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Water Consumption in the Production of Ethanol and Petroleum Gasoline

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Abstract We assessed current water consumption during liquid fuel production, evaluating major steps of fuel lifecycle for five fuel pathways: bioethanol from corn, bioethanol from cellulosic feedstocks, gasoline from U.S. conventional crude obtained from onshore wells, gasoline from Saudi Arabian crude, and gasoline from Canadian oil sands. Our analysis revealed that the amount of irrigation water used to grow biofuel feedstocks varies significantly from one region to another and that water consumption for biofuel production varies with processing technology. In oil exploration and production, water consumption depends on the source and location of crude, the recovery technology, and the amount of produced water re-injected for oil recovery. Our results also indicate that crop irrigation is the most important factor determining water consumption in the production of corn ethanol. Nearly 70% of U.S. corn used for ethanol is produced in regions where 10–17 liters of water are consumed to produce one liter of ethanol. Ethanol production plants are less water intensive and there is a downward trend in water consumption. Water requirements for switchgrass ethanol production vary from 1.9 to 9.8 liters for each liter of ethanol produced. We found that water is consumed at a rate of 2.8–6.6 liters for each liter of gasoline produced for more than 90% of crude oil obtained from conventional onshore sources in the U.S. and more than half of crude oil imported from Saudi Arabia. For more than 55% of crude oil from Canadian oil sands, about 5.2 liters of water are consumed for each liter of gasoline produced. Our analysis highlighted the vital importance of water management during the feedstock production and conversion stage of the fuel lifecycle.

Keywords Water consumption · Corn ethanol · Cellulosic · Oil sands · Conventional oil · Feedstock · Fuel production

Introduction

Water is an essential part of energy production, required both for resource extraction and fuel processing. Therefore, an increase in energy production from conventional, non-conventional, and renewable sources would lead to an increased demand for water. In recent years, with the growing public awareness that U.S. dependence on foreign oil reduces our energy security, retards economic growth, and exacerbates climate change, alternative and renewable fuels are gaining increased visibility and support. The 2007 *Energy Independence and Security Act* (EISA) is further committing this country to produce 36 billion gallons of renewable fuels by 2022. As a result, biofuels production in the U.S. is increasing at an unprecedented speed, exceeding a record of 9.0 billion gallons of ethanol in 2008 (RFA 2007). At the same time, as domestic crude oil production declined over the last 30 years, the U.S. became increasingly dependent on imported fuel (EIA 2008). Today, Canada, Mexico, Saudi Arabia, Venezuela, and Nigeria are the major suppliers of crude oil to the U.S. market, accounting for a combined 64% of crude imports (EIA 2007a, 2008). The Canadian oil industry, in particular, has rapidly expanded capacity to produce crude oil from oil sands, nearly doubling production from 0.66 million barrels per day (bbl/d) in 2001 to 1.2 million bbl/d in 2007 (CAPP 2008a). Oil-sands-derived crude has become the no. 1

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crude oil imported to the U.S. Such a rapid increase in fuel production requires increased water input and raises important sustainability questions. In today's business climate, sustainability considerations are becoming not only key inputs to business decisions, but also decisive factors affecting competition worldwide. In this context, a thorough examination of water consumption during biofuel and petroleum production is more than a useful exercise—it is a critical input to policy development.

The agricultural sector uses significant amounts of water to produce the food, feed, and fiber to meet ever-increasing worldwide demands. In the U.S., 42% of freshwater *withdrawals* are for agriculture, followed by 39% for thermoelectric generation. However, 85% of the total U.S. freshwater *consumption* is attributable to agricultural irrigation, compared with less than 3% for thermoelectric generation (Gollehon and Breneman 2007). Nevertheless, total irrigation water use in the U.S. has declined and stabilized at a lower level since 1980. As reported by the U.S. Department of Agriculture (USDA), the amount of water applied per acre has decreased from 64 cm (25 in.) in the 1970s to 51 cm (20 in.) today, despite an increase in the total irrigated cropland (Gollehon and Breneman 2007).

Historically, ethanol has been produced from grain-based crops, and water has been supplied by precipitation and/or irrigation. Today, forest wood residues, agricultural residues, dedicated energy crops, and other herbaceous biomass are being considered as feedstocks for cellulosic ethanol. A study conducted by the U.S. Department of Energy (DOE) and USDA estimated that more than a billion tons of biomass is available for biofuel production (Perlack and others 2005). Although forest wood generally does not require irrigation, the impact of large-scale production of cellulosic biofuel from dedicated energy crops on water resource availability has not been fully examined.

Similarly, water consumption has become an increasingly important factor in conventional and unconventional crude oil production. Recently, Canadian proven oil reserves have been rated second among those in oil-rich nations. 98% of Canada's reserves are deposited in oil sands (Radler 2008). Although large-scale production of oil-sands-based crude has grown rapidly in last few years, Canada's annual output may be limited by water resources because there is only enough water available to support production of 2–3 million bbl/d of oil-sands-based crude oil (Peachey 2005), a level that may be reached by 2012–2016 (CAPP 2008c).

The petroleum industry has begun to emphasize water management practices and look for alternative water sources to reduce freshwater consumption, particularly in regions where water resources are scarce. Saline water, brackish water, and even desalinated seawater are being used for oil exploration and production (E&P).

A number of attempts have been made to estimate water consumption in fuel production since early 90s. Gleick (1994) presented a comprehensive technology analysis of water use in energy produced from coal, petroleum oil, natural gas, bio-source, hydroelectric, nuclear, etc. In 2006, a U.S. DOE report projected an increase in water demands at an alarming speed resulting from conventional and biofuel production (DOE 2006). Water resource implications of a large scale biofuel production were explored by NRC (National Research Council) (2007). Based on earlier estimates, King and Webber (2008) analyzed water use from producing petroleum, biofuel, and electricity to drive plug-in vehicles. Most recently, Chiu and others (2009) examined various irrigation methods and their effect on irrigation water withdrawal in the production of ethanol at the state level, emphasizing regional variations. This study examines the water consumption in feedstock production and fuel processing/production, which are by far the most water intensive—for (1) ethanol from corn, (2) cellulosic ethanol from switchgrass, (3) gasoline from domestic crude oil obtained from onshore wells, (4) gasoline from Saudi Arabia conventional crude oil, and (5) gasoline from non-conventional Canadian oil sands. For this analysis, switchgrass was chosen as a representative cellulosic feedstock. Our analysis takes into account regional variations and historic trends in water consumption for the selected fuels and identifies opportunities to reduce water use at specific lifecycle stages. Beyond this, our efforts toward thorough and careful collection and examination of inventory and water intensity data are directed toward building a comprehensive life cycle assessment (LCA) of water consumption during the production of various liquid fuels. The outcome of this study will provide a critical baseline for decision makers who are planning sustainable large-scale expansion of biofuel production to reach the country's overarching goal of energy independence.

Methodology

System Boundaries and Water Balance

Water use for plant growth is an intrinsic part of the hydrologic cycle. Rainfall that precipitates on the ground and irrigation water that is applied to the crops follow several paths: absorption by plants, percolation into the soil, surface runoff to waterways, and infiltration into groundwater aquifers. Water is lost to the air by evaporation from soils and streams and by transpiration from plants (transpiration accounts for the movement of water within plants and the loss of water vapor through stomata in the leaves). The sum of transpiration and evaporation is termed *evapotranspiration* (ET). This study focuses on

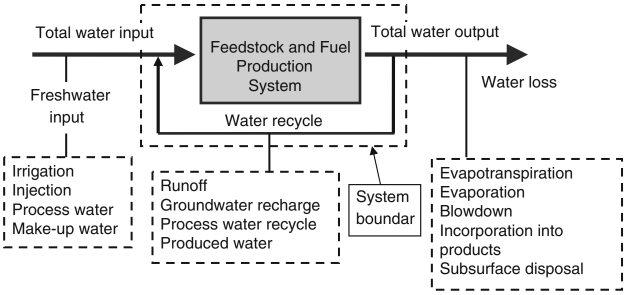


Fig. 1 System boundary, water inputs, outputs, and losses of a conceptual feedstock and fuel production system

consumption of irrigation water (not including precipitation) for growing biofuel feedstock and consumption of process water during fuel production.

As illustrated in Fig. 1, this study defines water consumption as freshwater input during feedstock and fuel production activities less output water that is recycled and reused. The *feedstock and fuel production system* consists of feedstock farming (or resource extraction) and fuel processing. *Total water input* consists of freshwater and recycled water that supports feedstock or fuel production as irrigation water, injection water for crude recovery, process water, or make-up water for process heating and cooling. *Total water output* consists of water losses (consumption) and recycled water. *Water loss,* which occurs across from the system boundary through ET, evaporation, discharge, disposal, and incorporation into products, can be in liquid (wastewater) or gaseous (vapor) form. *Water recycle* is the water that is reused in the system; examples include irrigation runoff recharged to a water body, produced water (PW) re-injected during oil recovery, and treated water reused during the fuel production process.

Ethanol production plants and oil refineries have well-defined system boundaries, and water consumption typically varies little from one location to another. By contrast, feedstock production requires much more water, and there can be considerable variation from one farm or oil well to another. Unfortunately, site-specific data (such as the amount of runoff from a particular cornfield to surface water or groundwater in its watershed, or injection water flow into a single well) are not readily available across the U.S. Thus, we examined feedstock production on a macroscale, as described below.

Figure 2 depicts the system boundaries of feedstock production and fuel processing/production that we developed for our study. As shown in Fig. 2a, the farm receives freshwater from irrigation as needed. Irrigation water that runs off the field to surface streams and recharges groundwater is ultimately returned to the watershed and reused. For this analysis, we assume a system that includes the farm and its watershed; surface water runoff and groundwater recharge are within this system. This assumption is appropriate because we focus on regional feedstock production, not individual farm operations. In this context, irrigation water consumption for corn accounts for irrigation water loss from soil percolation and ET across the system boundary, which cannot be reused in the system (the watershed). A small amount of the irrigation water is also consumed via absorption to the crop.

In an oil field, water is introduced through an injection well and PW is generated. Some of the PW is re-injected into the production well for oil recovery and some is pumped into the subsurface through disposal wells. For an individual oil field, local geology and hydrology strongly affect the system boundary—defining a closed system if injection water is retained in the formation or an open one if injection water flows to nearby formations. For this analysis, we assume a closed system; we also assume that the disposal wells that receive some of the PW are outside the system boundary. Given these assumptions, PW reinjection for oil recovery is conceptually equivalent to water recycle, and water consumption for oil recovery accounts for the water loss by PW disposal (to the subsurface, an evaporation pond, or discharge). Figure 2b illustrates this equivalence.

As shown in Fig. 2c, water consumption in the fuel production process includes (1) water lost through evaporation, drifting (which occurs when the cooling water flowing downward contacts upward-rising ambient air in the cooling tower), and blow-down from the cooling tower; (2) incorporation into products and co-products; (3) process water discharge; and (4) water lost via evaporation and blow-down from the boiler.

Data Collection and Processing

We identified regions to represent current production for each liquid fuel and used them to target the data search. Because data relevant to production and water consumption are mostly presented by state, this factor became the natural basis for analysis. State data are aggregated into regional estimates.

We obtained process-level data on water use (by fuel production technology) from the literature and weighted them by estimated market share to derive averages. We identified variations among regions, characterized them according to a range of data values, and (in the case of relatively large variations) reexamined them to identify responsible factors. Because liquid fuel industries typically use a volume-based product metric, results are expressed as liters of water consumed per liter of product fuel (L/L).

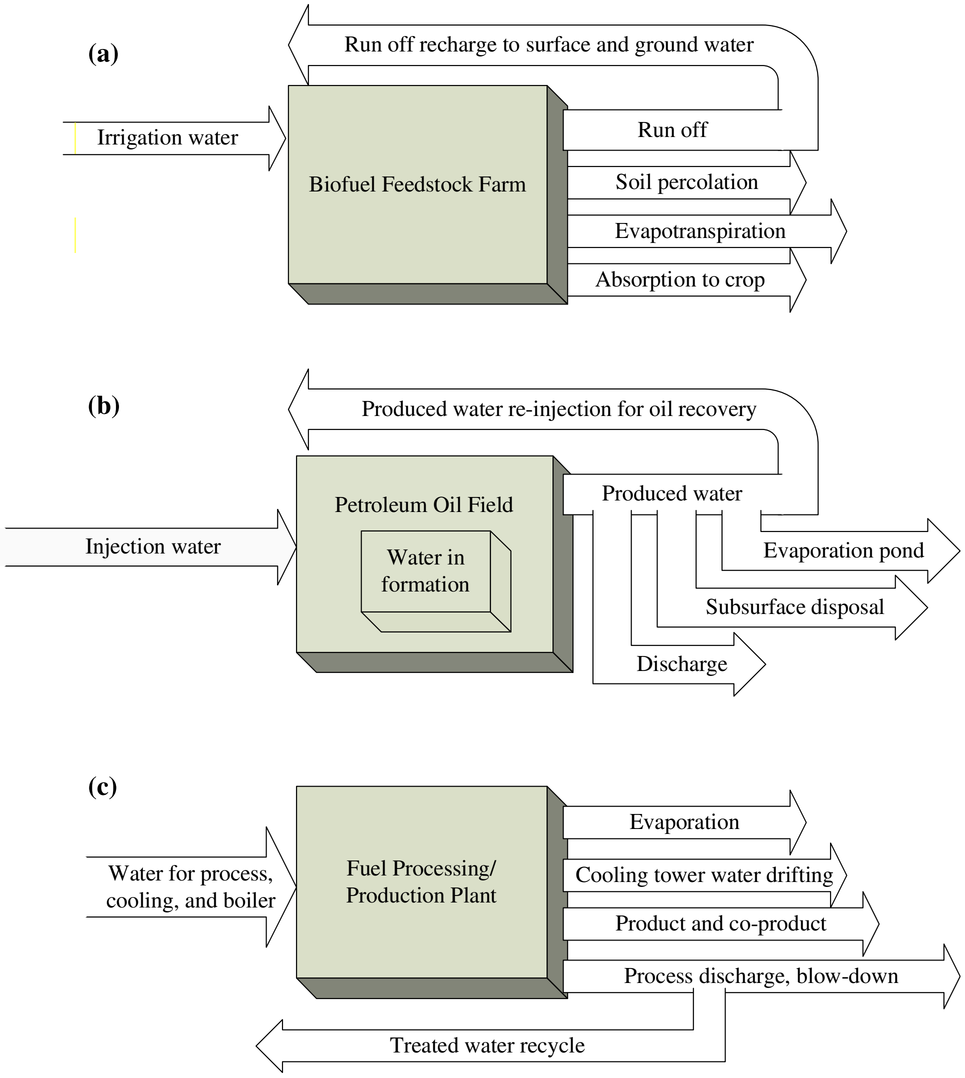


Fig. 2 Water inputs and outputs developed for this study for **a** biofuel feedstock production, **b** petroleum oil production, and **c** biofuel production/oil refining

Corn Ethanol

For the bioethanol analysis, we focused on the USDA farm production regions (Fig. 3) responsible for most biofuel feedstock and ethanol production. The main production regions are in the upper and lower Midwest: USDA Region 5 (Iowa, Indiana, Illinois, Ohio, and Missouri), Region 6 (Minnesota, Wisconsin, and Michigan), and Region 7 (North Dakota, South Dakota, Nebraska, and Kansas). Together, these regions account for 89% of corn production (USDA–NASS 2007, 2008) and 95% of ethanol production in the U.S. in 2006 (RFA 2007).

Consumptive irrigation water use was estimated on the basis of corn irrigation data from the USDA *Farm and Ranch Irrigation Survey* (USDA 2003) and water withdrawal and consumption data from the U.S. Geological Survey (USGS 1995). We first estimated regional total irrigation water applied for corn in USDA Regions 5, 6, and 7. USGS (1995) reported that 71% of irrigation water is consumed and the remaining 29% recharges to surface and groundwater. Using these percentages, we then estimated the consumptive irrigation water use for corn in each

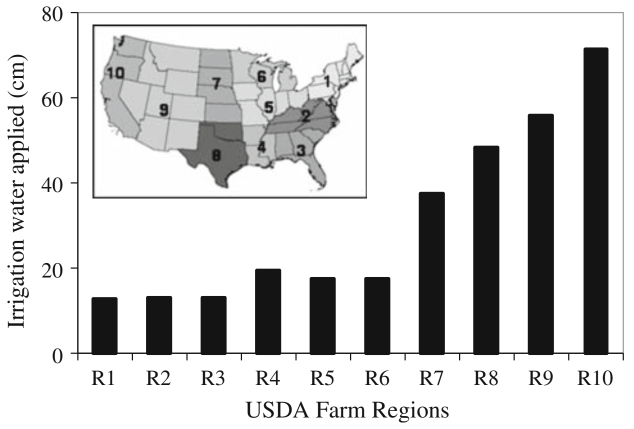


Fig. 3 Corn irrigation rate for the irrigated corn area by USDA region (Data source: USDA 2003)

region. Dividing this figure by the total corn production in 2003 (USDA-NASS 2008), we obtained a production-weighted consumptive total irrigation water use value. Note that this value represents an average value considering corn production from both irrigated and non-irrigated farms. This amount was further broken down into surface water and groundwater use for each region according to USGS 2000 survey (USGS 2000) and the split between surface water and groundwater per unit of corn was determined.

On the basis of the regional irrigation water estimate and assuming a dry mill ethanol yield of 0.4 liter per kg (2.7 gallons per bushel), we derived values for consumptive irrigation water use per liter of ethanol in the three USDA regions. By combining the irrigation values with water consumption values in the ethanol production plant, we further estimated the total amount of water consumed.

To analyze regional variations, we calculated the percentage of irrigated corn acreage by comparing total harvested corn areas that are irrigated with total harvested corn areas for each state in USDA Regions 5, 6, and 7. The regional estimates and three-region average were calculated the same way.

For corn ethanol plants, we estimated average water consumption for the existing stock of dry mill plants based on a 2007 RFA survey (Wu 2008). The total water consumption was weighted by the ethanol production.

Cellulosic Ethanol

In accordance with the literature, we assumed that switchgrass is grown in its native region to yield acceptable amounts of biomass without irrigation requirements. The harvested feedstock is transported to local biorefineries for conversion to ethanol via biochemical or thermochemical processes. Estimates of water consumption for switchgrass-based ethanol production are based on process simulation results from the National Renewable Energy Laboratory because the technologies are not yet fully commercialized.

Petroleum Gasoline

This analysis sought to construct a series of composite estimates of water consumption intensity for the regions accounting for the bulk of oil production. For conventional gasoline, we examined three Petroleum Administration for Defense Districts (PADDs) that represent 90% of U.S. domestic onshore crude oil production and 81% of U.S. refinery output (EIA 2007d). These regions are: PADD II (North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana, Ohio, Kentucky, and Tennessee), PADD III (Texas, New Mexico, Arkansas, Louisiana, Mississippi, and Alabama), and PADD V (California, Alaska, Arizona, Nevada, Oregon, and Washington).

We estimated water consumption for each of these regions. Oil recovery can be accomplished via several technologies, each of which has different injection water requirements. In addition, large amounts of PW are generated from oil wells and lifted to the surface along with oil. The PW is typically re-injected into the oil well for oil recovery (Fig. 2b). Thus, in order to estimate net water consumption for crude recovery, we need to determine technology-specific water injection requirements and market shares for each technology. Then, the amount of PW re-injected into the oil well must be subtracted from the total injection requirements.

This approach is described in Eqs. 1 and 2. We first estimated (1) technology-specific water requirements (L/L oil) from the literature and (2) the market share for each technology based on Energy Information Administration data and *Oil & Gas Journal* publications. Once we had estimated the contribution to oil production from each technology, we calculated the injection water requirement as a technology-weighted average (L/L oil) for the U.S. (Eq. 1). Because regional technology shares are not readily available, regional water usage was estimated by using national technology shares assuming similar market shares and intensity for each region of interest.

$$\begin{array}{c}\textbf{Technology share}\\ \textbf{of oil production}\\ \textbf{(\%)}\\ \text{Tech. 1}\\ \text{Tech. 2}\\ \text{Tech. 3}\\ \ldots\ldots\\ \text{Tech. n}\end{array} \times \begin{array}{c}\textbf{Injection water}\\ \textbf{required (l/l oil)}\\ \text{Tech. 1}\\ \text{Tech. 2}\\ \text{Tech. 3}\\ \ldots\ldots\\ \text{Tech. n}\end{array} \Rightarrow \begin{array}{c}\textbf{Technology weighted}\\ \textbf{injection water}\\ \textbf{requirement}\\ \textbf{(l/l oil)}\end{array} \quad \ldots \text{[Equation 1]}$$

$$\begin{array}{c}\textbf{Technology weighted}\\ \textbf{injection water}\\ \textbf{requirement}\\ \textbf{(l/l oil)}\end{array} - \begin{array}{c}\textbf{PWTO ratio}\\ \textbf{(l/l oil)}\end{array} \times \begin{array}{c}\textbf{Percentage of PW}\\ \textbf{re-injected for oil}\\ \textbf{recovery}\end{array} = \begin{array}{c}\textbf{Net water use}\\ \textbf{for oil E\&P}\\ \textbf{(l/l oil)}\end{array} \quad \ldots \text{[Equation 2]}$$

where l/l = L/L and E&P = exploration and production.

Next, we calculated the ratio of produced water-to-oil recovery (PWTO) and estimated the percentage of PW that is reinjected during oil recovery for each region. The amount of PW reinjection was then subtracted from this total. Both PWTO ratio and the reinjection share for national and PADDs were obtained from the American Petroleum Institute (API 2000) and Veil and others (2004). The remainder was net water use for crude oil recovery (see Eq. 2).

For oil sands crude production, data were collected and analyzed by location and recovery method. We estimated the market shares of surface mining and in situ technologies from CAPP (2006) and the share among the in situ recovery technologies from Isaacs (2007). Estimates of water consumption for each recovery technology were based on various publications (Peachey 2005; Heidrick and Godin 2006; and Gatens 2007).

Because of yield gain during crude processing (i.e., 159 liters [42 gallons] of crude generate 169 liters [44.6 gallons] of refined product), water consumption is expressed as liter of water per liter of crude or gasoline using this conversion.

Results and Discussion

Corn Ethanol

We found substantial variation by state and region in consumptive irrigation water use for growing corn. Corn production consumes most of the water and little water is required for ethanol production.

Corn Production

In areas where demand exceeds the water available from soil moisture and precipitation, irrigation must be applied to achieve high yield of crops. In the East-Central Region (including USDA Regions 5 and 6, and Arkansas, Mississippi, and Louisiana), only 14% of total water withdrawals (surface and groundwater) by all sectors are used for irrigation, compared with 64% in the Northern Plains (USDA Region 7, and Montana, Wyoming, Utah, and Colorado) (Gollehon and Breneman 2007). Similarly, the proportion of corn hectares that requires irrigation varies significantly across the corn-growing regions.

Seasonal water requirement for corn growing is typically in the range of 40–65 cm (16–26 in.) (White and Johnson 2003). This amount of water would be provided by precipitation and irrigation. Historical climate records show that annual precipitation in the three corn-producing regions varied significantly (USDC 2007). Region 7 is relatively arid and precipitation can be scarce. This region received an average of only 55 cm (22 in.) of rainfall per year over the past 45 years. By contrast, Regions 5 and 6 received 41 cm (16 in.) and 20 cm (8 in.) more rain, respectively (Table 1). On yield-weighted average, 39.7% of harvested corn hectares require irrigation in Region 7, compared with 2.2% in Region 5 and 3.9% in Region 6. Average of the irrigated hectares in the three regions is 12% (Table 1). Nationally, this figure is slightly higher (14%).

For the cropland that is irrigated for corn, the amount of water applied varies considerably across the U.S. (Fig. 3) with higher demand from regions 7–10. Even in the three Midwest regions, there are significant differences in irrigation rates. The variations in the proportion of corn irrigated and the amount of irrigation required for the irrigated crops contribute to the significant difference in consumptive irrigation water use in the three regions.

Producing one kilogram of corn in Region 7 consumes 129 liters of freshwater from irrigation. Since most of the corn grown in Regions 5 and 6 receives sufficient water from precipitation, irrigation water consumption in those regions is only 3 and 6 L/kg, respectively. In all three regions, most of the water used for irrigation for all crops

Table 1 Precipitation and corn irrigation by major corn-producing regions

USDA farm region	Average annual precipitation[a] (cm)	Area irrigated[b] (%)	Percent of U.S. irrigation water consumption for corn[c] Groundwater (%)	Surface water (%)
5	96	2.2	3.4	0.2
6	75	3.9	1.8	0.4
7	55	39.7	53.4	9.5
3 regions total		12	59	10

[a] *Source*: USDC. Average precipitation value from 1895 to 2006, normalized by land area of the region

[b] *Source*: USDA-NASS Quickstat database for 2003 harvested acreage (USDA-NASS 2007, 2008). Irrigated crop areas are from 2003 FRIS (USDA 2003). Irrigated areas are weighted by harvested area for each region for 2003

[c] Calculations of irrigation water applied for corn are based on 2003 *Farm and Ranch Irrigation Survey* (USDA 2003); irrigation water consumption is based on withdrawal/consumption ratio from USGS (1995); ground water and surface water shares are determined from USGS (2000)

(>82%) is withdrawn from groundwater aquifers and less than 18% is from surface water (USGS 2000).

Although Region 7 accounts for more than a half of the groundwater irrigation consumption for corn grown in the U.S. (Table 1), it produced a fifth of U.S. corn in 2003 (USDA-NASS 2008). Region 5 is a near-mirror image—it consumed only 3% of U.S. groundwater irrigation for corn, but grew 52% of the crop (USDA-NASS 2008). Together, the three regions accounted for 69% of total U.S. irrigation for corn (Table 1), while producing 88% of the U.S. corn crop in 2003 (USDA-NASS 2008). The bulk of the rest 31% of the irrigation water consumed by corn goes to Regions 8 and 9 because of their higher irrigation needs (Fig. 3).

The agricultural sector has begun to emphasize water management in recent years. Corn yield has risen by over 50%, but corn acreage has remained relatively flat over the past three decades. Further analysis in a recent report (Keystone 2009) indicates that the amount of irrigation water applied for corn declined 27% despite consistent corn yield increase over the past 20 years. This trend is likely to continue.

Corn Ethanol Production

Following the corn-growing portion of the ethanol lifecycle, corn is harvested and transported to ethanol plants for conversion. Corn ethanol production requires water for grinding, liquefaction, fermentation, separation, and drying. Water is used as process water and cooling water, and for steam generation for heating and drying. Water sources can include groundwater, surface water, and municipal water supplies. Water losses occur through evaporation, drift, and blowdown from the cooling tower; deaerator leaks and blowdown from the boiler; evaporation from the dryer; and incorporation into ethanol and DDGS (distiller's dried grains with solubles) coproduct. Typically, the losses vary with the ambient temperature of the production plant, the type of the cooling system, and the percent of water vapor captured in the DDGS dryer (which is a function of dryer type). As shown in Fig. 4, the cooling tower and dryer account for the majority (53% and 42%, respectively) of the water consumption (Kwiatkowski and others 2006; McAloon 2008).

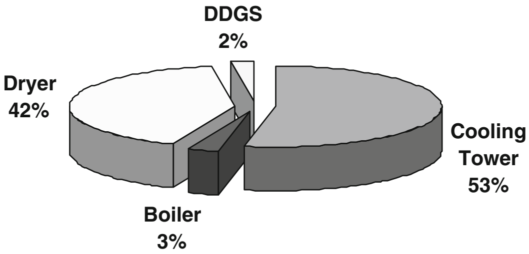


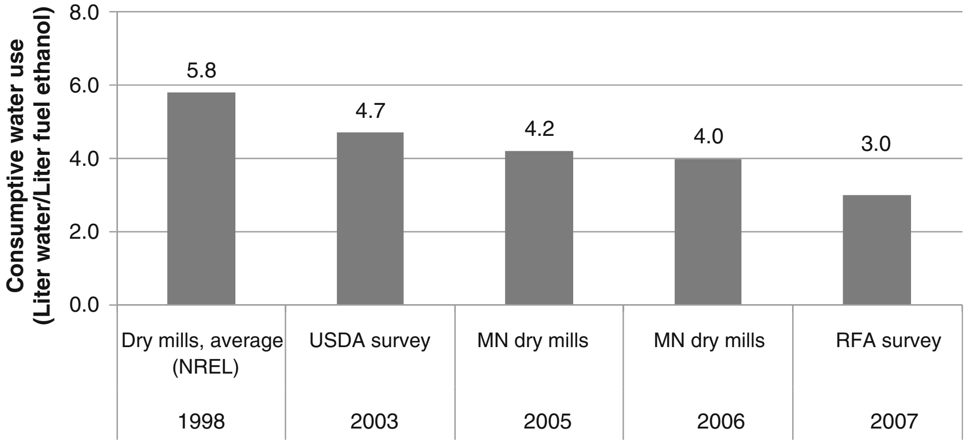
Fig. 4 Breakdown of water consumed during ethanol production via corn dry milling (determined by USDA dry mill model, Kwiatkowski and others 2006; McAloon 2008)

Water consumption in dry mills has decreased steadily since the 1990s. Shapouri and Gallagher (2005) report that older dry mill ethanol plants use up to 11 L/L, and Phillips and others (2007) report that, in 1998, the average dry mill consumed 5.8 L/L. The downward trend is also documented in a comprehensive database maintained by the State of Minnesota (Keeney and Muller 2006). This database shows a 21% reduction in water use by corn ethanol plants from 1998 to 2005, with an annual reduction rate of 3%. A similar trend has occurred nationally, as shown in Fig. 5.

With improved equipment and energy-efficient design, water consumption in newly built ethanol plants is declining still further. An analysis of the latest survey conducted by the RFA revealed that freshwater consumption in *existing* dry mill plants has declined to 3.0 L/L of ethanol produced, in a production-weighted average (Wu 2008)—a significant drop (48%) in less than 10 years. This value has been substantiated by recent case studies (Young 2009; Van't Hul 2009) and is 17% lower than a typical dry mill design value—3.6 L/L (Keeney 2007). In fact, some existing dry mills use even less water by producing wet distiller's grain (WDG) coproducts (Wang and others 2007), thereby eliminating steam requirements for drying. Water use can be minimized by increasing process water recycling, such as by capturing water vapor from the dryer and recycling boiler condensate to reduce the boiler make-up rate, by increasing cycles in cooling tower, or recycling treated process water and/or cooling tower blowdown water. Together with implementing steam integration and designing efficient new facilities, these measures can drive the water intensity down farther. The ethanol industry maintains that net zero water consumption is achievable by water reuse and recycling using existing commercial technology and with additional capital investment.

In addition to continued efforts to reduce fresh water needs in ethanol plant, the siting of new facilities is vital to a sustainable water supply. Although freshwater consumed in the production plant is relatively small when accounted by the water consumption factor—gallon water per gallon ethanol—the impact of such use could be significant to local community, since it represents a single point water user. At present, a majority of ethanol plant uses ground water as its water supply that provides consistent quality the production requires. Such development if not planned and sited diligently could affect groundwater level in nearby businesses and other industries. Furthermore, if the plant is to be built in the regions where groundwater recharge rate to the aquifer is slower than the rate of withdrawal, it could raise concern over resource depletion. Therefore, it is extremely critical to establish a siting

Fig. 5 Average water consumption in existing corn dry mill ethanol plants. (Data source: Phillips and others 2007; Shapouri and Gallagher 2005; Keeney and Muller 2006; Wu 2008)



process for biofuel plant, ensuring water resource conservation at local level.

Water Consumption in Major Steps of the Corn Ethanol Lifecycle

Table 2 presents estimates of total irrigation and process water consumption during current corn ethanol production from each region. Producing one liter of corn ethanol consumes a net of 10–17 liters of freshwater when the corn is grown in Regions 5 and 6, compared with 324 liters when the corn is grown in Region 7. On average, more than half of U.S. corn ethanol is produced at a water use rate of 10 liters water per liter of ethanol (USDA Region 5).

Cellulosic Ethanol

Switchgrass Production

As with corn, irrigation requirements for cellulosic biomass depend largely on the type and origin of the feedstocks, the climate in which they are grown, and soil conditions. Typically, forest wood does not require irrigation. Agricultural residues share the water requirements with crops (i.e., grain), which vary from region to region. Short-rotation woody crops and algae may require more water to achieve desirable yield. Switchgrass is deep-rooted and efficient in its use of water, and thus tends to be relatively drought tolerant. In its native habitat, switchgrass can yield 10–18 dry metric tons per hectare (4.5–8 dry tons per acre) (Downing and others 1995; Ocumpaugh and others 2002; Taliaferro 2002) without irrigation. If switchgrass were grown in regions where it is not native (e.g., certain parts of the northwestern U.S.) irrigation would be needed (Fransen and Collins 2008).

In this study, we examine switchgrass as the representative feedstock for cellulosic ethanol. We assume the switchgrass is grown in its native habitat to yield 9.0–15.7 dry metric tons per hectare (4–7 dry tons per acre); therefore, irrigation is not required.

Cellulosic Ethanol Production

Commercial-scale cellulosic biorefineries are still at an early stage in development. As of today, cellulosic ethanol can be produced via several processes: biochemical conversion (BC) using enzymatic hydrolysis and fermentation, thermochemical conversion (TC) using gasification and catalytic synthesis, TC using pyrolysis and catalytic synthesis, or a hybrid approach of gasification followed by syngas fermentation.

Table 2 Water consumption from corn farming to ethanol production in USDA regions 5, 6, and 7 (liter water/liter denatured ethanol produced)

USDA region	Region 5	Region 6	Region 7
Share of U.S. ethanol production capacity (%)[a]	51	17	27
Share of U.S. corn production (%)[b]	53	17	19
Corn irrigation[c]	7.1	13.8	320.7
Ethanol production[d]	3.0	3.0	3.0
Total (corn irrigation and ethanol production)	10.1	16.8	323.7

[a] Based on 2006 ethanol production capacity in operation (RFA 2007)

[b] Based on 2003 corn production (USDA-NASS 2007)

[c] *Source*: USGS (1995) and USDA (2003)

[d] *Source*: Wu (2008). Production-weighted average

The amount of water consumed during ethanol production depends on the production process itself and the degree of water reuse and recycling. Because of the differences in the coproducts, energy consumption, and capital and operational costs, process comparison could be complex. Nevertheless, gasification and pyrolysis in general consume relatively little water. The BC process requires additional water for pretreatment to break down the cellulosic feedstocks. With current technology, producing one liter of cellulosic ethanol via a BC process (such as dilute acid pretreatment followed by enzymatic hydrolysis) consumes 9.8 liters of water (Wallace 2007). With increased ethanol yield, it is estimated that water consumption can be reduced to 5.9 liters (Aden and others 2002). An optimized TC gasification process (a mixed-alcohol process that produces ethanol, methanol, butanol, and pentanol) requires only 1.9 L/L (Phillips and others 2007). Production of other cellulosic biofuels, such as a product containing 50% biobased diesel and 50% biogasoline produced from a recently developed fast pyrolysis of forest wood residue, consumes 2.3 L/L (Jones and others 2009). Process integration and optimization to reduce freshwater use has been a priority in the latest cellulosic ethanol process development efforts.

Water Consumption in Major Steps of the Cellulosic Ethanol Lifecycle

If no irrigation water is used for feedstock production, switchgrass- and forest-wood-residue-derived cellulosic ethanol consume only the water needed for conversion via BC, TC, or hybrid processes. As shown in Fig. 6, production of one liter of cellulosic ethanol consumes 1.9–9.8 liters of water. Cellulosic ethanol produced from switchgrass via a BC process with today's technology consumes nearly as much water (9.8 liters) as ethanol produced from corn grown in Region 5 (10.0 liters). However, cellulosic ethanol produced from switchgrass via a TC gasification process requires 80% less water.

Conventional Gasoline

Onshore Recovery of Domestic Crude Oil

Oil recovery is the major water consumption step in the petroleum gasoline lifecycle. However, there is considerable variation among wells, as well as within the same well over time. In the section below, we present analysis of oil recovery technologies, injection water for oil recovery, and PW production and use for oil recovery.

Recovery Technologies

Conventional recovery technologies have evolved to meet the need for maintaining oil production as wells age. Primary oil recovery uses the natural pressure of the well to bring crude oil to the surface. As production from primary recovery declines, secondary recovery (or water flooding) becomes the major recovery technology. In secondary recovery, separate injection wells are drilled, and water is injected into the formation to increase oil production. Eventually, however, oil production declines because the remaining oil is trapped in the reservoir rock by surface tension and/or the viscosity of the oil (Barry 2007). Tertiary recovery, or enhanced oil recovery (EOR), plays a critical role in preventing further declines in oil recovery.

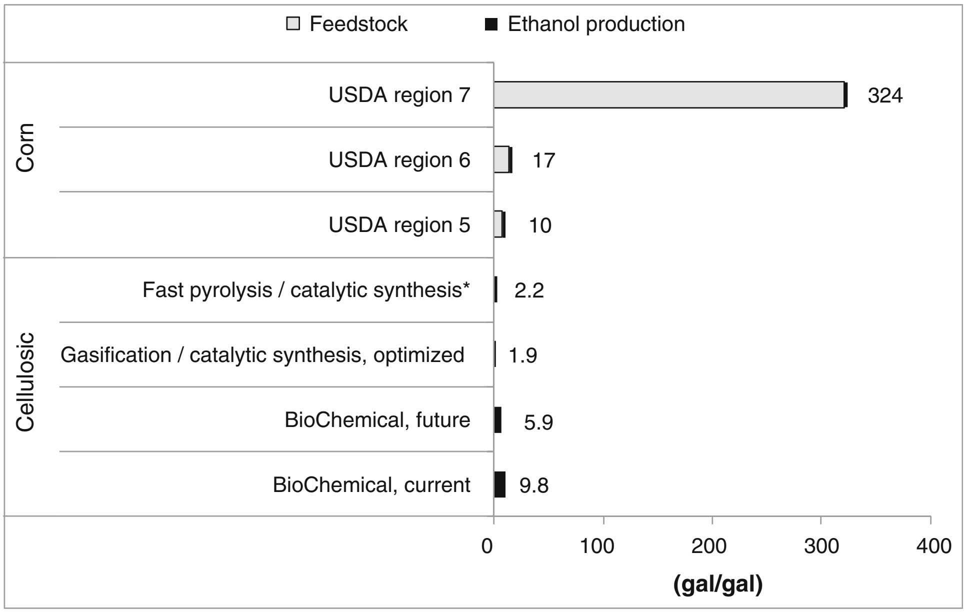


Fig. 6 Consumption of irrigation water and process water during the production of ethanol from corn via dry mill by different U.S. regions, from switchgrass via biochemical process, and from forest wood via gasification and fast pyrolysis. Note the switchgrass is assumed to be grown in its native region that no irrigation is required. * Fast pyrolysis produces a mixed fuels of gasoline and diesel from forest wood instead of ethanol

EOR targets trapped oil by reducing surface tension via surfactant injection or reducing viscosity contrasts via steam injection or other methods.

Although offshore wells could contain both primary and secondary wells (Bibars 2004), no technology-specific statistics were publicly available at the time of this study. Among the technologies, EOR is used in onshore operation and is well documented (O&GJ 2006) for its production share, while primary and secondary market share data are scarce. Since secondary recovery tends to use more injection water, we assume a worst-case scenario for this analysis, in which secondary recovery and EOR are used in all onshore production.

Figure 7 shows the distribution of U.S. onshore and offshore production and, within them, the distribution of recovery by primary, secondary, and tertiary technologies. Half of total production is estimated to come from secondary water flooding, 13% from EOR, and 38% from primary recovery. For onshore wells, water flooding is responsible for three-quarters of recovery. While thermal steam EOR is the most widely used tertiary recovery technology, the use of CO_2 injection (miscible) has been expanding rapidly and is now the second most commonly used EOR technology. Other EOR technologies include N_2 injection, forward air combustion, hydrocarbon miscible/immiscible, and a small amount of hot-water injection. Each of these technologies represents about 2% of total EOR (O&GJ 2006).

Injection Water Consumption for Oil Recovery

Injection water requirements vary with recovery technology. Primary recovery requires an average of only 0.21 liters of freshwater per liter of crude oil recovered (Gleick 1994). Typically, secondary recovery is relatively water intensive. Based on their analysis of the histories of 80 U.S. secondary oil wells, Bush and Helander (1968) found that over the water-flooding lifetime of these wells, an average of 8.6 liters of water was injected to recover one liter of crude.

The amount of injection water used for EOR can be as low as 1.9 L/L of oil recovered, with forward combustion or as high as 343 L/L of oil with micellar polymer injection Gleick (1994). With CO_2 injection, reports of water use are extremely variable. Based on a survey of 14 oil companies, Royce and others (1984) reported use of 13 liters of injection water per liter of crude oil recovered. In the early 1990s, Gleick (1994) reported 24.7 L/L. At the same time, based on 10 years of data (from 1988 to 1998) on Shell's CO_2 EOR Denver City project, injection water averaged only 4.3 L/L (Barry 2007). In this analysis, we assume 13 L/L with CO_2 EOR. For EOR technologies for which water use is not reported in the open literature (such as hydrocarbon miscible/immiscible, hot water, and N_2 technologies), we assume 8.7 L/L, the average injection water use of CO_2, steam, and combustion EOR schemes. Although micellar-polymer-based recovery consumes large amounts of water, there are no reported active projects currently employing this technology in the U.S. (O&GJ 2006). The same is true for caustic/alkaline, surfactant, and other polymer-based oil recovery methods (O&GJ 2006). These technologies are therefore not included in our analysis.

As of 2005, domestic onshore recovery operations required 4,432 million liters of injection water to produce 553 million liters of conventional crude oil. The technology-weighted national average water injection rate for oil recovery was 8.0 L/L. This estimate does not include treated PW injected for oil recovery (discussed in the following section). Secondary water flooding is responsible

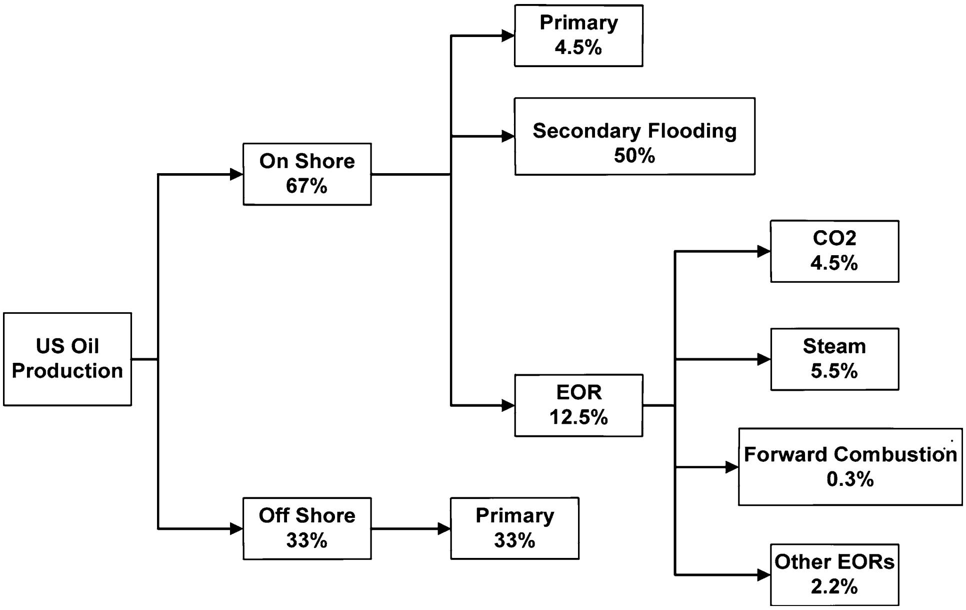


Fig. 7 Technology shares for onshore and offshore U.S. crude oil recovery (Data sources: EIA 2007b; O&GJ 2006) Note that offshore technology share was not available at the time of the study. Assume all secondary and EOR wells are onshore. EOR = enhanced oil recovery

for about 80% of injection water use in U.S. onshore oil production (Fig. 8).

Produced Water Reinjection for Oil Recovery

Produced water (PW)—the saline water that is part of a crude oil–water mixture lifted to the surface during recovery—is an inextricable part of the oil E&P process. The crude and PW are separated and the water is then re-injected for oil recovery, evaporated in an evaporation pond, discharged to surface water (where permitted), or injected to a separate inactive stripper well for disposal. Lifting, treatment, and disposal of PW have become significant operating costs for the oil industry.

PW is the largest waste stream generated by the oil and gas industry. In 1995, about 2,861 billion liters (18 billion barrels) of PW were generated at U.S. onshore operations (API 2000). Worldwide, 12.2 trillion liters (77 billion barrels) of water were produced from oil wells in 1999 (Khatib and Verbeek 2003). The oil production weighted PW generation (PWTO ratio) fluctuates. For wells nearing the end of their productive lives, the PWTO ratio can be as high as 10-20, sometimes even 100 (Weideman 1996).

Reuse, recycling, and reclamation are increasingly common in PW management in response to water scarcity issues in several existing oil fields and tighter environmental regulations. PW has become a major source of injection water for oil recovery. According to API's 1995 survey, 71% of the PW in the U.S. is reinjected into the reservoir for oil recovery (API 2000).

Using an 8 L/L injection water requirement, assuming a PWTO ratio of 6.8 L/L (Veil and others 2004), and assuming that 71% of PW is re-injected for oil recovery, national net water consumption is estimated to be 3.2 L/L crude from U.S. onshore operations.

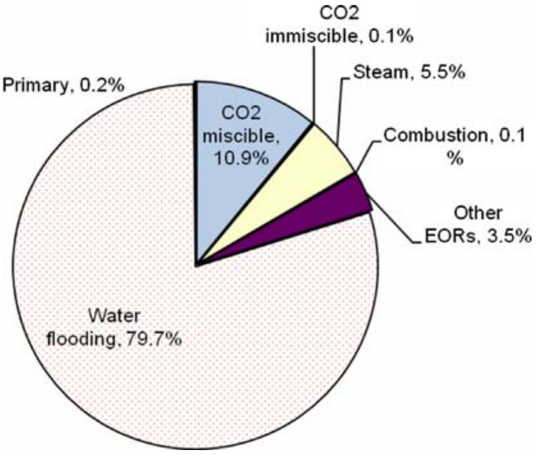


Fig. 8 Injection water use by crude oil recovery technology, U.S. Onshore (EOR = enhanced oil recovery)

Regional Water Consumption

Three PADD regions (II, III, and V) account for the bulk of total and onshore crude production in the U.S. PADD III accounts for more than 43% of domestic onshore oil production, while PADD V accounts for one-third. Well productivity varies considerably among the three regions. Although PADD II and III have nearly equivalent numbers of production wells, PADD III produces three times the oil of PADD II. Similarly, PADD V accounts for one-third of domestic production but less than one-tenth of the wells.

Similar to crude production, PW generation among the PADDs is variable. PADD V generates a lower amount of PW than the other regions, and the range of PWTO in the PADDs widens over the years (from 3.3–11.3 in 1995 to 3.4–14.7 in 2002 [Veil 2004]). The percent of PW re-injected for crude recovery also differs from one region to another. PADD I re-injects 99% of PW while PADD II and III re-inject about half. On a per-liter crude production basis, PADD V has the lowest PW re-injection rate (2.6 L/L of oil)—about half of the PADD III rate (5.7 L/L). Detailed analysis of US onshore oil E&P and water use can be found elsewhere (Wu and others 2009).

A net value of 2.1–5.4 liters of water is consumed to produce one liter of crude oil in PADDs II, III, and V. Clearly, PWTO and the degree of PW reinjection for oil recovery have considerable effects on water consumption. Wells with large amounts of PW (PWTO 14.7, PADD IV) can have low net water use if there is extensive re-injection of PW for recovery (92% of PW is recycled in PADD IV). For wells or regions with small amounts of PW (e.g., PWTO 3.4, PADD V), recycling or reuse of PW is critical to reducing net water use. For example, increasing PW re-injection in PADD V from the current rate of 76% to 99% could cut injection water consumption to 4.7 L/L. Because PADDs II, III, and V together account for 90% of U.S. onshore crude oil production reducing injection water consumption in these regions could have a much greater national impact. The constraint to increased PW recycling and reuse is the cost for water treatment compared with other alternatives.

Recovery of Saudi Arabian Crude Oil

Saudi Arabia is the largest oil producer in the world, and its Ghawar field is the world's largest oil field. Scarce rainfall, a lack of surface water, and low recharging rates for the seven major aquifers make water supply for oil recovery a serious problem.

Faced with accelerated groundwater depletion caused by industrial and urban development, Saudi Arabia has launched major efforts to develop new water supply sources and water conservation projects since the 1970s. A major portion of these efforts has focused on oil recovery

(Al-Ibrahim 1990). Today, Saudi Arabia relies almost entirely on brackish water and desalinated seawater for oil recovery. Although a complete survey of net water use for Saudi crude oil production is not publicly available, results of individual projects provide an indicator of current practices and recent trends. For example, results of a 6-year water management program at North ‘Ain Dar indicate that water injection dropped from 6 to 4.6 L/L (a 30% reduction), while oil production and reservoir pressure remained constant (Alhuthali and others 2005). In the Ghawar field, where more than half of Saudi Arabia's crude oil is generated (EIA 2007c), 1.4 liters of treated seawater was injected to produce 1 liter of crude oil (Durham 2005).

Aside from water management, advances in recovery technologies play a critical role in water consumption. The PWTO ratio has declined steadily for Ghawar, from 0.54 to 0.43, because of a shift in recovery technology to horizontal drilling and peripheral water injection (SUSRIS 2004; Durham 2005). Today, the ratio is reported to be 0.39 (SUSRIS 2004) for Saudi operations, compared with an average of 6.8 for U.S. onshore production. Although data on reuse and recycling of PW are not available, little PW from Saudi oil production is available for re-injection. For this study, we used a range for water consumption, from 1.4 (Durham 2005) to 4.6 L/L (Alhuthali and others 2005).

Oil Refining: Conventional Crude

Conventional crude is transported to oil refineries, where it is processed to petroleum products such as gasoline and diesel oil. In response to growing worldwide demand for oil products, refining capacity is expanding. New refineries are being built in regions with scarce water resources. By 2025, forecasts suggest that 40% of global refining capacity may be in water-scarce regions (Buchan and Arena 2006). In the U.S., water scarcity is a perennial issue in certain regions—such as notoriously drought-prone West Texas and the West Coast, where most refinery facilities are located.

Refining includes various processes, such as crude desalting, distillation, alkylation, fluid catalytic cracking (FCC), hydrocracking, and reforming, among others. Crude distillation and FCC require the majority of the steam and cooling water use and generate 44% and 26% of refinery wastewater, respectively (Buchan and Arena 2006). According to Mavis (2003), approximately half of refinery water requirements result from cooling needs. Water loss from cooling and heating operations accounts for 96% of refinery water consumption. Many refineries depend on municipal water supplies to meet their needs.

On the basis of estimates from 1994 to 2006 (Gleick 1994; Ellis and others 2001; Buchan and Arena 2006), processing one liter of crude oil in U.S. refineries consumes, on average, 1.0 to 1.85 liters of water. The average of these estimates is 1.53 L/L. Accounting for variations from each prior estimate, water consumption can be as low as 0.5 L/L or as high as 2.5 L/L. In general, newer facilities tend to be more water efficient.

As with crude-oil recovery operations, refineries are initiating water management projects in response to increased competition for limited freshwater supplies. Today, approximately 70% of steam condensate is recovered in well-maintained and new refineries around the world, compared with only 30% recovery in older refineries (Seneviratne 2007). Wastewater recycling and reuse are also becoming increasingly common (Chevron 2008). Reclaimed water from municipal wastewater treatment plants to supply refinery water needs shows substantial cost benefits in Australia (Buchan and Arena 2006). Water reuse in oil refining is expected to rise 350% from 2004 to 2015 globally (Buchan and Arena 2006).

Water Consumption in Major Steps of the Conventional Gasoline Lifecycle

As indicated above, 90% of U.S. onshore oil production consumes 2.1–5.4 liters of water per liter of *crude* produced (PADDs II, III, and V). Together with refining, a total of 3.6–7.0 L/L is required in the three major PADD regions (3.4–6.6 L/L gasoline). Similarly, for Saudi Arabian crude, 2.9 L/L crude (2.8 L/L gasoline) is consumed for more than half of the crude oil produced and refined.

Canadian Oil Sands

Recovery of Canadian Oil Sands

The production share of Canadian oil sands grew rapidly since early 2000s and by 2005 reached 39% of the total oil production in Canada. Surface mining is the dominant recovery technology and a major water consumer.

Oil Sands Recovery Technologies

Oil sands are recovered by open-pit or surface mining of relatively shallow deposits or by thermal in situ techniques for deeper deposits. Approximately 18% of Canada's remaining oil sands reserves, mainly in Athabasca (NEB 2004), are amenable to surface mining (CAPP 2008c). In surface mining, oil sands ore is transported to a processing facility, where oil sand bitumen (crude oil) is extracted by steam and solvent. Residue slurries (containing mainly solids, residue bitumen, and water) are sent to a tailing pond (Flint 2005). After settling of fine solids and recovery of additional bitumen in the tailing pond, water can be recycled. Surface mining can recover more than 90% of the bitumen in the deposit.

In situ extraction has expanded to account for a large share of oil-sands-derived crude oil in the deeper Peace River and Cold Lake deposits (as well as non-minable portions of the Athabasca deposit). Approximately 82% of Canada's oil sands reserves are only recoverable via in situ technologies (CAPP 2008c). The dominant in situ technologies are cyclic steam stimulation (CSS) and steam-assisted gravity drainage (SAGD). Other in situ recovery schemes—termed multi-scheme—combine various elements of CSS, SAGD, and other recovery techniques.

CSS involves drilling into the reservoir, heating it via cycling of high-pressure steam, and lifting the bitumen to the surface (Flint 2005). In SAGD, a pair of horizontal wells is drilled into the reservoir. The upper well injects steam to oil sand deposits and the second well below collects and pumps bitumen to the surface. While CSS can recover 20–35% of the bitumen in the reservoir, SAGD reportedly increases recovery to 60–65% (Flint 2005; Woynillowicz and others 2005). The SAGD process is becoming the most common method for in situ recovery.

Following recovery, oil sands bitumen is further upgraded into synthetic crude (refining-ready). Currently, this upgrading is achieved either in specially equipped refineries (many in the U.S.), or at the bitumen production site as part of integrated surface mining operations.

In 2006, surface mining accounted for 59% of Canadian oil-sands-based crude oil production (up from 56% in 2005), while in situ extraction accounted for 41% (CAPP 2008a). Using CAPP's share for total in situ recovery (CAPP 2008b) and Isaacs' share among the recovery technologies (Isaacs 2007), we estimated that technology-specific shares for in situ production are 55.6% for surface mining, 22% for SAGD, 21% for CSS, and 1.2% for multi-scheme production in 2005.

Water Consumption in Oil Sands Recovery and Refining

As with conventional oil, oil-sands recovery technology has a major effect on water consumption. For surface mining, the choice of extraction solvent affects water consumption. Using naphtha as the solvent can result in bitumen recovery rates over 98%, but increase water consumption and create problems downstream in upgrading operations. In comparison, a paraffinic solvent can reduce water and solids, but oil yield tends to decline (Flint 2005).

Surface mining operations in the Athabasca region involve water withdrawal from the Athabasca River, where public concerns regarding resource use have prompted extensive efforts to better manage water resources. According to Gleick (1994), the oil-sands industry used an average of 4.8 liters of freshwater to produce one liter of bitumen oil (before upgrading) via surface mining. By 2005, that average had dropped to 4 liters, including upgrading (Peachey 2005). More recently, it was reported (Heidrick and Godin 2006; Isaacs 2007) that water consumption is down to 2.18 L/L. For our estimate, we used Peachey's (2005) industry average (4.0 L/L).

In situ technologies require large volumes of steam which, in turn, requires water and energy. However, since over 80% of the steam used for oil extraction and processing is recycled, their water consumption is relatively low (Isaacs 2007). SAGD tends to use lower injection pressures and results in lower steam/oil ratios, making it less water intensive. Water consumption rates during upgrading are low—less than 1 L/L (Peachey 2005).

The water requirements for refining of the synthetic crude produced from oil sands are comparable to those of conventional crude. We estimate refining water use at 1.53 liters of water per liter of synthetic crude oil.

Water Consumption in Major Steps of the Oil Sands Gasoline Lifecycle

It takes 2.8–6.5 liters of water to produce and process one liter of crude from Canadian oil sands (2.6–6.2 L/L gasoline). Using reported shares and water intensity by production technology, we found that 56% of oil-sands-based crude is produced and refined from 5.5 liters of water per liter of bitumen (5.2 L/L gasoline). Comparing the share of oil-sands-derived crude oil production by location and recovery technology with our estimates of total water consumption for recovery (including upgrading), we found that surface mining is a major water user—Athabasca produces 56% of oil-sands-derived crude, yet consumes 78% of the water used for oil sands crude production. By contrast, in situ recovery by means of SAGD at Athabasca uses the least amount of water.

Summary Results

Figure 9 presents net water use in major stages of petroleum gasoline production from conventional and Canadian oil sands by recovery technology by location and by crude source. In summary, water consumption varies from less than 3 liters in Ghawar (conventional technology) and Athabasca (SAGD, oil sands) to nearly 7 liters in PADD V (conventional technology). Water consumption for gasoline produced from multi-scheme techniques in Peace River, conventional oil in North 'Ain Dar, and surface mining in Athabasca is close to the latter value (Fig. 9). Results did not show marked differences in water consumption for producing a liter of gasoline from conventional and non-conventional crude sources examined in this study.

Table 3 summarizes results of the net consumption factor of irrigation water, process water, for the production

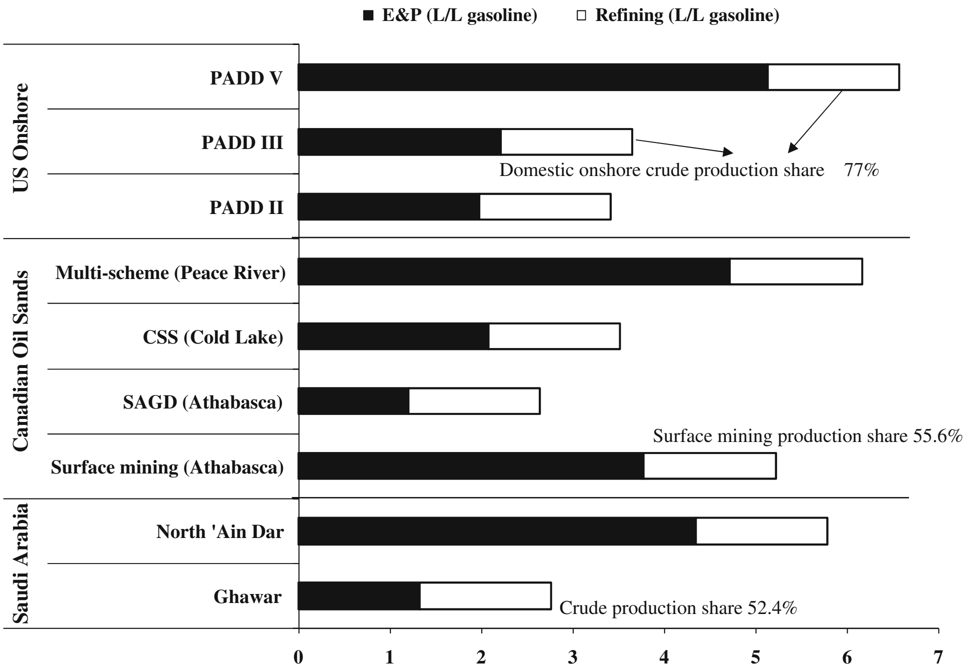


Fig. 9 Net water use for gasoline production from conventional (U.S. and Saudi) and Nonconventional Crude (Oil Sands) by Lifecycle Stage, Location, and Recovery Method (E&P = exploration and production)

Table 3 Water consumption for ethanol and petroleum gasoline production

Fuel (feedstock)	Net water consumed	Major factors affecting water use
Corn ethanol	10–324 L/L ethanol[a]	Regional variation caused by irrigation requirements due to climate and soil types
Switchgrass ethanol	1.9–9.8 L/L ethanol[a]	Production technology
Gasoline (U.S. conventional crude)[b]	3.4–6.6 L/L gasoline	Age of oil well, production technology, and degree of produced water recycle
Gasoline (Saudi conventional crude)	2.8–5.8 L/L gasoline	Same as above
Gasoline (Canadian oil sands)[c]	2.6–6.2 L/L gasoline	Geologic formation, production technology

[a] USDA regions 5, 6, and 7 combined for corn. Water consumption for corn, switchgrass, forest wood farming includes irrigation. All water used in ethanol conversion is allocated to the ethanol product

[b] PADD II, III, and V combined

[c] Including thermal recovery, upgrading, and refining

of ethanol (corn and switchgrass) and well injection water, process water for petroleum gasoline (conventional and oil sands) during feedstock production/extraction and conversion/processing. Major factors affecting water consumptions are also listed. These data clearly underscores benefits of cellulosic ethanol produced from native perennial grass such as switchgrass, which has a small water footprint comparable to current gasoline production. This analysis recognizes significant regional variations in feedstock production which resulted in fuel producing areas with disproportionally high irrigation water consumption. As indicated from Table 2, Figs. 6 and 9, more than a half of the ethanol currently produced from U.S. corn consumes water volumes (irrigation and process water, 10 L/L), on a per liter basis, close to the upper bound of cellulosic ethanol (9.8 L/L) while about 20% is produced at a much higher water factor.

The per-liter water use factor provided one aspect of the water use, as it does not address the quality dimension of the water issue. While all water is created equal, the quality requirement for water that is used in different sectors, such as crops irrigation water, industrial cooling water, or oil-well injection water for recovery, etc. is not equal. In fact, there are marked differences between growing crops and extract oils. Agricultural crops generally require freshwater whereas in oil-well E&P operation, water quality is simply not an issue that brackish water with high salt concentrations has been used throughout the world. Efforts are now being undertaken to characterize and estimate the type of water and quality associated with energy production.

Uncertainties

Statistics compiled by the USDA, USGS, API, and others contain a number of gaps. For the most part, data on water use in oil production contain more gaps than comparable data for biofuel. Efforts have been made to use most up-to-date sources in this study. As new data becomes available, results in this work may be updated and refined. These gaps are described below.

Inconsistent base-year data and lack of production data on cellulosic ethanol. USDA data describing corn production and water applied for irrigating corn are reasonably complete for 2003. However, consumption of irrigation water was last reported by USGS for 1995. For cellulosic ethanol, because commercial-scale production is not yet underway, conversion data are limited to process simulation results.

Lack of complete reporting of oil recovery and injection water use by oil recovery technology. For E&P of domestic onshore and offshore crude oil, neither U.S. nor PADD/state production is reported by recovery technology. Data on oil well injection water use were last reported in 1994 (Gleick). Recent statistics are scarce.

Lack of complete reporting of PW from U.S. oil wells. PW is reported as a total quantity from both gas and oil wells.

Conclusions

Our analysis revealed that water consumption for feedstock and fuel production varies considerably depending on the following:

- Type of feedstock
- Climatic condition and locations
- Conversion technology for ethanol
- Geological condition and age of oil well
- Recovery technology
- Extent of PW re-injection for petroleum gasoline

There are substantial regional differences, particularly for corn production. Without irrigation, water consumed for switchgrass ethanol production is comparable to that of gasoline produced from conventional crude or oil sands. Average water use for oil sands recovery and upgrading is not significantly different from that used for conventional oil recovery. Ethanol production plants and oil refineries consume relatively small amounts of water compared with the much greater water intensity of feedstock recovery.

Water use is declining because of the rapidly evolving technologies used for second-generation biofuel (cellulosic ethanol) production and the steady improvement in existing first-generation corn ethanol production. This is also true for crude oil recovery and refining.

Our analysis indicates that conservation measures to reduce water consumption are needed to achieve sustainable biofuel and gasoline production. Improved irrigation water management—in particular, groundwater use—is critical in those areas where water is scarce and in locations with high concentrations of biofuel or oil production facilities. Development of drought-resistant crop strains that maintain corn yield is also desirable. For cellulosic feedstocks, an emphasis on planning and selecting feedstock site at their native habitat is vital to minimizing irrigation requirements while achieving desirable production levels. In an oil production field, the use of PW re-injection and saline water for oil recovery will further reduce water use. Additional improvements in water management during ethanol production and oil refining can be achieved by modifying processes to increase water recycling and improve steam integration. Finally, an integrated system designed to optimize water use is needed for new facilities.

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