the closed-loop systems found on most modern facilities. It has been estimated that 31% of existing generating capacity in the U.S. utilizes open-loop cooling. However, future generating plants will likely utilize closed-loop cooling [6]. For simplicity, the water factors applied in the MARKAL model represent closed-loop cooling systems on all thermoelectric technology options. Future work will distinguish between closed- and open-loop systems for existing facilities in the MARKAL technology characterization. This will affect withdrawal numbers more than consumption, but we will focus on water consumption for this current analysis.

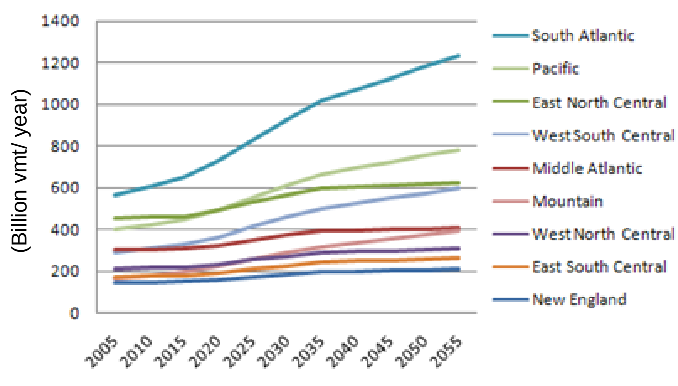
The largest source of water usage for biofuels is the irrigation water for biomass feedstock production. For corn starch ethanol, the water requirements for corn production were estimated based on the 2007 Census of Agriculture Farm and Ranch Irrigation Survey, along with data from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Services for total corn production by state [13-14]. In order to capture regional differences in feedstock water requirements, state-level USDA data were used for irrigated acres harvested and average acre-feet applied per irrigated acre harvested to estimate the total volume of water withdrawals for irrigation by state. These volumes were then aggregated up to the U.S. Census division and divided by the total feedstock production (irrigated and non-irrigated) for each division. This is expressed as gallons of irrigation water per ton of both irrigated and non-irrigated feedstock, therefore reflecting the percentage of irrigated acres and the differences in yield between irrigated and non-irrigated acres within each state. While the regions differ substantially, there is a large intra-regional variability as well, as illustrated by comparing Iowa (287 gal/ton) and Nebraska (33,790 gal/ton). Both states are major corn producers, and thus potential areas for siting both corn and stover-based ethanol refineries. Using state-level U.S. Geological Survey (USGS) data on total consumptive use and conveyance losses as a percentage of total withdrawals [15], we also derived a regional factor for water consumption, ranging from 52% in the Middle-Atlantic to 99% in West North Central. For corn stover, the largest cellulosic feedstock supply in EPAUS9r, we assigned 50% of the water values for corn to the stover component. This is based on a 1:1 grain to stover ratio [16], but does not factor in that the actual stover removed from the field may be well below half of the total stover mass given equipment, erosion, and soil carbon constraints. Water use factors for refining biofuels, both corn-grain ethanol and cellulosic ethanol, were based on King and Webber [1]. Water requirements for domestic oil extraction and refining are substantially lower than those for electric power and biofuels, with the majority of the water use from oil extraction related to the use of enhanced oil recovery (EOR) [6].

Scenario A: Baseline.

The baseline scenario A assumes no CO_2 policy but does reflect the biofuels volumetric targets specified under the Federal Renewable Fuels Standard Program [17]. Available biomass feedstocks include corn grain, soybean oil, yellow grease, corn stover, wheat straw, forest residues, primary mill residues, and urban wood waste. Although the model does have supply curves for switchgrass, we did not include switchgrass for these current scenarios. This will be incorporated in future work. The model allows for multiple conversion pathways for biomass feedstocks to be used not only as liquid fuels, but also for electricity generation (e.g., co-firing with coal) and process heat.

For the baseline and three alternative scenarios, the end-use demand for light-duty vehicle (LDV) transportation is specified exogenously as regional vmt per year by census division. Regional transportation demand was based on the 2010 Annual Energy Outlook (AEO 2010), with the regional breakdown of vmt from the Energy Information Administration's (EIA) Transportation Energy Consumption Survey [18-19] out to 2035, while vmt growth to 2055 was based on Census Bureau population projections, holding vmt/capita constant at 2035 levels. The South Atlantic (encompassing the Atlantic Coast from Florida to Maryland and Delaware) has both the highest vmt demand and is the most rapidly growing region, followed by the Pacific and East North Central, which includes Wisconsin, Illinois, Indiana, Ohio and Michigan. These regional variations in travel demand are important not only for understanding the regional distribution of fuel and electricity demands, but also have implications for the interregional trading of liquid fuels, electricity, and the water embodied in those energy sources. Thus, we can describe how transportation in one region is dependent upon water resources in another. Figure 1 indicates the assumed increasing LDV travel demand by census division.

Figure 1. Light-Duty Vehicle Demand by Census Division (billion vmt/yr).



While the travel demand is specified exogenously, the LDV fleet and fuels that meet that demand will vary across scenarios. EPAUS9r includes approximately 100 types of vehicles in the light duty fleet, representing different combinations of vehicle classes, fuel/engine, flex fuel capability, and model years.

Scenario B: High light-duty vehicle electrification.

For this scenario, we use baseline MARKAL assumptions for electric sector generation, vehicle fleet and the minimum renewable fuel volumes. However, we then apply a constraint on the LDV fleet that simulates a high electrification future. This constraint is applied in terms of a minimum total electricity use in the light-duty transportation sector, with an approximate value of 9,700 PJ (2,700 TWh) of electricity. This value was calculated as approximately 50% of total LDV fuel use for 2035 for the baseline run (no vehicle electrification or CO_2 constraint). However, because the total LDV fuel use is an output of the model, total LDV electricity may not equal exactly 50% of total LDV fuel use.

Scenario C: CO_2 constraint.

Scenario C is the same as the baseline scenario A, except we add a CO_2 constraint that represents a 40% reduction from 2005 levels by 2055 for CO_2 emissions across the full energy sector, including electric power, fuel production, and all end-use energy demand sectors – transportation, industrial, commercial, and residential. Because this is a system-wide constraint, the model will look for the optimal solution across all sectors, affecting the LDV fleet, electric power production, and biomass/biofuels production. That is to say, each sector does not need to reduce CO_2 emissions by 40%.

Scenario D: CO_2 constraint with high LDV electrification.

Scenario D represents high electricity use in the LDV sector under a carbon-constrained future. For scenario D, we apply the constraints from both scenario B (high LDV electrification) and scenario C (40% CO_2 reduction). We focus primarily on this scenario, which represents the largest divergence from the baseline (scenario A), when we examine the water implications at the regional level.

RESULTS OF MODELED SCENARIOS

For the four modeled scenarios, we look first at the differences in LDV fuel mix, and then examine the upstream changes in the production of the two fuels of interest for these scenarios, biofuels (primarily in the form of E85, 85% denatured ethanol by volume) and electricity for electric and plug-in hybrid electric vehicles (EVs and PHEVs). We will then show the results of these scenarios for water consumption at the national level. Finally, we examine the regional differences in water consumption and the implications for trading of water in the form of embodied water in fuels and electricity.

All of the following graphs, including the regional trading results, are derived from the MARKAL model results for the four scenarios that were run. Although the model solves from 2005 to 2055, we focus on the results out to 2035. This time frame has the advantage of capturing the dynamics of fleet and equipment turnover in the transportation sector and energy conversion/processing sector, in order to show the market penetration of new, more advanced technologies and fuels. Beyond 2035, there is less information and a much greater degree of uncertainty in the characteristics of new technologies and their water use.

The vmt splits are shown in Fig. 2 for 2005 and the four alternative 2035 scenarios. The 2005 pie chart highlights the homogeneity of the LDV fleet, with the majority of vehicles using gasoline or E10 (10% denatured ethanol by volume blended with gasoline). Both of these fuels are utilized by the existing fleet of light duty cars and trucks, and require no flex fuel capability. Diesel vehicles constitute a small segment of the LDV fleet. While flex fuel vehicles (FFVs) capable of using E85 were part of the LDV fleet in 2005, they were operating mainly on gasoline [20].

For the 2035 scenarios, three major changes occur. First, there is a substantial growth in light-duty vehicle travel demand (billions of vmt) from 2005 to 2035. This travel demand, specified exogenously, represents a 57% increase over 2005 levels. Second, E10 becomes a major fuel completely displacing all gasoline with the exception of the high electrification scenarios (B and D). Third, the vehicle mix diversifies, with a greater share of diesel and E85 for all scenarios. The 15 billion gallon per year limit for corn ethanol to 2022 is assumed, in accordance with the national RFS2 standard. However, we allowed the model flexibility to produce corn ethanol above those levels for later periods, recognizing that from a policy perspective this may be unlikely. To meet the high EV constraint, more electricity – for electric and plug-in hybrid electric vehicles – comes into the market for scenarios B and D.

Comparing the four scenarios, several interesting, and sometimes non-intuitive, dynamics emerge. The CO_2 constraint (scenario C) without the vehicle electrification constraint brings in more diesel vehicles, which are generally more efficient than their gasoline counterparts, and a larger E85 share. This larger slice of the pie for E85 is not due to greater ethanol production (see Fig. 4), but is due to the fact that the carbon constraint leads to a more efficient vehicle fleet and less fuel use overall. With lower demand for gasoline/E10, the denatured ethanol that normally would be blended as E10 is instead blended as E85.

The impacts of the vehicle electrification constraints (scenarios B and D) are more complex. As expected, the high electrification constraint brings in more electricity as an LDV fuel input. However, what is less intuitive is the relative increase in the utilization of other fuels. In particular, the share of diesel increases substantially, and the share of E85 use increases, leading in part to greater ethanol production (see Fig. 4), but also leading to a lower share of E10 with respect to gasoline. These results are driven in large part by the ability for fuel switching and fuel arbitrage by end-users in the LDV fleet, as newer vehicles in the model include flexible platforms for multiple types of fuels. For example, one of the vehicle types that appears in scenarios B and D is plug-in electric hybrid vehicles that are also flex-fuel capable, meaning that when they fuel up at the pump, instead of via the plug, they are capable of using either gasoline, E10 or E85. Because the vehicle electrification constraint led to the uptake of a greater number of these hybrid/flexible fuel vehicles, there was more switching between fuels based on relative changes in their marginal costs.

Figure 2. National vehicle miles traveled (vmt) by fuel input from 2005 to 2035 for the four scenarios. The charts are sized relative to the change in total national vmt over the period from 2005 to 2035. Fuels include gasoline, diesel, E10, E85, electric vehicles (EV), compressed natural gas (CNG), and liquefied petroleum gas (LPG).

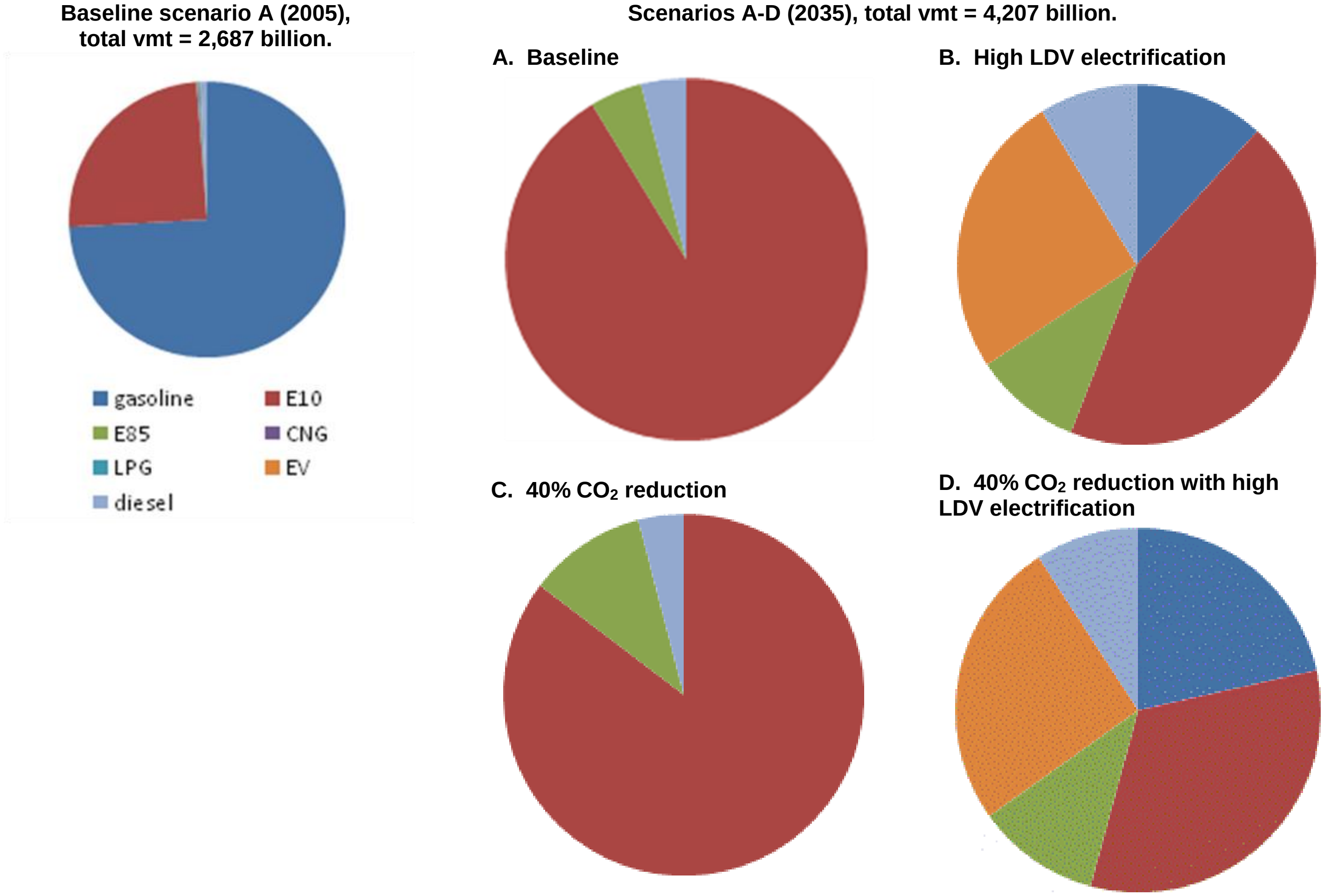
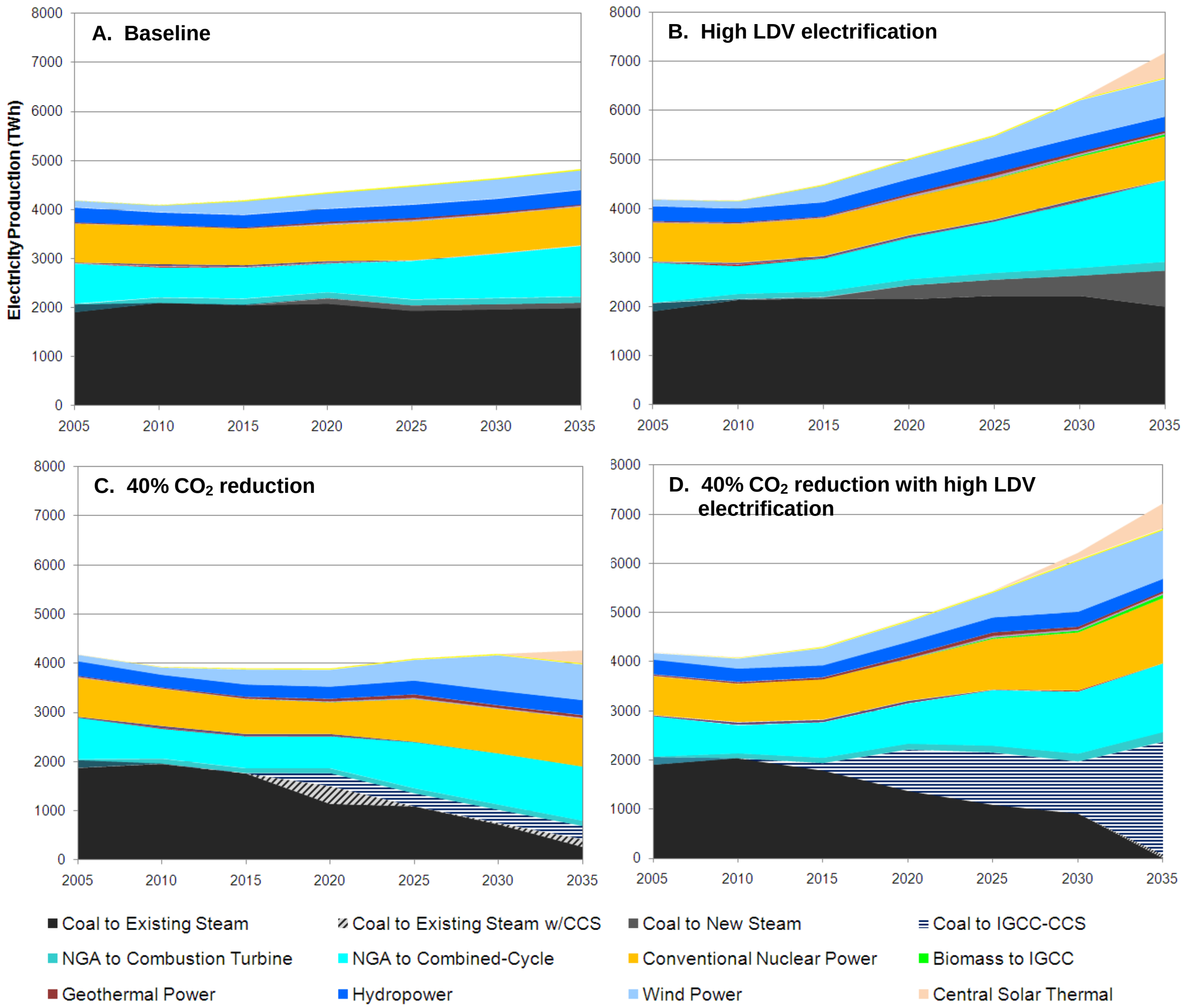


Figure 3 illustrates the total U.S. electricity production by technology for each of the four modeled scenarios. As can be seen in sub-figures (B) and (D), the electricity production is greatly increased for these two high LDV electrification scenarios in response to the high demand for electricity in the transportation sector. Electricity demand in non-transportation sectors (i.e., commercial, residential, and industrial) either remains relatively constant or is reduced in these scenarios, indicating that total increase in electricity output goes toward satisfying the vastly increased demand (+99%) from electric vehicles.

The baseline scenario A shows little change in the original mix of electricity generating technologies, with only a slight increase in the share of natural gas combined cycle (NGCC) to satisfy increasing demand over the modeled time horizon. When the LDV electrification requirements are imposed in scenario B, total demand for electricity rises by approximately 50%. This increase in demand is satisfied by roughly equivalent increases in the shares of renewable [wind and concentrated solar thermal (CST)] and fossil fuel (coal to steam and NGCC) technologies. This increase in renewable energy reflects the increased viability of these technologies over time, despite the lack of a dedicated carbon constraint, due to increased cost of fossil fuel generation brought on by existing policies and competition for resources. Shares of hydroelectric and conventional nuclear technologies, the other major contributors of generated electricity, remain unchanged – a reflection of their upfront costs and capacity constraints.

Figure 3. Electricity production (TWh) by technology from 2005 to 2035 for the four scenarios. (NGA = natural gas, IGCC = integrated gasification combined cycle, CCS = carbon capture and sequestration)



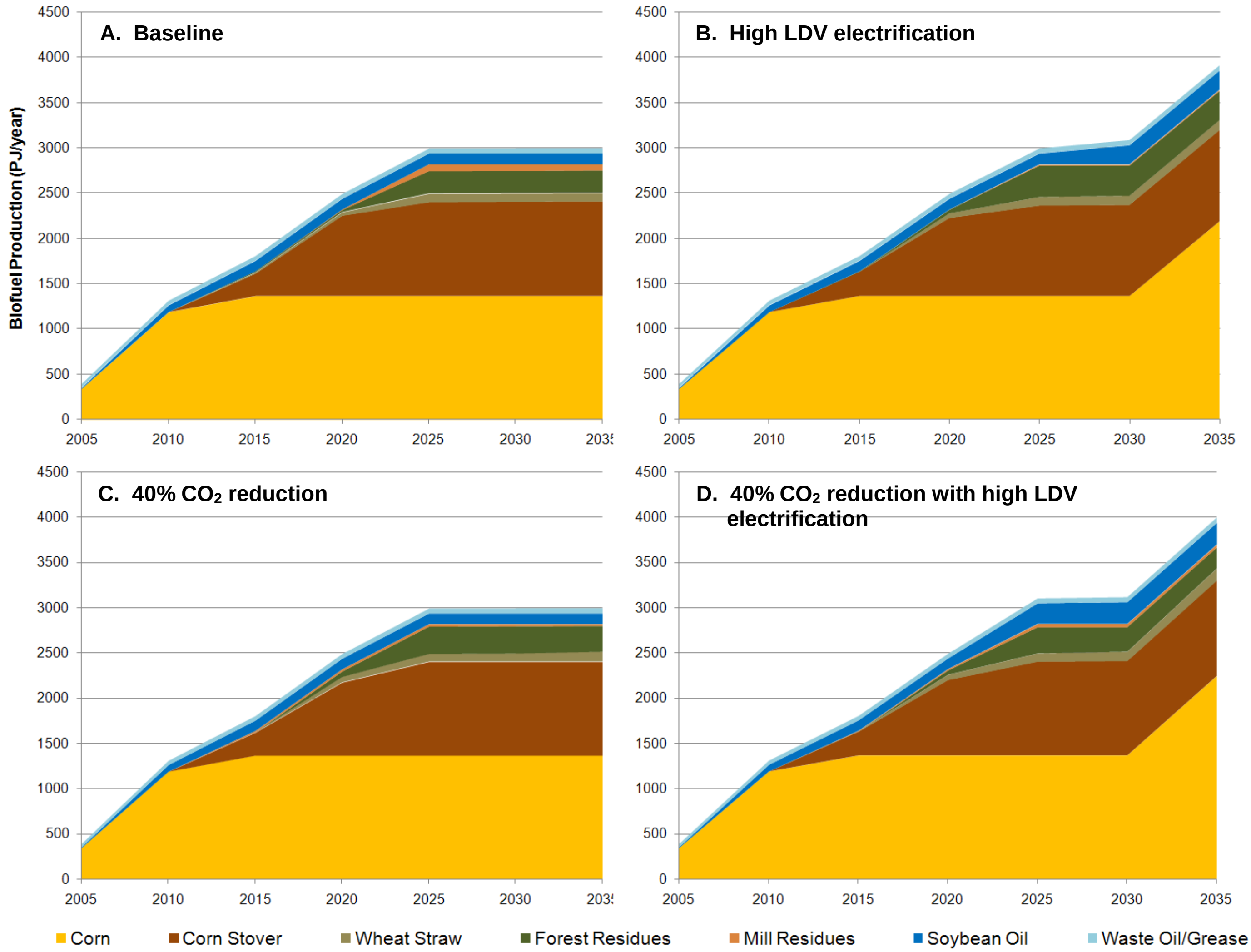
Scenario C, with the addition of a CO_2 reduction policy to the baseline, is most notably characterized by a 75% reduction of existing coal generation by 2035. Much of the existing coal capacity that does remain is retrofitted with carbon capture and sequestration (CCS) and is joined by a roughly equivalent amount coal used in integrated gasification combined cycle generation with CCS (IGCC-CCS). Overall, the use of coal-fueled generation technologies is reduced by slightly more than 60% in this scenario, with the balance of electricity demand provided by additional shares of NGCC, nuclear, wind, and CST.

When the CO_2 reduction policy is combined with the high LDV electrification scenario D, existing coal generation is nearly completely phased out (95%) by 2035. Coal, however, maintains a large share of the fuel market for electricity generation in the form of IGCC-CCS, a more energy-efficient and less carbon-intensive technology. This reintroduction of coal-fired generation makes up most of the additional electricity demand under the combined CO_2 reduction and LDV electrification requirements, and is joined by relatively equal increases in shares of the other major generation technologies. It is interesting to note that the relative shares of each technology type are quite similar in the two LDV electrification scenarios B and D through 2035. The obvious difference is that the portion of coal-fired generation in scenario D is in the form of IGCC-CCS whereas conventional coal to steam generation is utilized in the absence of a CO_2 policy.

Turning to biofuels production levels, Fig. 4 compares the production of corn grain ethanol, cellulosic ethanol from stover, wheat straw, forest and mill residues, and biodiesel from soybean oil and waste oil/yellow grease. This assumes a maximum limit of 15 billion gallons per year for corn ethanol out to 2022 in accordance with the renewable fuel standard.

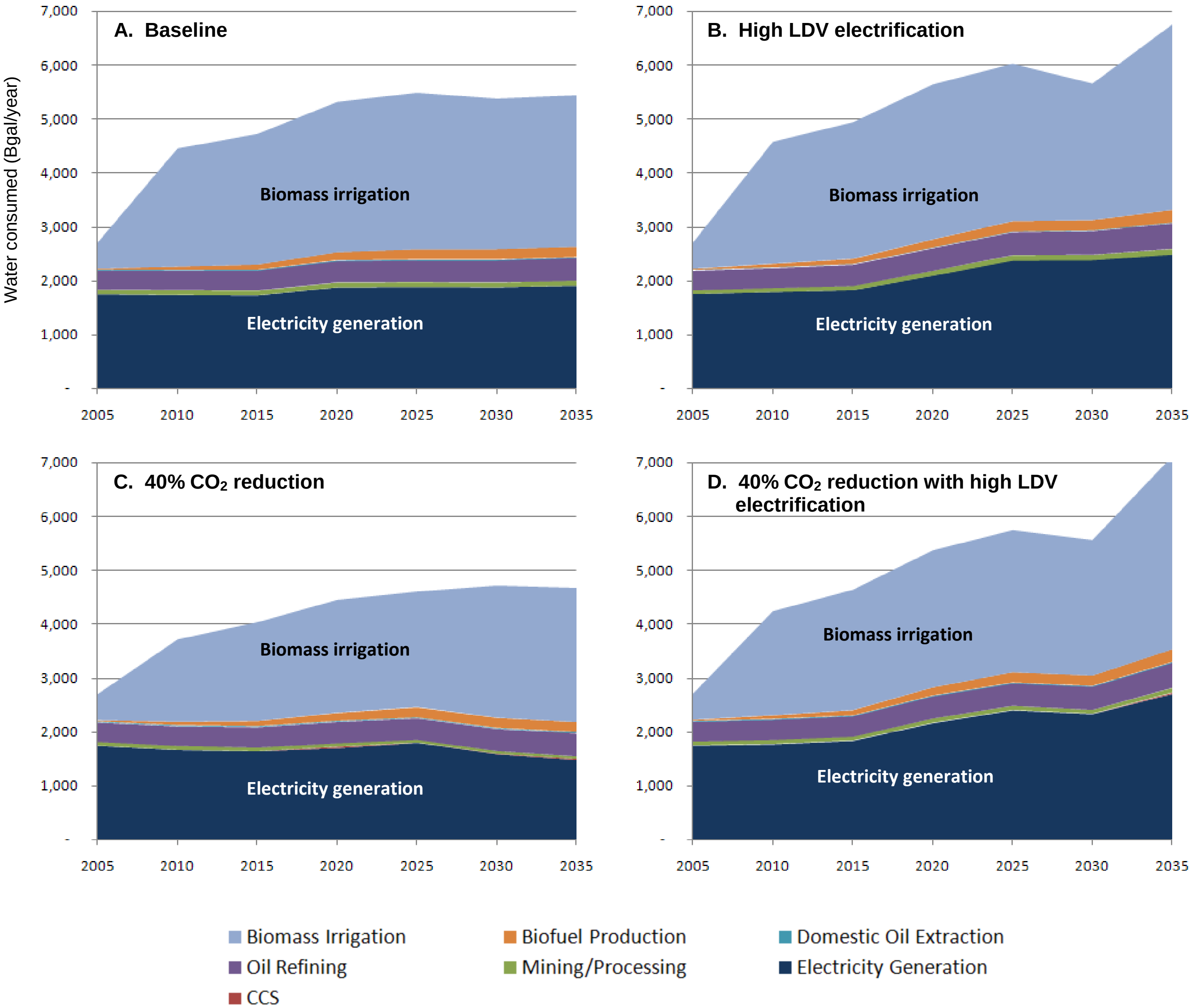
However, in order to explore the potential longer range scenarios, the model has flexibility to produce above these limits in the later model years. In 2035, the model actually produced above the 15 billion gallon limits for scenarios B and D. Again, this was an unexpected result, with the additional ethanol production due to increased fuel arbitrage for plug-in hybrid, flex fuel vehicles in the later model periods. In 2035, there is also an expansion of biodiesel from soybean oil. The application of the 40% CO_2 constraint resulted in only negligible changes in the total biofuel production levels and the mix of feedstock.

Figure 4. Biofuel production (PJ /year) by feedstock from 2005 to 2035 for the four scenarios.



Based on the water usage factors described earlier, we estimate the total water consumption for each of the four scenarios. Figure 5 illustrates that the most significant increases in water usage from the electric sector through 2035 are brought on by the increases in electricity demand under the high LDV electrification scenarios. A reduction in water demand from electricity generation is actually seen when imposing only the CO_2 reduction policy (scenario C). This is an indication that most measures taken to reduce CO_2 in such a scenario involve less water-intensive technologies, as seen by a reduction in coal-fired generation offset by increases in wind in Figure 3. Added electricity demand in the LDV electrification scenarios, however, does require use of these more water-intensive technologies. This illustrates the inability of low-water technologies (e.g., wind) to shoulder a larger portion of the load over this time frame due to capacity limitations such as technology maturity and resource availability. Therefore more water-intensive technologies must be utilized, such as fossil and nuclear fuel thermoelectric generation along with CST. Embodied water in biomass has very little effect on the overall water usage in the electric sector as crop-derived fuels are not preferred by the model as a way to satisfy electricity demand. In contrast, biomass irrigation and biofuel production water needs increase substantially, and become the predominant consumer of water in the energy system. For all of the scenarios, by 2035, water consumption for biofuels is higher than all electricity generation water consumption. Water requirements for biofuel production grow with the increasing biofuel volumes, but are substantially less than those for the biomass irrigation.

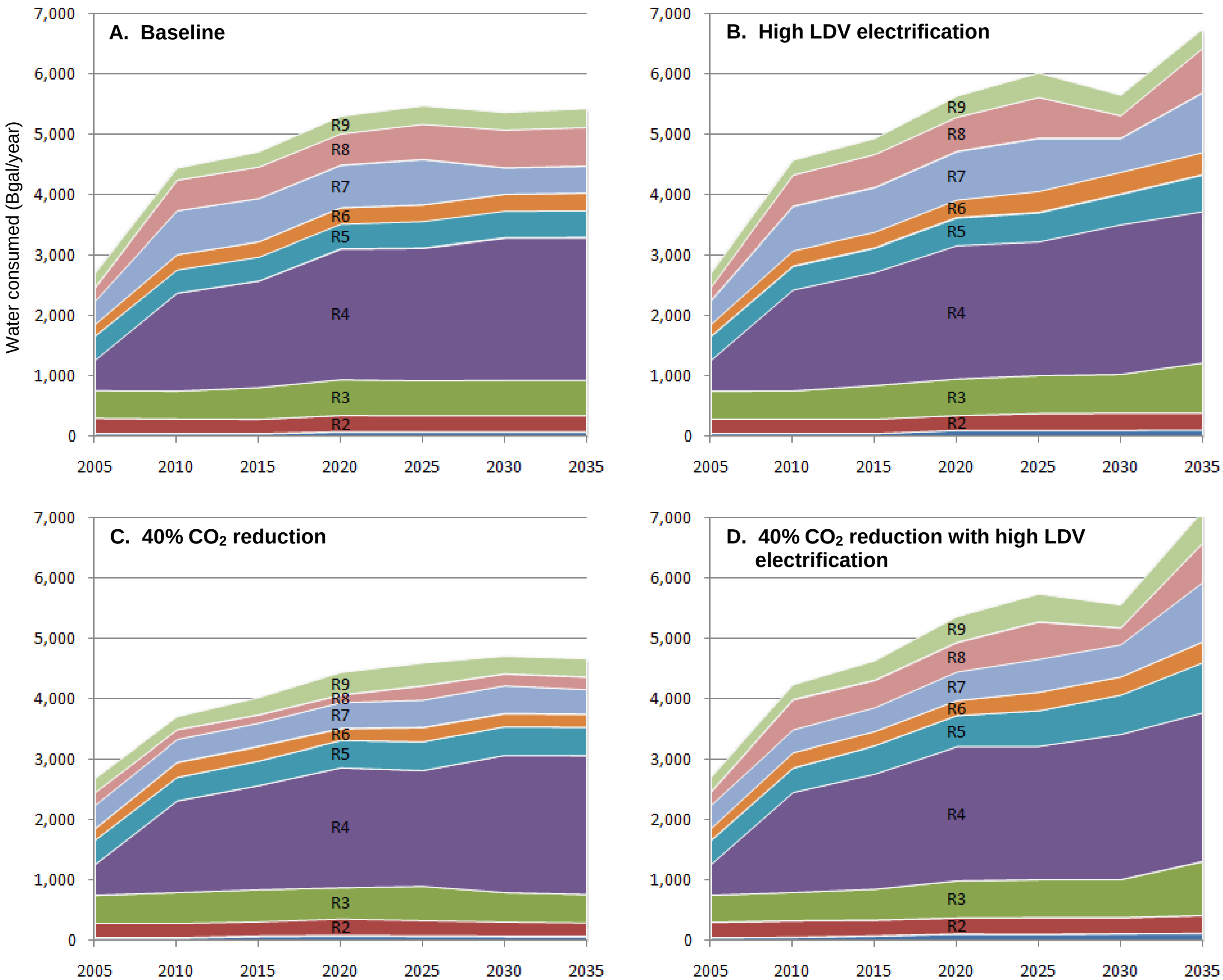
Figure 5. Total water consumption (billion gallons per year) by technology type, from 2005 to 2035 for the four scenarios. Water consumption includes all electric power production (with the exception of hydropower), mining of coal/uranium, domestic oil extraction and oil refining, biomass feedstock, and biofuel production.



REGIONAL RESULTS AND TRADING

The previous graphs depict water consumption disaggregated by the energy fuel/process for each of the four scenarios. In this section we discuss some of the regional implications of these scenarios. Figure 6 shows aggregated regional water consumption across the four scenarios and includes all electric power production (with the exception of hydropower), mining of coal and uranium, domestic oil extraction and oil refining, biomass feedstock and biofuel production.

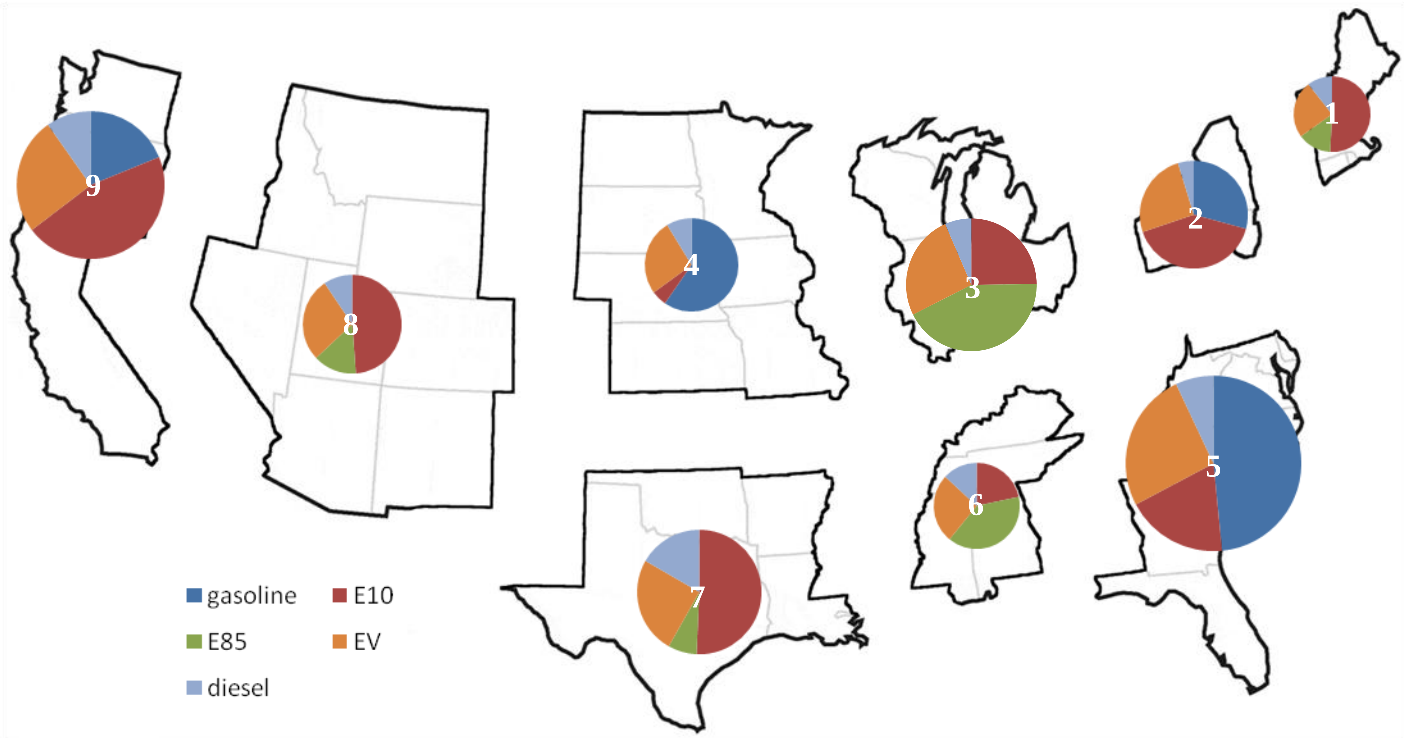
Figure 6. Total water consumption (billion gallons per year) by census division, from 2005 to 2035, for the four scenarios.



Region 4 (West North Central), which includes Iowa, Missouri, Minnesota, Kansas, Nebraska, and the Dakotas, stands out as the fastest growing in terms of the water embodied in the energy and liquid fuels it produces, with most of this growth coming from the use of irrigated crops for biofuels. This result is intuitive, given that in Region 4 states such as Nebraska have both high irrigation rates and corn production. As with Figs. 4 and 5, two pairs of scenarios share similar results: scenarios A and C, and scenarios B and D. A move from the baseline (A) to a 40% CO_2 reduction (C) results in a roughly symmetric reduction in total water consumed. Alternatively, a move from the baseline to either of the light-duty electrification scenarios (B or D) leads to higher water consumption in later years, where the effect of LDV electrification trumps that of a CO_2 mitigation policy.

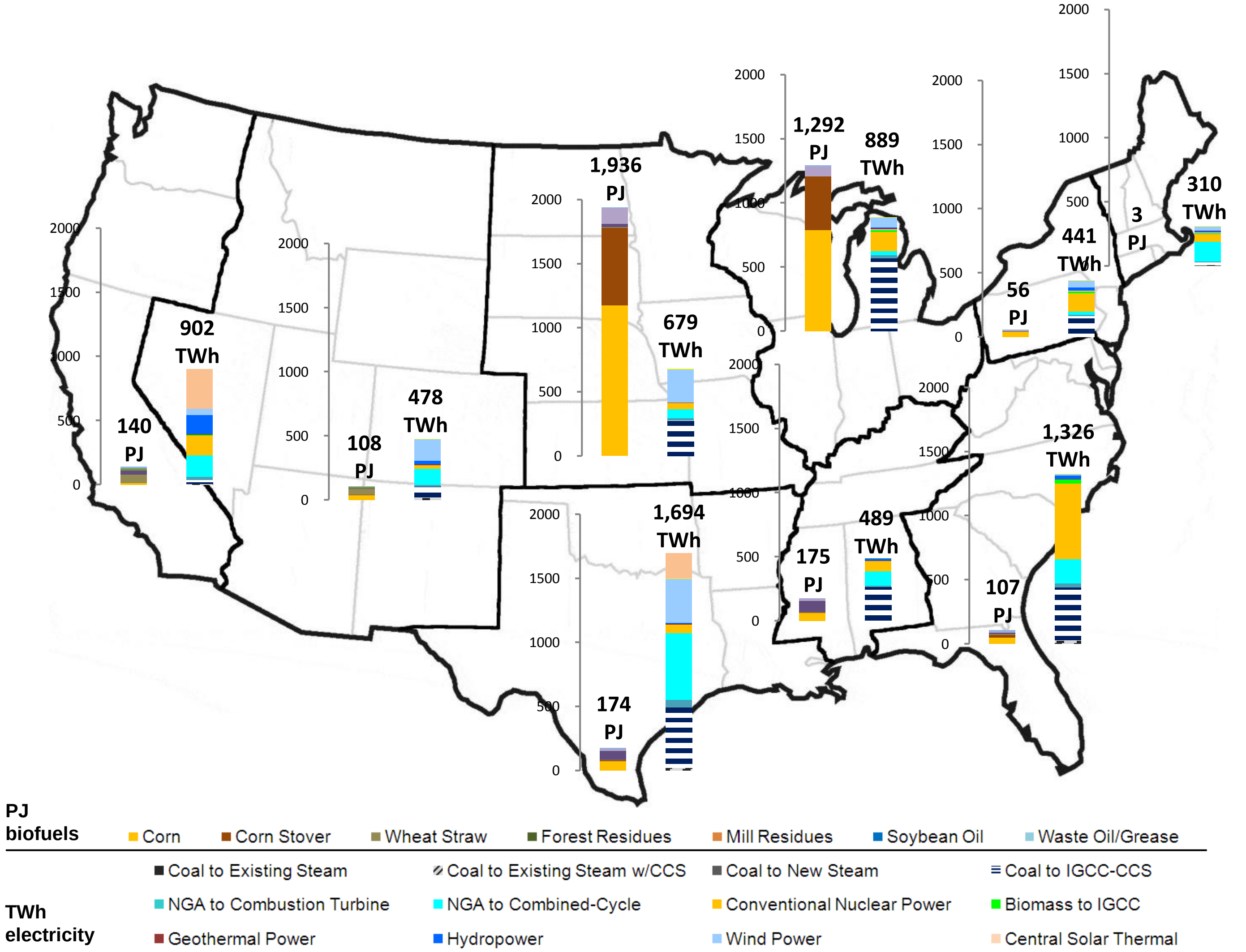
In order to explore the regional variability in travel demand, LDV fuel mix, electric power generation mix, and biofuel production, we look at a snapshot of 2035 for scenario D – a 40% reduction of CO_2 by 2055 and high LDV electrification. Figures 7-11 and the summary in Table 1 focus exclusively on the results of this scenario in 2035. Figures 7-9 examine the regional results, and Figures 10 and 11 show the related trading of fuels and embodied water.

Figure 7. Regional variation in 2035 in total vehicle miles traveled and fuel mix under scenario D. Pie charts are sized in proportion to the total vmt by region. CNG, LPG, and hydrogen do not appear in any regional vehicle fuel mix in 2035.



In 2035, under all scenarios, the South Atlantic (region 5), Pacific (region 9) and East North Central (region 3) are anticipated to have the highest travel demand in 2035, determined exogenously as with Fig. 2. Figure 7 also shows the variation in the LDV fuel mix. With the high LDV electrification constraint, all regions have a relatively high share of electricity as a fuel input. There is also considerable variation in the share of diesel fuel and E85. In particular, the share of E85 in the total fuel split ranged from insignificant in the Pacific, South Central, and West North Central, to nearly half of total fuel use in regions such as East North Central. There is a transportation cost associated with moving ethanol for blending in E85, which in turn increases the cost of E85 that is made from ethanol produced in the Midwest for use on the coasts. However, an interesting result is the fuel split for the West North Central (region 4), where the majority of the ethanol is produced. Only a fraction of the ethanol produced was utilized in the local LDV fleet in the region, with almost no E85 and little E10 blending. As will be seen below, these regional differences in total travel demand and the fuel split of the end-use vehicles will shape the interregional trading patterns for transportation fuels and the water embodied therein. This result should be interpreted with some caution, in that this is the most constrained scenario, where both the high LDV vehicle electrification constraint and 40% CO2 system-wide limit are in place. Therefore, this would not represent a typical business-as-usual scenario. For example, we have not incorporated state-level mandates for biofuel blending requirements that would affect the regional fuel mix, and the incremental costs of E85 distribution stations may need to be updated to capture the retrofits needed for higher ethanol-based scenarios.

Figure 8. Regional variation in biofuel volumes (in PJ) and feedstock type, and electricity production (in TWh) and technology mix in 2035 under scenario D.



Looking upstream at the production technologies, Fig. 8 shows the regional breakdown of the production of biofuels for transportation fuels and the electricity generation for all purposes. In terms of electricity production, West South Central leads with 1,694 TWh of production following by the South Atlantic and Pacific regions. The regions with the highest electric power generation capability closely track the high LDV travel demand regions, as both are generally linked to the major population centers. In contrast, biofuel production is not linked to the major demand centers. Instead, for these scenarios, biofuel production is generally sited more closely to the biomass feedstock sources than to where those fuels will be blended and used.

Figure 9. Regional variation in water consumption (billion gallons per year) for biofuels, petroleum fuels, and electricity production in 2035 under scenario D. Above the dashed line represents liquid transportation fuel production, whereas below the dashed line represents electricity production for all end uses.

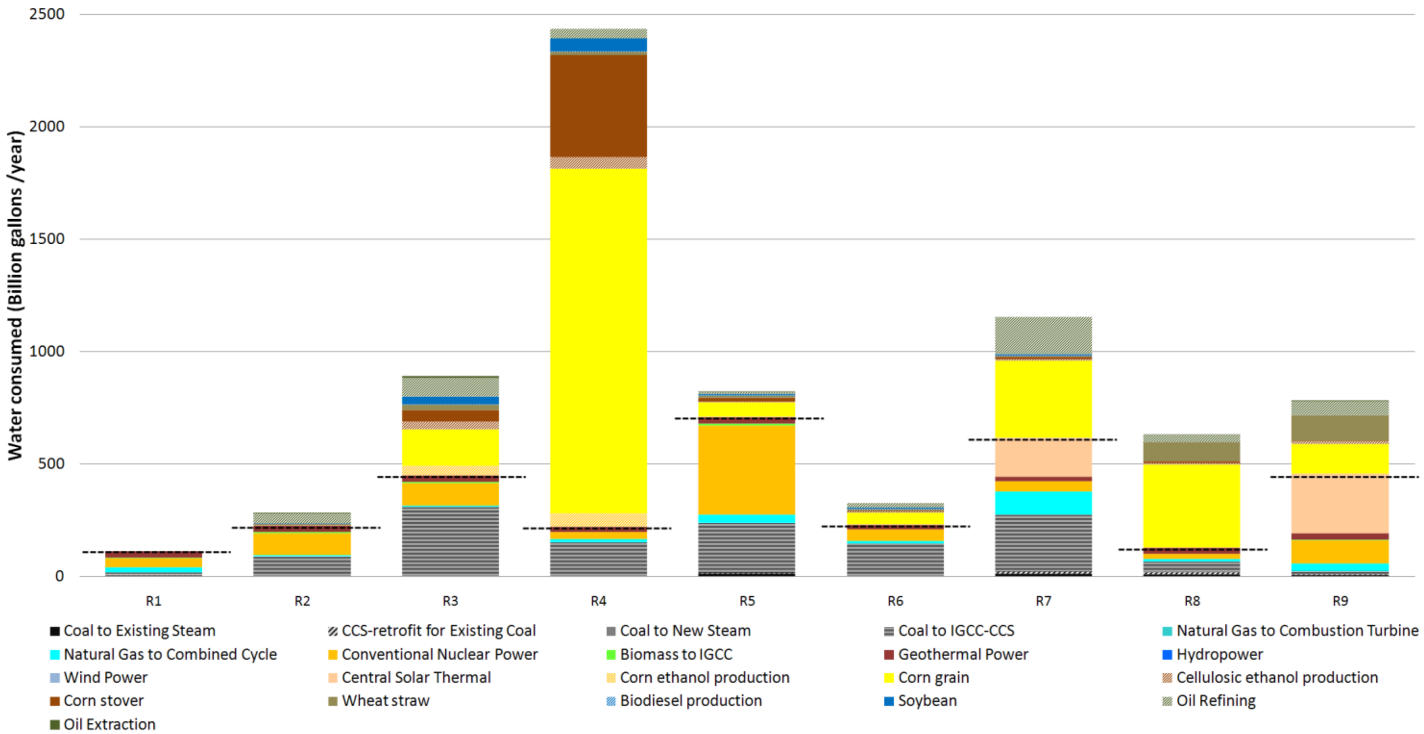


Figure 9 summarizes the associated water use for the biofuels and electricity production shown in Fig. 8 and also shows water consumption for petroleum-based fuels. This captures the major categories of water use for energy as summarized in Fig. 5, but highlights the unique water demands of each region with respect to the energy sector. The Northeast (Regions 1 and 2) and East South Central (Region 6) are similar in terms of total water consumption and the small share of biofuels production. East North Central (Region 3) has a relatively even split of water consumption between biofuels production (with much lower irrigation demands) and electric power production, with predominately coal to IGCC with CCS (following retirement of existing coal facilities under the low CO_2 constraint). The South Atlantic (Region 5) stands out with its heavy reliance on nuclear, which has high consumption rates, but relatively low levels of biofuel production and associated water use.

West North Central (Region 4), with its high levels of biofuel production from corn grain and corn stover, is the major water consumer, with more than double the water use of the next highest region. As shown in Fig. 6, trends in ethanol production from this region are a key determinant of national water consumption trends. However, this result should be taken with the major caveat that this represents a very high level of corn-based ethanol production exceeding 15 billion gallons. Limiting corn-ethanol production to the 15 billion gallon limit would bring the associated water usage down by approximately one-third. Nevertheless, the potential water consumption in this region is substantial, and, as will be shown in Fig. 11, much of that is exported to other regions in this scenario.

The West South Central, Mountain and Pacific (Regions 7, 8 and 9), are heavily irrigated despite their relatively small volumes of biofuel production (as seen in Fig. 8), in terms of both share of acres irrigated and the irrigation rates, placing their water burden for biofuels on par with or greater than Region 3, a much larger producer of biofuels in terms of total fuel output. In addition, Regions 7 and 9 also have increased use of CST, starting around 2035, which places an additional demand on water resources, particularly in the Pacific. Although Region 8 has good-quality solar resources, for this scenario the model favored wind power over CST to satisfy the low carbon portion of electric power generation capacity. Another source of water consumption that appears more prominently in the regional context is that of oil refining, with West South Central (including Texas, Oklahoma, and Louisiana) showing a relatively high contribution of oil refining to the total water consumption.

Figure 10. Net interregional ethanol (green) and electricity (red) flows in 2035 under scenario D, high vehicle electrification and 40% CO_2 reduction. Units are PJ for both flows, where arrow widths are proportional to flow volume. Net is for any regional pairing.

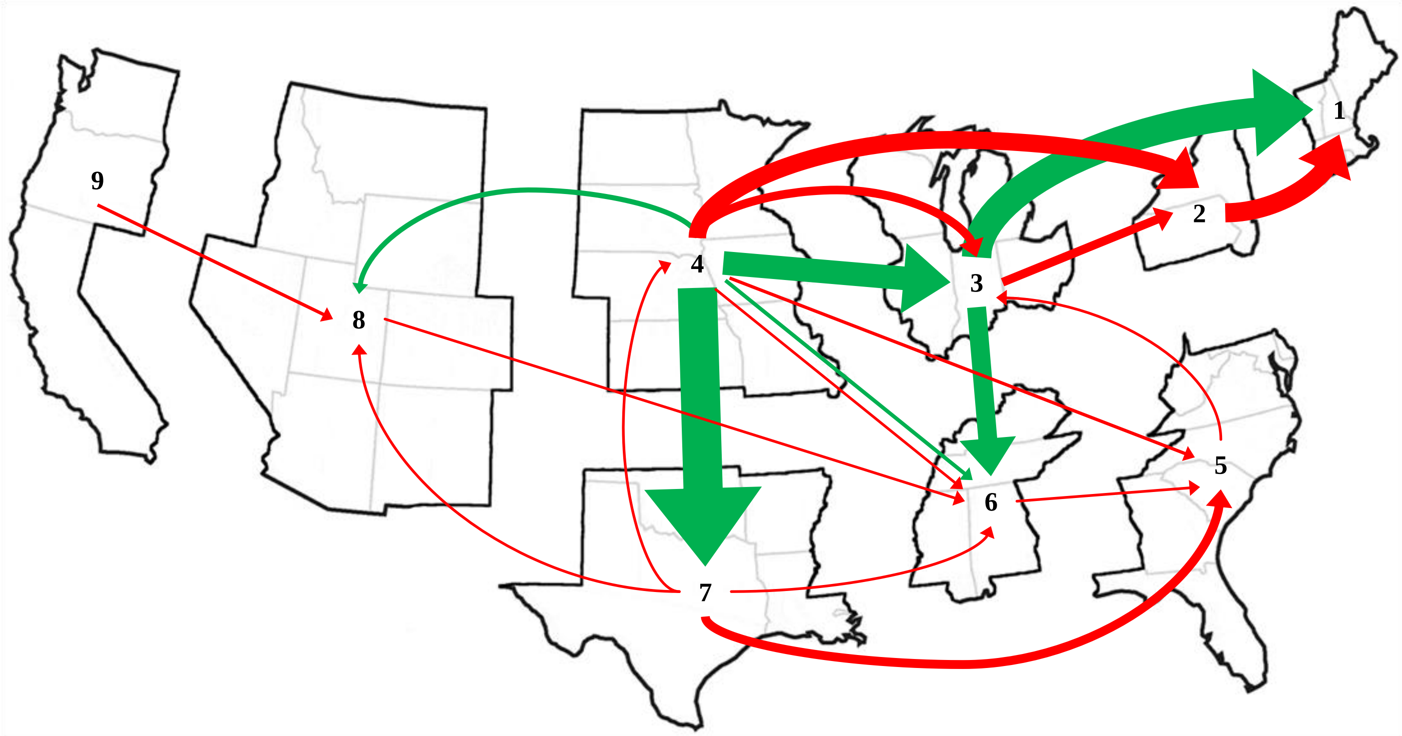
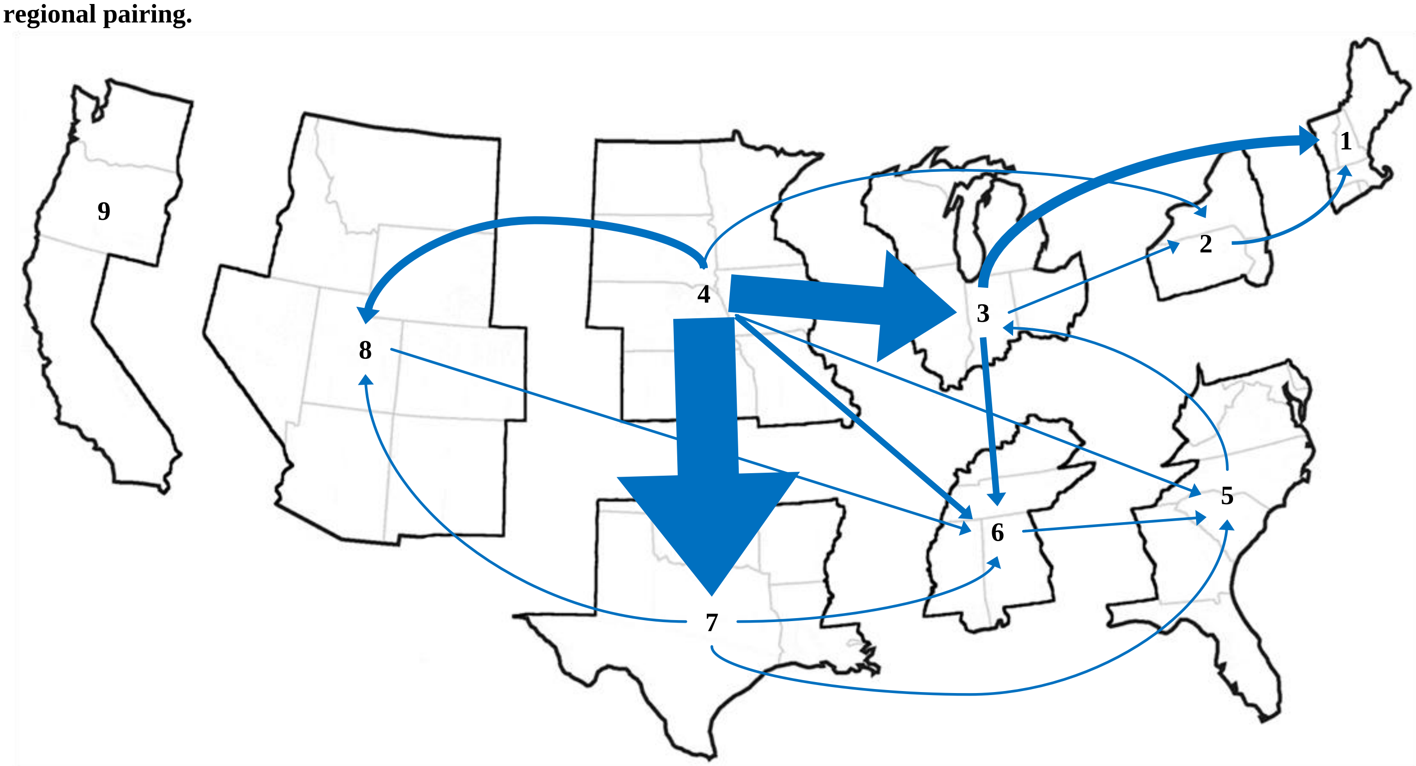


Figure 11. Total net embodied interregional water flows (billion gallons per year) due to both ethanol and electricity transfers in 2035 under scenario D. Arrow widths are proportional to flow volume. Negligible flows are not shown, and net is for any regional pairing.



Having examined the regional distribution of LDV travel demand, fossil fuel and biofuel production, and electricity production, and the regional water consumption associated with each of those fuels, we now look at how these regional demand and supply dynamics drive interregional trading of transportation fuels and, to a lesser extent, electricity, and their embodied water.

Interregional trades of fuels and electricity are modeled explicitly and endogenously in the EPAUS9r model. Figure 10 summarizes the net flows of ethanol and electricity between regions. Not surprisingly, based on the LDV fuel splits and the concentration of ethanol production in the Midwest (Regions 3 and 4), these two regions are major exporters of ethanol to the other regions, especially to the regions that have high E85 and E10 blends for their vmt fuel portfolio. Electricity flows are smaller, but also show more complex trading linkages between the regions. In contrast to liquid biofuels, which almost exclusively serve the transportation sector, electricity meets a number of end-use sectors including industrial, residential and commercial. Because it cannot be discerned to which end-use imported electricity is used, total electricity flows between regions are shown, recognizing that only a share of that will go to LDVs. We recognize that the USEPA9r MARKAL regional electricity flows represented in Figure 10 do not correspond to Regional Transmission Organizations (RTOs). Future work can relate embodied water to RTOs.

Comparing the relative flows of electricity and ethanol (Fig. 10) with their associated flows of embodied water (Fig. 11), there is a clear contrast between what is being exported from Region 3 and Region 4. The embodied transfers for ethanol exported from Region 4 are proportionally larger, due to higher water consumption per PJ of ethanol produced in Region 4. In contrast, the ethanol exported from Region 3, shows proportionally smaller exports of embodied water. This is due to the disparate irrigation rates between the two regions. Another interesting result related to Region 4 is the relatively large export of electricity out of this region. Yet, in contrast to the ethanol exports leaving Region 4, the embodied water associated with the electricity exports is actually minimal. Again, this has to do with the mix of technologies producing the electricity in Region 4. A large share of the electricity produced in this region under this scenario for 2035 comes from wind generation, which has negligible water usage.

Table 1 provides a summary of all interregional trading of ethanol, electricity and the embodied water for each fuel for the actual PJ and billion gallons of interregional trading.

Table 1. Summary of interregional trading of ethanol, electricity and the embodied water for 2035 under scenario D.

Exporting Region \ Importing Region	1		2		3		4		5		6		7		8		9	
1																		
2	0	477																
	0	67																
3	736	0	0	216							473	0						
	192	0	0	30							123	0						
4			0	438	590	215			0	82	96	2	981	0	128	0		
			0	39	690	19			0	7	112	0	1,149	0	150	0		
5					0	25												
					0	4												
6									0	41								
									0	6								
7							0	12	0	221	0	20			0	62		
							0	1	0	16	0	1			0	4		
8											0	10						
											0	1						
9															0	83		
															0	5		

ethanol (PJ)	electricity (PJ)
embedded water from ethanol (Bgal)	embedded water from electricity (Bgal)

DISCUSSION

Caveats regarding the interpretation of scenarios

As noted earlier, MARKAL is an optimization model, and as such, the scenarios should not be interpreted as predictions, or the most probable futures, but rather as the optimal, lowest-cost energy system-wide solution to meet the constraints imposed by the scenarios. In particular, we highlight that Scenario D is a more extreme scenario, where both a high light duty vehicle constraint is applied at the same time that a tighter carbon limit is place on the entire system (electric sector, transportation and all other end uses). For this reason, some of the results may seem unlikely given current trends.

Water for agriculture versus water for energy

Given the high water consumption levels of biofuels for the irrigation of biomass feedstocks, understanding the role of irrigated biomass is critical. Tracking the contribution of irrigation to the embodied energy of biofuels raises a number of issues. First, we are not simultaneously tracking the water usage for all agricultural products. Nor are we assigning credit to the co-products of biofuel production (e.g., dried distillers grains with solubles, DDGS) that displace water use for other crops (corn grain for animal feed) [21]. Therefore, a key question is to what extent this represents a transfer of water use from food production versus fuel production, or whether there is additional irrigation under high biofuels scenarios. A second, related issue is how scaling up the production of cellulosic biofuels may induce changes in land use and field management and the impact on water consumption (as well as quality) [22]. Such changes have already been seen with corn-based ethanol [23]. Third, when feedstocks such as corn stover and wheat straw are extensively utilized for energy purposes, the water consumption should be allocated between the food crop and the crop residues. However, how to allocate water between the crop and the residues remains an open question [21].

Level of resolution of water factors by fuel type

This paper represents a first-cut analysis looking at internally consistent, alternative scenarios for the evolution of the energy system, associated water requirements, and interregional trading of embodied water. Because the technology characterization in the model is defined to track flows of energy, the water factors utilized were averages or representative factors for each fuel technology category. However, there is a great deal of variation within fuel technology categories, and future work should focus on coupling scenarios of shifts in the generation mix with the different combinations of potential cooling technologies.

The role of regional analyses

Improving our understanding of the energy-water nexus will require not only better data [24, 12], but also analyses at a number of different scales. At one end of the spectrum there is a need for understanding national and even global shifts in energy extraction, production and use, how those are affected by policies regarding biomass-based fuels, heat and power, GHG emissions reductions, and renewable energy. At the local level, there is also a need to identify potential conflicts and constraints with a higher degree of spatial resolution and technology-specific detail. As highlighted in the DOE's 2006 Report to Congress [6], water-energy conflicts are already occurring across the country, including states such as Georgia, Nevada, Idaho, and Massachusetts. There are also potential opportunities for improvement related to water resources and energy production [25]. Regional analysis, such as the work described in this paper, can help to bridge the gap between different scales, and place local analysis in the context of national energy system trends and policies.

Looking at the interregional trading of fuels and embodied water could also provide insights into what similar trading of fuels and water might look like at the global scale. For this current analysis, the oil extraction water use is only for domestic crude oil, but we capture the refinery water use for refining of all crude oil, whether imported or domestic. Water use is also not included for imported finished petroleum products, given that the water use associated with these fuels occurs outside the United States. Similarly, the water use for biofuels, mainly ethanol, imported into the United States also falls outside of our system boundaries. Expanding the system boundaries to examine global trade in energy and fuels could reveal important patterns of international transfers of embodied water.

Future work

This work highlights how the MARKAL model can be used to examine the water implications of alternative energy futures. For future work, we will continue to refine and expand the scenarios, as well as the MARKAL input data for the USEPA9r database. Because of the importance of the role of biofuels and electricity, these will be the two key sectors for further work. Another potential fuel option of interest for future work is compressed natural gas (CNG), and looking upstream at natural gas water use, in particular, water injection for shale gas extraction.

Additional biofuel pathways, such as biofuels via gasification or pyrolysis, are currently being added in order to capture the differences in cost and performance of these different conversion technologies. We will also refine the biofuel production water input data. Other biofuel related factors to consider include: (a) the introduction of blends such as E15, (b) improving the regional characterization of state-level mandates for particular biofuel blends, and (c) improving the additional cost associated with ethanol distribution and E85 station retrofits.

For the electric sector, efforts are currently underway to distinguish between closed- and open-loop cooling systems for existing thermoelectric facilities in the MARKAL technology characterization. Other upcoming work may incorporate advanced technology options for reducing water use in future electric power generation systems. Additional scenarios could look more specifically at impacts of concentrated solar thermal electricity generation, high biomass use in the electric power production via co-firing or biomass gasification, expansion of wind power, or CCS retrofits, to give some examples.

Our goal for this paper is to present a set of different scenarios, in order to understand potential water implications of a range of possible energy futures. Future work, however, could start to assess how those energy futures might change based on restrictions in water availability. Those restrictions could be due to a number of policy, economic and other factors, but a major driver will be climate change and its effect on water availability in regions across the nation. Future scenario analyses will assess how constraints on water use may change energy choices across the regions, and by extension, interregional trading of water embodied in fuels and electricity.

CONCLUSIONS

Our results indicate that the regional water demand and interregional transfers of embodied water could be significant as the LDV fleet moves away from petroleum-based fuels toward a more heterogeneous LDV fleet and fuel mix. Water consumption associated with energy could increase from less than 3,000 Bgal/yr in 2005 to over 6,000 Bgal/yr by 2035. Regional exports of embodied water are on the order of hundreds of billions of gallons per year for ethanol from the Midwest (Table 1). Interregional transfers of water embodied in electricity may also reach tens of billions of gallons per year. However, this outcome will vary substantially based on the light-duty vehicle mix, carbon policy, electric power generation mix, biofuel production levels and feedstock characteristics. There is also a need to understand if total water consumption, for all sectors, increases under these scenarios.

These scenarios represent only a subset of the many possible mid- to long-term scenarios for the evolution of the energy system and its water needs, taking into account regional differences. Future work should not only explore a broader range of scenarios regarding the regional water pressures of energy and fuel production, but also identify potential synergies in terms of CO_2 reductions and conservation of scarce water resources.

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