

Impact of emerging clean vehicle system on water stress



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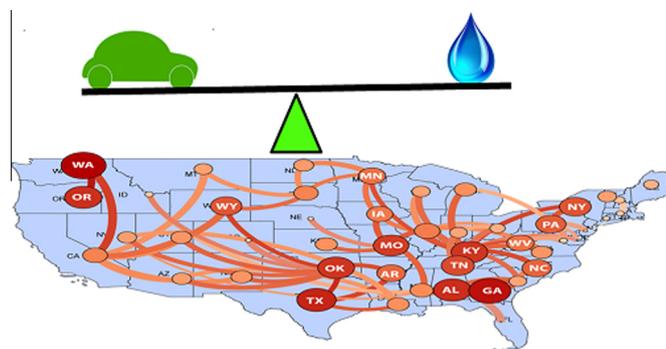
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HIGHLIGHTS

- Clean vehicles may increase US water consumption up to 2810 billion gallons/year.
- Large-scale clean vehicle adoption could lead to severe regional water stress.
- Fuel choice for clean vehicle is crucial in minimizing regional water stress.
- Regional optimization illustrated the importance of regional consideration.

GRAPHICAL ABSTRACT



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ABSTRACT

While clean vehicles (i.e., vehicles powered by alternative fuels other than fossil fuels) offer great potential to reduce greenhouse gas emissions from gasoline-based vehicles, the associated impact on water resources has not yet been fully assessed. This research provides a systematic evaluation of the impact of a fully implemented clean vehicle system on national and state-level water demand and water stress. On the national level, based on existing policies, transitioning the current gasoline-based transportation into one with clean vehicles will increase national annual water consumption by 1950–2810 billion gallons of water, depending on the market penetration of electric vehicles. On the state level, variances of water efficiency in producing different fuels are significant. The fuel choice for clean vehicle development is especially crucial for minimizing water stress increase in states with already high water stress, high travel demands, and significant variations in water efficiency in producing different alternative fuels. Current development of clean vehicle infrastructure, however, has not reflected these state-level variations. This study takes an optimization approach to further evaluate impacts on state-level water stress from a fully implemented clean vehicle system and identified potential roles (fuel producer or consumer) states may play in real world clean vehicle development scenario. With an objective of minimizing overall water stress impact, our optimization model aims to provide an analytical framework to better assess impacts on state-level water resources due to clean vehicle deployment.

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1. Introduction

Clean vehicles (i.e., vehicles powered by alternative fuels other than fossil fuels) have shown great potential in alleviating national

dependence on foreign oil and reducing greenhouse gas (GHG) emissions from the transportation sector [1–3]. In the US, the Renewable Fuel Standard (RFS2) passed as part of the Energy Independence and Security Act of 2007 mandates the use of 36 billion gallons of biofuels as transportation fuel by 2022 [4]. In his 2011 State of the Union address, President Obama also set a goal to put one million electric vehicles on the road by 2015 [5]. At state level, 27 states and the District of Columbia offer incentives to

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promote clean vehicles [6]. As of August 2012, there are 2270 ethanol (E85) fueling stations and 4364 electric charging stations in the US [7].

Despite the promise of greening the transportation sector, the development of clean vehicle system could significantly impact the nation's demand on water given that the life cycle of producing alternative fuels (e.g., electricity and biofuels) can be more water intensive than that of producing gasoline [8,9]. Previous research has focused on comparing life cycle water demand of alternative fuels on a per unit basis (kWh, gallon, etc.) [10–13] or on a per vehicle mile traveled (VMT) basis [14–17]. However, little attention has been paid on understanding the total water demand of a clean vehicle system and potential impacts of fueling mix strategies on regional water stress. In particular, King et al. examined the national water need for the US light duty vehicle fleet from 2005 to 2030 based on government projected transportation fuel consumption [18]. The projections on which King et al. based their study predict that fossil fuels will still dominate transportation fuel consumption by 2030 and electricity will only contribute to as high as 8%. Given the high uncertainties in clean vehicle system development, it is important to examine national water demand from a fully deployed clean vehicle system and its impacts on regional water stress, which remain largely unknown. This research aims to fill this knowledge gap by synthetically assessing the impact of clean vehicle systems on water stress at multiple geographic scales in the US. At the national level, we measured the additional amount of water required to support the transition into clean vehicle based road transportation. At the state level, we analyzed the variances of water intensity in adopting different fueling strategies for clean vehicles in each state. Using an optimization framework to minimize impacts on overall national and state-level water stress, we also identified roles that different state might play in a clean vehicle based transportation system under water-constrained conditions. Among various alternative fuels (biofuels, electricity, compressed natural gas, hydrogen, etc.), biofuels and electricity are perhaps the most promising and mature options today. Therefore, we focus primarily on biofuels and electricity as alternative fuels for clean vehicles in this study. In addition, we refer “transportation system” to road transportation including light duty vehicles, commercial light trucks, and freight trucks. Other modes of transportation (e.g., rail and air) are out of scope of this research.

2. Methods and data

2.1. National assessment

We evaluate how RFS2 mandates and market penetration of electric vehicles could impact national water demand in the next 10 years. RFS2 mandates that the volume of biofuel used as transportation fuel to reach 36 billion gallons by 2022, with 15 billion gallons come from corn starch derived ethanol, 16 billion gallons from cellulosic ethanol, and 5 billion gallons from other advanced biofuels. It specifies the mandated volume of each type of fuel year by year to 2022 and capped the volume of corn-based ethanol at 15 billion gallons per year starting from 2015. Because high uncertainties exist for market penetration of different types of vehicles, we modeled fuel consumption from the perspective of travel demand instead of fleet composition. To assess the impact of fully implemented RFS2, biofuel usage is evaluated on the RFS2 required level. Vehicle mileage traveled (VMTs) that could be met by available biofuels is then calculated based on this assumption. We then divide the fuel demand for the remaining national VMTs between gasoline and electricity based on the degree of car electrification (α). Water consumption required for producing clean vehicle fuels

is calculated based on water intensity of and VMTs powered by each type of fuel. In particular, water consumption for electricity generation is measured using the Water Use in Electricity Generation Model (WEGM) developed by the Argonne National Laboratory [13], with the grid mix projection by the Energy Information Administration (EIA) as inputs [19]. Water consumption of producing different biofuels is from previous studies (Table S2). Because cellulosic ethanol has not reached commercial scale production and have high uncertainties in technologies, we use switchgrass (a relatively mature feedstock in this category) to represent cellulosic ethanol feedstock [20–22]. Travel demand for road transportation is obtained from the national VMT projection in the reference case of the Annual Energy Outlook 2012 (AEO 2012) [19]. Note that our analysis focuses on water consumption from the fuel cycle but not the vehicle cycle. In addition, water demand and water usage both refer to water *consumption* in this paper, which is the amount of water withdrawn in the life cycle of fuel production and not returned to the original catchment. Details about methods and data on national assessment can be found in the Supporting Information.

2.2. State-level assessment

The state-level assessment is conducted for the contiguous US; Alaska, Hawaii, and other off-shore US territories are not included due to data limitation. We assume that each state will only use locally produced electricity or biofuels to fulfill travel demands in order to understand advantages and constraints of each state in producing alternative fuels. Interstate trade of biofuels and electricity is not included in state-level assessment but in state-level optimization (next section). In particular, we compared the “water mileage” (interchangeably used with “water intensity”) of electricity, corn-based ethanol, and cellulosic ethanol in each state that currently produces these alternative fuels. The water mileage refers to the amount of water embodied in transportation fuels (consumptive water) to power one unit of VMT, with a unit of gallon of water per mile. Water intensity of power generation in each state is obtained from the WEGM model [13] in a similar way described above in the National Assessment. We use data from Chiu et al. [11] for water intensity of corn-based ethanol production and Manley [23] for cellulosic ethanol production. Biofuel mileage is obtained from Harto et al. [14], while electric vehicle mileage is from Samaras and Meisterling [24]. Travel demand in each state is provided by the Department of Transportation [25]. More information can be found in the Supporting Information.

2.3. State-level optimization

Based on the state-level assessment of water impacts, we seek to identify roles that states might play (producer or consumer) in future national clean vehicle development given constraints posed by limited water resources in each state. This can be done straightforwardly by forecasting clean vehicle fleet development and measuring associated water consumption; however, significant uncertainties exist in simulating the diffusion of clean vehicle technologies. Instead, we use a reverse-engineering approach by constructing an optimization model for state-level clean vehicle fuel mixes to minimize water stress impact. States that appear to produce particular types of fuels in the water-optimized scenario are likely be more suitable for doing the same in reality from the water point of view. Similarly, states appearing to rely on fuel imports from other states will possibly face water stress to increase the cost of producing fuels themselves.

The goal of the optimization is not to minimize the total water consumption but to minimize overall impact on national and state-level water stress instead. We take into account not only water

efficiency in each state to produce alternative fuels, but also current water stress and incremental water stress due to the adoption of clean vehicles. Modified water stress index (mWSI) is used as a measure of water stress at state level. Water stress index (WSI) is commonly defined as the ratio of total annual freshwater withdrawal to total hydrological water availability at the watershed level [26]. Because alternative fuels policies are often made by state governments, we aggregated the withdrawal and availability data to the state level in this study. In addition, due to data limitation on recent hydrological water availability for the US (“National water availability and use has not been comprehensively assessed in 25 years” [27]), we used available precipitation, which is the amount of precipitation that is not lost to evapotranspiration and available for other uses, as an approximate measure of available renewable water in each state. The data we used to calculate each state’s mWSI were 2005 freshwater withdrawal and available precipitation data reported by Tetra Tech [28]. However, mWSI alone is not sufficient in evaluating the impact of additional water demand on water stress. For example, if two states have the same mWSI but state A’s available water is one magnitude greater than state B’s, increasing water demand by the same quantity will have greater impact in state B than in state A, because state A has a larger denominator. Currently there is no indicator available to assess the impact of additional water consumption on water stress; therefore, in this study, we introduced an Overall Water Stress Impact Indicator (OWSII) to quantify this impact. OWSII is expressed as the modified quadratic mean (or root mean square) of the product of each state’s current mWSI and additional mWSI ($\Delta mWSI$) due to clean vehicle adoption. $\Delta mWSI$ is the ratio of water consumption due to clean vehicle adoption in a state to total available water in that state. γ is a constant to normalize OWSII to be between 0 and 1, with OWSII equals to 1 when all available water is used. OWSII measures the overall impact of additional water consumption in the context of existing water stress. With minimization of OWSII as the decision objective in the optimization model, we are able to discourage additional water consumption in states that already have higher water stress, fewer available water resources, and lower water efficiency in producing certain fuels.

$$OWSII = \gamma \times \sqrt{[(mWSI_1 \times \Delta mWSI_1)^2 + (mWSI_2 \times \Delta mWSI_2)^2 + \dots + (mWSI_n \times \Delta mWSI_n)^2] / n}$$

Following key assumptions are made in the optimization model:

- i. To fully gauge the impact of clean vehicle development, road transportation will only be powered by electricity, corn-based ethanol, and cellulosic ethanol. Transportation of other modes is out of scope of this study.
- ii. Electricity consumption by electric vehicles will not be significant enough to impact state level grid mix or interstate electricity trade composition. The grid mix change due to electric vehicle use will largely depend on the charging behavior (charge at night vs. at peak hours) [29,30] and is outside of the scope of this study.
- iii. Production capacity of corn-based ethanol and cellulosic ethanol in each state will not exceed the level projected by US Billion Ton Study [31] in the high-yield scenario with 3% increase of energy crop yield and biomass price at \$60 per dry ton, year 2022 value. The Billion Ton Study projected values have taken land constraints into consideration.
- iv. Water efficiency will stay at current level regardless of amounts of fuels produced. Given the fact that water efficiency could be improved with higher production due to scale of economy and that it could be reduced because high production may exhaust most efficient resource and push the use of less efficient ones (e.g. less water efficient land),

we think this assumption is reasonable for the purpose of this study.

- v. National total consumption of corn-based ethanol and cellulosic ethanol as transportation fuels will meet RFS2 requirements for year 2022.
- vi. Travel demand (VMTs) of each state can either be met by producing transportation fuels locally or importing from other states. Water consumption occurring in transporting traded fuels is included in this model.

The optimization model can be mathematically expressed as below:

$$\min \left\{ OWSII = f(C, E, D) = \gamma \times \sqrt{\frac{1}{n} \sum_{i=1}^n \left(\frac{\sum_{j=1}^n (c_{ij} + \frac{e_{ij}}{k_i} + \frac{d_{ij}}{k'_i} + t_{ij})}{a_i} \times mWSI_i \right)^2} \right\}$$

s.t.

$$\sum_{i=1}^n \sum_{j=1}^n (c_{ij}/m_i + e_{ij}/m'_i + d_{ij}/m''_i) = VMT_j$$

$$\sum_{j=1}^n C_{ij} \leq Q_i$$

$$\sum_{j=1}^n d_{ij} \leq Q'_i$$

$$\sum_{i=1}^n \sum_{j=1}^n C_{ij} = R'$$

$$\sum_{i=1}^n \sum_{j=1}^n d_{ij} = R''_i$$

$$c_{ij} \geq 0; \quad e_{ij} \geq 0; \quad d_{ij} \geq 0$$

- C, E, D are each a 49×49 matrix. c_{ij} , e_{ij} , and d_{ij} represent corn-based ethanol, electricity, and cellulosic ethanol produced by state i and consumed by state j in million gallons, million kWh, and million gallons, respectively.
- k_i , k'_i , and k''_i stand for water efficiencies of corn-based ethanol, electricity, and cellulosic ethanol, respectively, representing the amounts of fuels (million gallons, million kWh, and million gallons, respectively) can be produced by consuming one gallon of water in state i .
- t_{ij} represents water consumption in million gallons as a result of transporting fuels (only corn-based ethanol and/or cellulosic ethanol) from state of origin i to state of destination j .
- a_i is the available precipitation in state i (million gallons).
- $mWSI_i$ is the current modified water stress index of state i .
- γ is a constant which equals to 6 to normalize OWSII to be between 0 and 1. If different set of data are used or the scope extends to include other states or territories outside of the contiguous US, γ should be recalculated to ensure normalization of OWSII.
- m_i , m'_i , and m''_i are fuel efficiencies of corn-based ethanol, electricity, and cellulosic ethanol, respectively, representing VMTs can be fulfilled by consuming one gallon of fuels or one kWh of electricity in state j (mile/gallon or mile/kWh).
- VMT_j represents travel demand in state i (million miles).
- Q_i and Q'_i are production capacities of corn-based ethanol and cellulosic ethanol in state i (million gallons).

– R_i' and R_i'' are mandated amounts of corn-based ethanol and cellulosic ethanol in RFS2 by 2022 (million gallons).

Distances between states for ethanol transportation are adopted from Stroger et al. [32]. Water intensity data are obtained for electricity generation [13], corn-based ethanol [11], and cellulosic ethanol [23]. Interstate electricity trade is estimated using the model from Marriott and Matthews [33] updated with up-to-date data by the authors. State level travel demand data are obtained from the US State Transportation Statistics [25]. The impact of “blend wall” on ethanol distribution and the charging behavior of electric vehicles are out of the scope of this study. More information about the optimization model can be found in the Supporting Information.

3. Results and discussion

3.1. National assessment

Results of the national assessment show that transition into clean vehicle based transportation will increase the national annual water consumption by 1950–2810 billion gallons, depending on market penetration of electric vehicles (Fig. 1). Water demand increases over time as RFS2 requires greater amount of biofuels as transportation fuels. In addition, more water is required along with increasing penetration of electric vehicles. Based on the most recent national water consumption data (1.27×10^5 billion gallons in 2005 [34]), clean vehicle deployment will increase national water consumption by 1.5–2.2%, largely due to consumption of corn-based ethanol. Approximately 65–80% of additional water consumption comes from the production of corn-starch derived ethanol, although RFS2 has capped the volume of corn-starch ethanol to be 15 billion gallons per year starting from 2015 (Fig. S1).

The 1.5–2.2% increase of national water consumption due to clean vehicle development may not seem alarming numerically.

However, the true impacts at regional scale are more important depending on the level of water stress that already exists. When occurring in states that are already under severe water stress, the same amount of increase of water consumption will cause more significant impact than in states with relatively abundant water resources. In addition, water intensities of producing particular fuels are different in each state depending on climate conditions and geographic locations. Our state-level assessment takes one step further to examine regional differences and the implications on water stress in each state.

3.2. State-level assessment

State-level assessment results show significant variations of water intensity across states (Fig. 2 and Table S3). For example, water intensity of corn-based ethanol is orders of magnitude higher than that of electricity or cellulosic ethanol in some states (e.g., California, Utah, and Arizona). These states are more susceptible to increasing level of water stress if clean vehicle fleet is fueled primarily by corn-based ethanol. On the other hand, water intensity of electricity is orders of magnitude lower than that of biofuels in states such as Florida and Rhode Island. An electric vehicle-dominated clean vehicle fleet is obviously more desired in order not to significantly increase the level of water stress in these states. Fig. 2 also shows travel demand in VMTs and mWSI as a measure of level of water stress in each state. The fuel choice for clean vehicle development is more crucial for minimizing water stress increase in states with higher VMTs and higher mWSI (e.g., Colorado and Nebraska).

Despite the significant variations of water intensity of alternative fuels and level of water stress across states, they have not been reflected on current clean vehicle infrastructure development. Using the number of E85 fueling stations each state currently has as an indicator of infrastructure development and adoption of biofuel-based clean vehicle system, Fig. 3 shows that E85 fueling

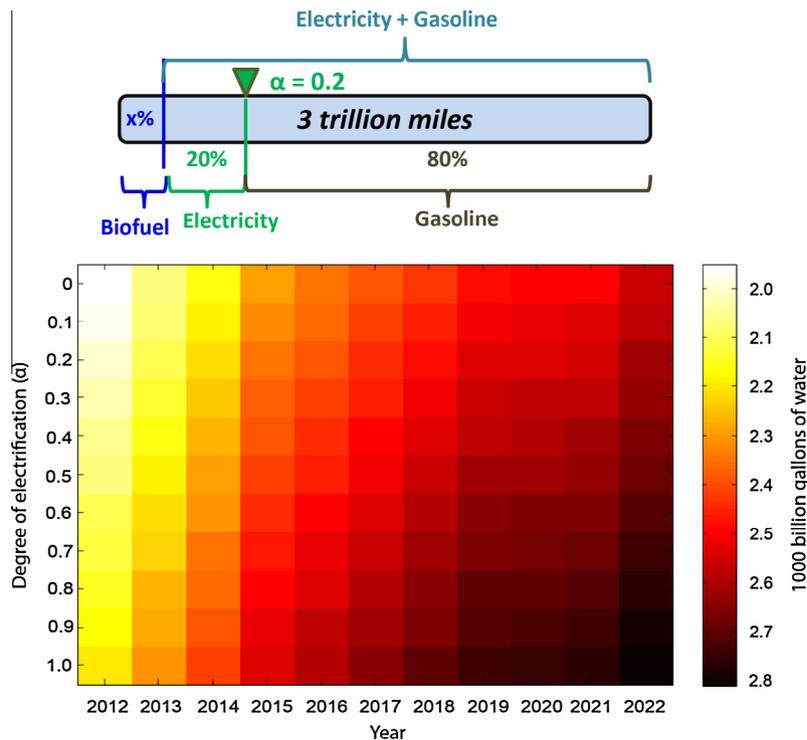


Fig. 1. Projected additional water consumption due to clean vehicle deployment. Degree of electrification (α) refers to the percentage of remained travel demand (after applying biofuels mandated by RFS2) that is fulfilled by electric vehicles (the rest by gasoline).

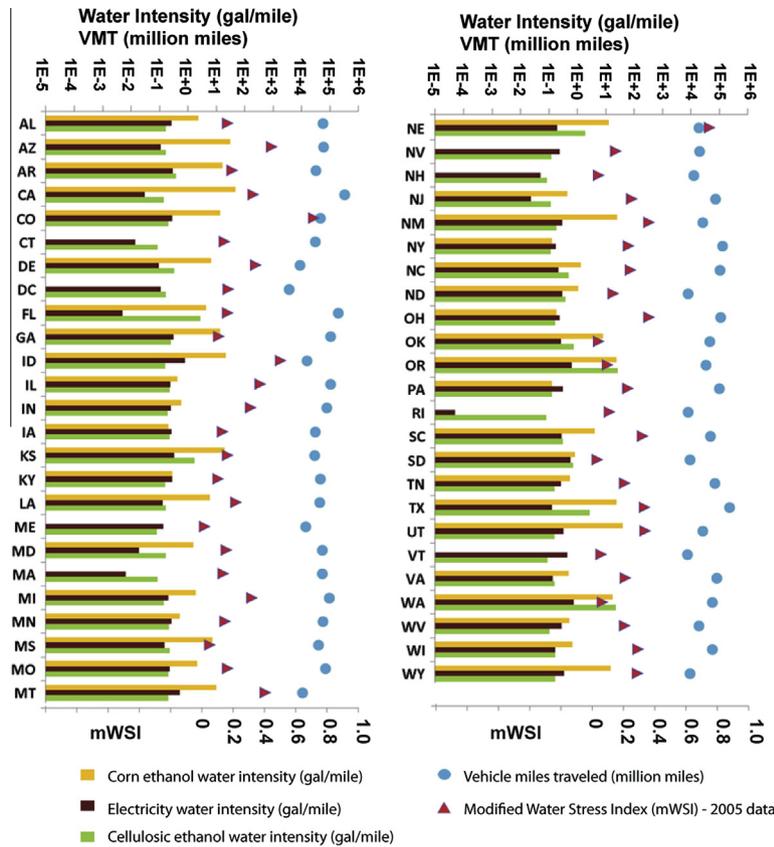


Fig. 2. Comparison of water intensity of alternative fuels, travel demand (VMTs), and level of water stress (mWSI [28]) in each state.

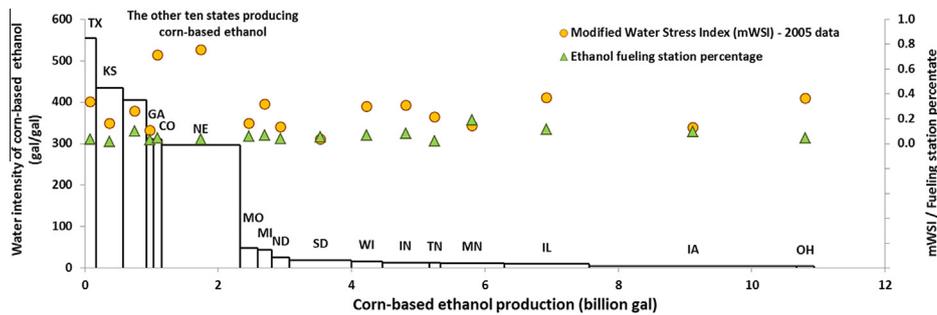


Fig. 3. Comparison of corn-based ethanol production, water intensity, mWSI [28], and E85 fueling station across states.

station ownership is similar across states and does not reflect state-level difference in water intensity of alternative fuels or potential water constraints indicated by mWSI. In addition, the development of biofuel infrastructure also does not correlate with state-level corn-based ethanol production (*x*-axis) or water consumption due to corn-based ethanol production (the area of each bar).

3.3. State-level optimization

In the real world, fuels are produced in particular states and can be consumed by either the producing states or other states. Given the state-level variations described above, two approaches can be taken to further evaluate state-level water impact from a fully implemented clean vehicle system: projection and optimization. One can project the mix of clean vehicle fleet in each state and then measure associated water consumption, with significant uncertainties of course due to the fact that a clean vehicle-based transportation system does not exist and its development depends on so many intertwined factors. Alternatively, we choose to optimize fuel mixes for clean vehicle deployment to minimize the impact on

national and state-level water stress. In a clean vehicle-based transportation system in the real world, states are likely to play similar roles (fuel producer or consumer) to the roles that they play in the optimized scenario, provided that minimizing impacts on water stress (not minimizing gross water consumption) is one of the goals of policymaking in clean vehicle development.

Results of state-level optimization show that Iowa, Ohio, South Dakota, and Minnesota produce 88% of the 15 billion gallons of corn-based ethanol mandated by RFS2 (Fig. 4a), because they have not only relatively high water efficiency for producing corn-based ethanol but also lower level of water stress and abundant water resources (Fig. 2). Iowa is the leading producer which contributes 55% of total production. The remaining 12% corn-based ethanol is produced by Kentucky, Illinois, Pennsylvania, Tennessee, Mississippi, and New York. These states share similar pattern of relatively high water efficiency, low level of water stress, and high available water resources (Fig. 2). Land is a bounding constraint in Kentucky, New York, Pennsylvania, and Tennessee, which means higher production capacity in these states can benefit the system OWSII. Iowa, Minnesota, and South Dakota are already current leading

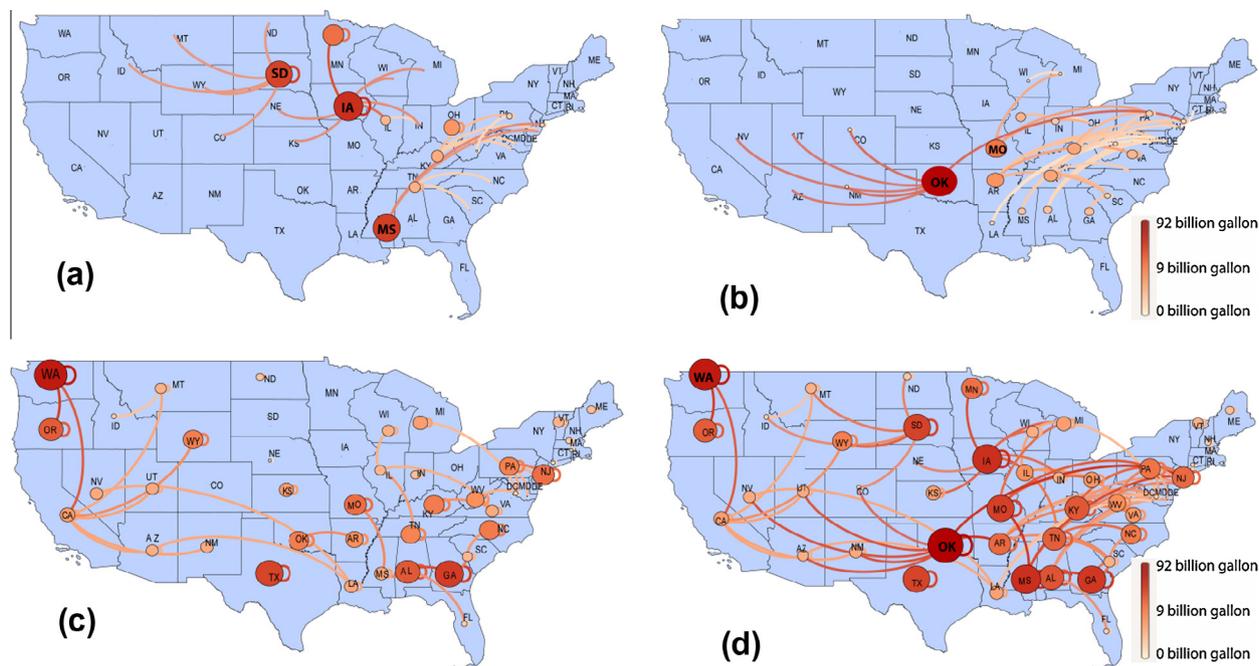


Fig. 4. Optimized state-level water consumption and water flows embodied in interstate trade of alternative fuels: (a) corn-starch derived ethanol; (b) cellulosic ethanol; (c) electricity; and (d) total water consumption and flows. Size and color of circles indicate the amount of water consumption (in log scale) related to producing designated fuels, including fuels consumed within the state and those transported to other states. Lines go clockwise from states producing to states consuming designated fuels. Line color indicates the amount of water embodied in interstate trade of fuels. All graphs are on the same scale. Color of lines and circles share the same scale as well. The “ear” on the circle represents self-consumption. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

producers of fuel ethanol, respectively producing 28%, 9%, and 9% of fuel ethanol in 2009 [35]. Nebraska, however, which produced 11% of fuel ethanol in 2009, is not recommended by our model to be a corn-based ethanol producer due to lower water efficiency and higher water risks.

Production of cellulosic ethanol is clustered in the optimized scenario in the way that either one state (e.g., Oklahoma, Missouri, Arkansas, Kentucky) supplies several other states or several other states supply one state (e.g., South Carolina, District of Columbia, Pennsylvania) (Fig. 4b). These clusters exist because the production capacity of cellulosic ethanol is still relatively low by 2022 in many states. Nineteen states, led by Oklahoma, would be producing cellulosic ethanol at their peak capacities to meet RFS2 targets. These states, with relatively high water efficiency for producing cellulosic ethanol and lower level of water stress, are likely to be major cellulosic ethanol producers.

Corn-based ethanol and cellulosic ethanol together can fuel approximately 35% of the national travel demand by 2022 in the optimized scenario, while the rest 65% is powered by electricity. This is not to imply that market penetration by 2022 will be high enough to take up 65% of the travel demand. Instead, this result indicates that in a fully deployed clean vehicle system, to minimize overall water stress impact, electricity would be the dominant transportation fuel source. At state level, 28 out of the 49 states use electricity as the main transportation fuel (Fig. 4c and Table S4). The amount of water needed for producing electricity for transportation is significant in states with relatively lower level of water stress and high travel demand, such as Washington, Georgia, Texas, and Alabama, while water intensity of power generation seems to play less important role.

Altogether, a fully deployed clean vehicle system optimized under water constraints consumes approximately 629 billion gallons of water in the US. Comparing with the gasoline scenario in the national assessment, the incremental water requirement is 240 billion gallons of water, about 10% of the value estimated in the national assessment, which indicates significant potential in reducing addi-

tional water demand due to clean vehicle system development. Fig. 4d shows total fuel production-related water consumption in each state and flows of water embodied in interstate fuel trade. Overall, major water-consuming states (e.g., Oklahoma, Washington, Mississippi, Iowa, Georgia, South Dakota, Texas, Alabama, Oregon, Kentucky, and Missouri) identified in the optimization are likely to face significant increase of water demand as clean vehicles develop. States that only rely on fuel imports from other states in the optimization are likely to face significant challenges of increasing water stress due to clean vehicle development.

The state-level optimization results separation of production and consumption of transportation fuels for clean vehicles across the US. (Fig. 5). In particular, fuel production is divided by the borderlines of North Dakota and Minnesota from the north to Texas and Louisiana. In the west, except in Oklahoma, South Dakota, Colorado, Arizona, and New Mexico, electricity is the only fuel produced in the optimization, while biofuels are mostly produced in states in the east. This segregation of fuel production is largely due to the fact that states in the west are in general under higher water stress. In contrast, the consumption of transportation fuels is spread across states, meaning that states with server water stress can potentially fulfill their travel demand using clean vehicles by importing fuels produced in other states.

3.4. Sensitivity analysis

Sensitivity analysis is conducted to test the robustness of our results against key assumptions and identify parameters that the results are most sensitive to. We employ the perturbation method [11] to test the sensitivity of incremental national water consumption to mWSI, water efficiency of producing particular fuels, travel demand, and total available precipitation in each state. While detailed results of sensitivity analysis can be found in Supporting information Fig. S3, we summarized states and parameters that the model is most sensitive to in Table 1. Because Iowa, Mississippi, and Oklahoma are leading producers of biofuels, changes in their

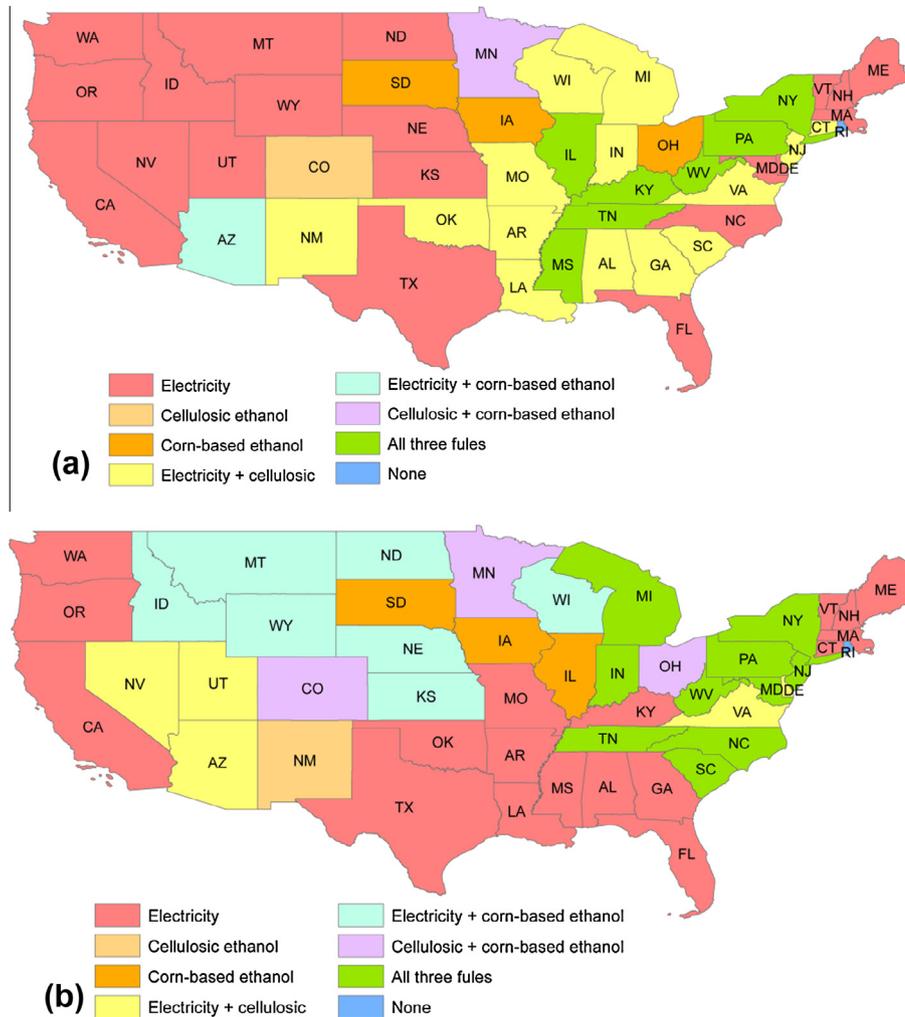


Fig. 5. Segregation of transportation fuel production (a) and consumption (b) under the optimized scenario minimizing clean vehicle development impacts on water.

Table 1

Selected states and parameters that the optimization model is most sensitive to.

Parameters	States whose parameter change by 10% can cause total water consumption to change by more than 1%
mWSI	Iowa, Mississippi
Water intensity of corn-based ethanol	Iowa
Water intensity of cellulosic ethanol	Oklahoma
Water intensity of electricity	None
VMT	None
Total available water	Iowa, Mississippi

mWSI, water intensity of fuel production, and total available water can change the model outputs most significantly. We have also tested biofuel price and yield's impact on total water consumption and found that the model is more sensitive to the production capacity of cellulosic ethanol than that of corn-based ethanol (Fig. 6). This is mainly due to the fact that corn-based ethanol production is relatively more mature than cellulosic ethanol so that biomass price change generally impacts the amount of corn-based ethanol that each state produces but not the number of states producing. Cellulosic ethanol, on the other hand, as one of the second generation biofuels, is more sensitive to biomass price. Therefore, changes in cellulosic ethanol production capacity often impact

not only incremental water consumption but also the pattern of interstate trade.

4. Conclusion

This research shows that impact on water stress from additional fuel production should be considered in clean vehicle development and deployment. Large-scale clean vehicle fuel production could lead to severe water stress in particular regions and potentially a long-term “drink or drive” dilemma. To avoid unintended consequences on water resources, state-level variations should be taken into account in clean vehicle development policymaking. Our optimization results show that Iowa and Oklahoma are suitable for producing corn-based ethanol and cellulosic ethanol, respectively, given relatively high water efficiency in production, lower level of water stress, and abundant water resources. Thus clean vehicles fueled by biofuels should be encouraged in states like Iowa and Oklahoma, while other states should focus on electric vehicles. The national assessment in this research shows that total incremental water consumption for clean vehicle systems would be 2310–3190 billion gallons. This can be reduced to 240 billion gallons when state-level impacts on water stress are minimized in the optimization scenario. The difference demonstrates the great need of considering the issue of state-level water stress in clean vehicle development decision making.

Our state-level optimization is conducted in order to minimize impacts of clean vehicle development on level of water stress

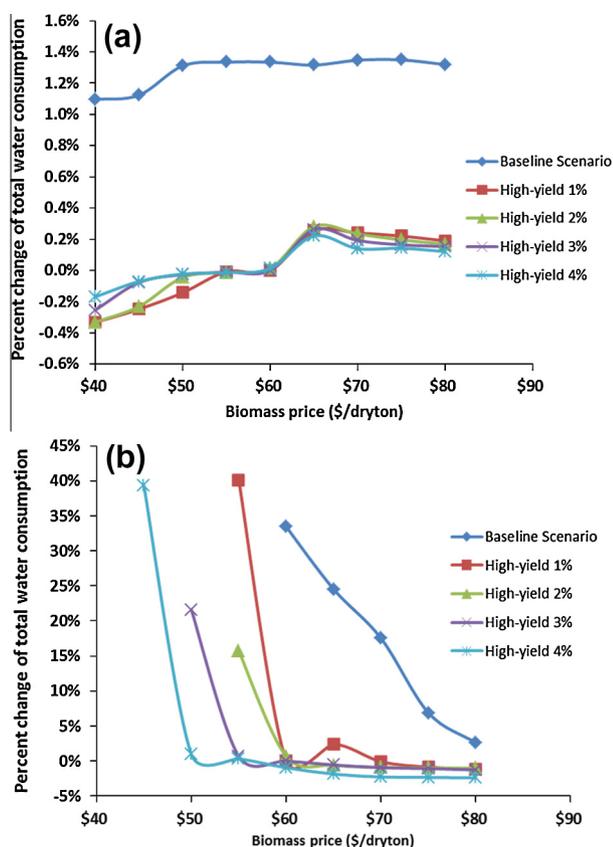


Fig. 6. Sensitivity analysis results of biofuel production capacity's impact on total water consumption in the state-level optimization. (a) corn-based ethanol and (b) cellulosic ethanol.

across states. While state may not be the best boundary when assessing water resources, policies regarding renewable energy and transportation are generally made at the state level. Future research at county level or taking watershed boundaries into consideration is encouraged. Other factors also need to be taken into consideration in clean vehicle deployment, such as cost of energy, direct and indirect land use change, and technology limitation. This research does not provide a “plan” for clean vehicle deployment per se, but aims to provide an analytical framework to better assess impacts on state-level water resources due to clean vehicle deployment. With this optimization framework, a multi-criteria optimization model can be developed to account for other factors important to clean vehicle development decision making.

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Appendix A. Supplementary material

Detailed description of methods, assumptions, and data. Supplementary figures and tables presenting the results and

sensitivity analysis. Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.apenergy.2013.05.023>.

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