Life Cycle Water Consumption of Alternative, Low-Carbon Transportation Fuels

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Introduction

This study is part of an ongoing effort by Arizona State University and the Arizona Water Institute (AWI) to understand the important linkages between water and energy. While it is generally understood that energy is required to transport and treat water, few studies have attempted to understand the opposite link. In fact, significant quantities of water are also required in the production of various forms of energy. This study focuses on water consumption of transportation energy sources; specifically on emerging, low-carbon technologies that seek to mitigate the problems of global climate change.

Over the past decade, evidence of the impact that large emissions of carbon dioxide (CO_2) are having on the global climate system has been mounting. Carbon dioxide is a greenhouse gas (GHG) and is one of the leading causes of global climate change. Greenhouse gases accumulate in the atmosphere and block infrared radiation from emitting back into space, thus warming the atmosphere and altering the global energy balance. Although carbon is emitted and absorbed through a number of natural processes, including respiration and photosynthesis of plants, anthropogenic sources, dominated by the combustion of fossil fuels, have lead to a marked accumulation of CO_2 in the atmosphere. This may be leading to an imbalance in natural systems. Recognition of this problem has lead to calls for action at all levels from individuals to city, state, and national governments, and even in global cooperation in the form of treaties such as the Kyoto Protocol.

When tackling a problem of the magnitude of global climate change it is useful to focus first on the largest sources of the problem in order to achieve improvements on a relevant scale. Figure 1 shows a breakdown of greenhouse gas emissions by sector in Arizona. Not surprisingly, the two sectors most dependent upon fossil fuel energy, transportation and electricity, show the highest percentages of emissions at 39% and 38% respectively (ACCAP 2006). The current study focuses strictly on the transportation sector. This sector was chosen not only because it has the highest impact, but also because the fossil fuel upon which it is most dependent faces high risks related to the reliability of supply.

Unlike coal and natural gas which are produced domestically and used primarily for electricity and home heating, over 60% of the oil used in the US is imported and is used almost exclusively for transportation. Much of the world's remaining oil reserves lie in geologically (deep under the ocean) or politically (Middle East) challenging locations. Significant portions of these reserves are also owned by national oil companies that have been known to overtax oil production, significantly reducing the capital available for reinvestment in increased production (CIA 2008). When combined with explosive growth in developing nations, this has lead to very tight supplies of oil in recent years and has caused prices to spike to record levels. Due to the limited availability of ready alternatives to oil as a transportation fuel, continued dependence on oil imports presents a significant economic security risk for the United States.

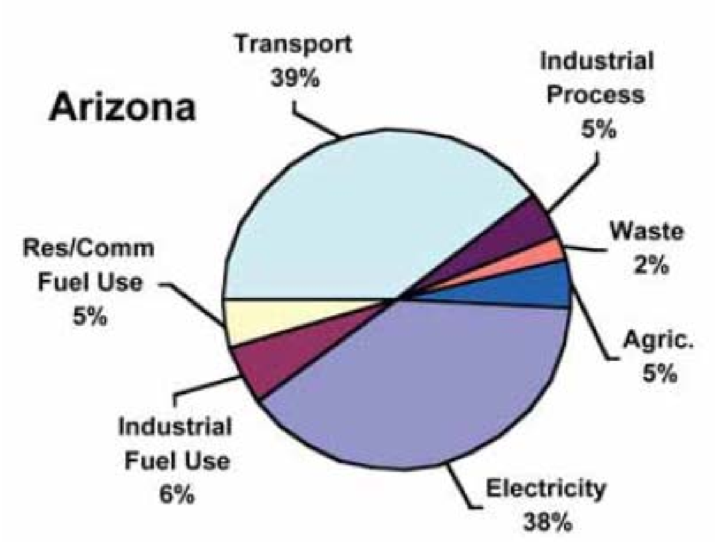

Figure 1: Arizona GHG emissions by sector (ACCAG 2006)

This risk is expected to increase rather than decrease in the foreseeable future. Many scientists and geologists are predicting that global oil production will soon reach a peak followed by a plateau and/or continuous decline. There is significant disagreement on the exact timing of the peak as it depends on a number of uncertain factors, however nearly all estimates put the timing of "peak oil" before 2040, with a majority predicting peak before 2020. The Department of Energy (DOE), the Army Corp of Engineers, and the Government Accountability Office (GAO) have all released reports in the last few years exploring the risks of peak oil and calling for coordinated action in attempts to mitigate them (Hirsch et. al. 2005, Fournier and Westervelt 2005, and GAO 2007).

As we search for solutions to these confounding energy challenges we must be proactive in evaluating our options with a very broad view to ensure we do not simply exchange one set of problems for another. A useful tool in attempting to characterize technologies is life cycle assessment (LCA). It can be used to attempt to characterize the cradle-to-grave environmental impacts of specific technological systems.

In this study, LCA is used to explore one potential impact of particular interest in Arizona, the consumption of water. Arizona has relatively limited water resources due to its arid climate and limited surface water. Only about 14% of Arizona's water supply is made up of in-state renewable surface water. However Arizona has rights to 2.8 million acre feet of water from the Colorado river which equates to approximately 40% of current demand. A little over half of the water is diverted through Central Arizona Project (CAP) canals to Phoenix and Tuscan while the other half is used by communities and agriculture near the rivier. The difference between surface water supply and total water demand is mostly made up of groundwater that is being extracted at an unsustainable rate. A small but growing amount of water (less than 3%) is made available through reclaiming effluent and is typically used for things like golf courses, parks or industrial applications (ADWR 2008).

Traditional forms of energy production are known to consume large volumes of water and account for approximately 20% of non-agricultural water consumption in the United States (USDOE 2006). The numbers for AZ are slightly less with total industrial uses of water making up around 17% of non agricultural water consumption (AZDWR 2006). This concern is magnified by the fact that the EIA has estimated (in their reference case) that world demand for liquid fuels for transportation will grow by 50% between 2005 and 2030. An updated projection, taking into account today's high energy prices and expecting continued increases, predicts a somewhat lower, but still significant increase in transportation fuel demand over the same time period (EIA 2008). If Arizona is going to meet its future energy demand, it must do so while both decreasing harmful CO_2 emissions and without putting significant strain on its limited water resources. This study attempts to provide decision makers with data to help make informed choices on which technologies are best suited to meet this challenge.

Approach

The goal of this study was to estimate the life cycle water consumption for a range of potential low-carbon energy sources for future transportation in Arizona. The approach used was a hybrid life cycle assessment (Suh et al 2004, Williams 2004). Where data was available, major water consuming processes were evaluated on a process by process basis. The remainder of the system, including construction and maintenance, was evaluated based upon aggregated sector by sector economic input-output (EIO) data from the Carnegie Mellon University EIOLCA.net tool (CMUGDI 2008). Details on the specific EIO data used are described in appendix A. The total water consumption was then calculated for the entire life cycle by combining the impacts for all processes. For most technologies, multiple estimates were made based upon different data and assumptions. The purpose was to scope out the general range of the potential impacts on water use.

A range of potential technologies were explored using this methodology, each falling into one of two main categories. The first category was biofuels, including corn ethanol, soy biodiesel, cellulosic ethanol, and microbial biodiesel. While biofuels are currently controversial, they are the only alternative fuels as yet making any significant contribution to transportation energy. The main advantage of biofuels is that they are compatible with current transportation infrastructure. In addition, some more advanced biofuels do not require food crops, eliminating one of their biggest drawbacks.

The other category is electric vehicles (EV) and plug-in hybrids. These vehicles draw electricity from the grid that is stored in batteries and used to run an electric motor. While there are few EVs on the road today, they are expected to enter the market in larger numbers over the next few years. Highly anticipated plug-in vehicles include the Tesla Roadster, the Chevy Volt, and a plug-in version of Toyota's popular Prius hybrid. The largest roadblock to mass adoption of electric vehicles is limited range due to expensive batteries with relatively low energy density. Steady progress is being made in this area, but battery cost and capacity will ultimately determine the long term market penetration of EVs. Also, while electric vehicles use no gasoline, they are only as clean as their source of electricity. Three low carbon electricity sources with significant potential in Arizona were evaluated including coal power tied to carbon sequestration, solar photovoltaics (PV), and concentrated solar power (CSP).

It is recognized that a number of potential technologies were left off the list. The most glaring omissions are probably nuclear or wind powered EVs and hydrogen vehicles. Nuclear was left off the list because there are currently significant roadblocks to the construction of new nuclear power plants and unresolved issues with disposal of nuclear waste. Wind power was neglected because Arizona does not have very high wind potential compared to other states and it is expected to have limited water consumption except for possibly in the construction phase (NREL 2008, DOE 2006). Hydrogen vehicles were not evaluated because hydrogen is simply an energy carrier and shares many of the same properties as electric vehicles with additional infrastructure requirements and generally higher costs and lower efficiencies.

For the purposes of this study water consumption was defined as water evaporated from a process or discharged as wastewater. Water withdrawals that were either in continuous use or returned to the source were not included. The functional unit for the analysis was gallons of water consumed per vehicle mile traveled (VMT). This was chosen for comparison purposes to compensate for different energy densities of different fuels and different efficiencies of the vehicles that use them. However, data is also presented in units appropriate to each energy source including per gallon of fuel or kilowatt-hour (kWh) to provide numbers that are free of any bias introduced due to assumptions regarding the specific vehicle used.

The vehicle assumed for the calculation of VMT was Toyota Prius, which gets an EPA estimated 46 mpg combined fuel economy running unleaded gasoline. To account for difference in energy density of gasoline, ethanol, and biodiesel, ratios of fuel efficiencies for a number of 2008 models available in both gasoline and flex fuel or diesel were averaged. The ratios used were 1.31 for diesel to gasoline and 0.73 for ethanol to gasoline fuel efficiency (fueleconomy.gov 2008). Data for electric vehicles on the other hand was limited. Listed energy efficiencies for the Chevy Volt and the Tesla roadster were 200 and 180 Wh/mile respectively (GM 2007, Tesla Motors 2008). Taking into account that producers tend to be optimistic with their estimates for new technologies, the higher value was used for all EV calculations.

While it is recognized that there would certainly be water consumption in the production of vehicles, no attempt was made to estimate this value. For the purposes of this study only the water used in the production and delivery of the fuel was considered.

Petroleum Based Fuels

Prior to exploring the impacts of advanced transportation fuels, it is important for comparison purposes to take a brief look at the technological system they will be replacing. Water comes into the petroleum production process in two main areas: refining and oil extraction. During the refining phase, it is estimated that 1 to 2.5 gallons of water are consumed for each gallon of product produced (DOE 2006). The oil production phase is not nearly as straightforward, since in many locations water is a byproduct of oil production. The American Petroleum Institute estimated that 2.7 barrels of water were produced for every barrel of oil equivalent (boe) from oil and gas production in 1995 (API 2000). The amount and quality of the water however varies significantly from well to well. Much of this water is recycled for enhanced oil recovery (EOR) which can require significant amounts of water input. After the natural pressure of an oil well decreases, water can be pumped into the well to increase production rates. The amount of water required can vary significantly depending on the geology and age of the field and the technology employed. Three separate EOR technologies, air injection, CO_2 injection, and micellar polymer typically require 2, 24 and 320 barrels of water per boe produced respectively (DOE 2006).

Due to the significant uncertainty in the water use in oil extraction, no attempt was made to estimate the average net water consumption for this process. However, it seems logical that net water consumption will only increase in the future as more mature oil fields deplete and there is more dependence on EOR methods to maintain oil production. For comparison purposes, the water use in oil refining was used as an estimate for total water consumption. This value comes to between 0.02 and 0.05 gallons of water per mile.

Biofuels

Biofuels are an alternative fuel source highly favored by U.S. policymakers and the agriculture sector. Corn ethanol is the most well-known and established such fuel, though cellulosic ethanol and soy biodiesel are rapidly being developed.

A primary advantage of biofuels is that they can be grown and produced regionally within the US, enhancing energy security and allowing the country to produce more of its own energy. They also fit into the existing national transportation infrastructure, which is currently designed to service automobiles that run on gasoline or diesel—both of which, like biofuels, are combustible liquids. From an infrastructure standpoint, the switch to biofuel-powered transportation would not be difficult.

However, there are problems associated with biofuels. Increasing demand for food crops for ethanol production can inflate food prices. Another problem with the use of biomass for fuel production is that most plants have relatively poor solar efficiencies and therefore may not represent the best use of their land from an energy standpoint. Table 1 shows the average biomass productivity in barrels of oil equivalents (boe) per hectare per year for a number of crops currently considered for biofuels. Solar efficiencies are calculated based on an estimate of 10,000 boe average solar energy per hectare per year and are all very low. Sugarcane is the only traditional crop that has a solar efficiency above 1%, but its utilization is limited due to climate and moisture requirements.

One promising alternative to traditional crops is the production of biofuels from microorganisms. There are a number of algal and bacterial strains that are capable of functioning at much higher solar efficiencies. The advantages of using microorganisms are numerous: they can grow in environments not suited for traditional crops, they can be grown in highly controlled and optimized systems, they grow quickly under the correct conditions, and they also generally contain a high percentage of lipid content which can be more easily converted into useful fuels through a relatively simple transesterification process. The main drawback however is high upfront capital investment.

Table 1. Average biomass productivity

Biomass Source	Fuel Type Produced	Productivity (boe/ha-yr)[a]	Solar Efficiency
Corn	Ethanol	20	0.2%
Switchgrass	Ethanol	23-50	0.2-0.5%
Sugarcane	Ethanol	210-250	2-3%
Soybean	Biodiesel	13-22	0.1-0.2%
Sunflower	Biodiesel	8.7-16	0.1-0.2%
Microalgae	Biodiesel	390-700	4-7%
Average Solar Energy[b]	NA	~10,000	

[a]Huber et. al. 2006; [b]Estimated based on 200 w/m^2 global average solar energy (Pinker and Lazlo 1992)

A significant potential issue with biofuels, especially in an arid state such as Arizona, is that they require large amounts of water to produce feedstock. With an average annual evapotranspiration rate of between 3 and 8 feet, there are very few locations within the state that receive enough rainfall to get by with no or even little irrigation. Average rainfall throughout the state is shown in figure 2 (AZDWR 2006).

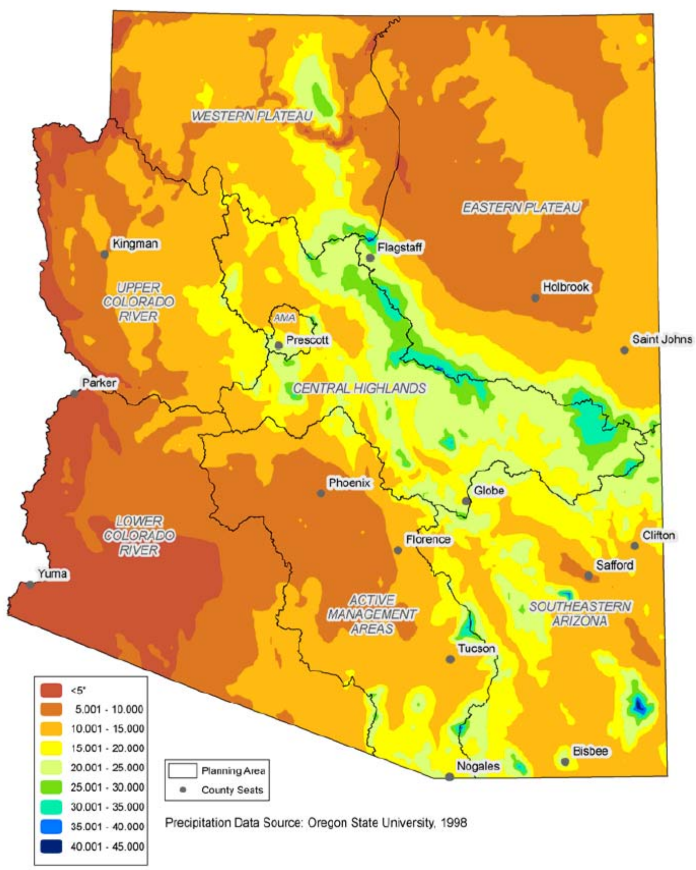

Figure 2. Average annual precipitation across Arizona

Corn Ethanol

Ethanol derived from corn is produced in relatively large quantities within the US—3.9 billion gallons in 2005 (EIA 2007a). Corn ethanol production seems to be a logical first step in US biofuel production, since the country is the world's largest producer of corn with 72.7 million acres harvested in 2000 (USEPA 2007). The infrastructure and knowledge base for making and handling ethanol are already in place since corn has been distilled into alcohol for centuries and the crop is currently grown in abundance throughout the country. Unfortunately, as the scale of ethanol production from corn has increased—mainly attributed to increased subsidies—problems have arisen. In February of 2007, Mexican citizens took to the streets to protest a price increase of 400% in the price of tortillas due to increased demand for corn used for ethanol production (BBC News 2007). In addition, recent research into the life cycle impacts of corn ethanol for energy has determined that the energy yield is only about 25% due to significant fossil fuel inputs for planting, harvesting, transporting and distilling. It has also been concluded that even if 100% of the US corn crop is devoted to ethanol production, only the net energy equivalent of 2.4% of US transportation fuel demand could be met (Hill et. al. 2006).

The majority of corn ethanol is created via the dry mill process, which is briefly described as follows: first, the starchy corn kernels are stripped off the cob and fed to a hammer mill to create corn meal. The meal is then liquefied, heated, and enzymes to induce saccharification are added. The resulting mash is cooled and moved to tanks where yeast is added and the fermentation process occurs. The resulting brew is then distilled, cooled, condensed, and stored.

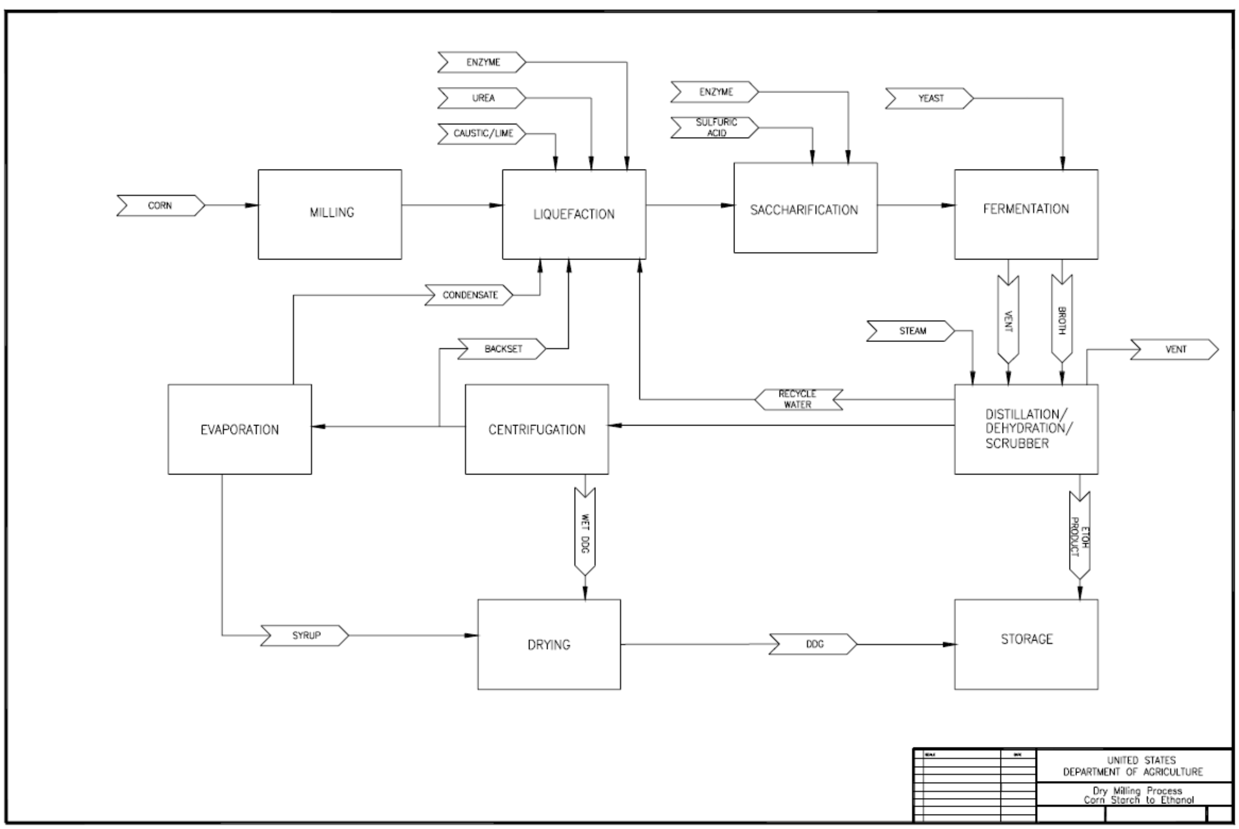

Figure 3. Dry milling process (source: NREL 2000).

Processes considered in the creation of ethanol from corn include water usage from: crop irrigation, other farm inputs (such as fertilizer and gasoline), ethanol plant construction, and ethanol production via the dry mill process. The results are shown in tables 2 and 3.

Table 2 contains data for irrigated corn crops only. Irrigation data in the high water usage column specifically applies to Arizona. But only 15% of all US corn crops are irrigated, so these numbers do not represent the national average for all corn crops (Ayden 2007). When this fact is taken into account, average water use declines steeply.

The totals in table 3 represent a more realistic national average for water used in the ethanol lifecycle. However, as mentioned above, corn crops in Arizona need intense irrigation and the high water use column in Table 2 is the most applicable.

Table 2. Corn ethanol lifecycle water use, irrigated crops only

Process	**Unit**	**Low Water Use**	**Avg. Water Use**	**High Water Use**
Crop Irrigation	gal H2O/gal ethanol	186[a]	820[a]	2240[a,b]
Farm Inputs	gal H2O/gal ethanol	3.3[c]	5.1[e]	7.0[d]
Ethanol plant construction	gal H2O/gal ethanol	0.03[f]	0.1[e]	0.18[f]
Ethanol production	gal H2O/gal ethanol	1[g]	4.7[g]	11[g]
Total - Fuel	**gal H2O/gal ethanol**	**190**	**830**	**2260**
Total - Vehicle	**gal H2O/VMT**	**5.7**	**25**	**67**

[a]DOE 2006; [b]High water-use irrigation from Arizona; [c]Oliveria et. al., 2005, Graboski 2002, Shapouri et.al. and CMUGDI 2008; [d]Pimentel 2005, Graboski 2002 and CMUGDI 2008; [f]USDA 2002, and CMUGDI 2008; [e]Average of low and high values; [g]USDA 2005.

Table 3. Corn ethanol lifecycle average water use (includes non-irrigated crops)

Process	**Unit**	**Low Water Use**	**Avg. Water Use**	**High Water Use**
Crop Irrigation	gal H2O/gal ethanol	39[a,b]	158[a]	433[a,b]
Farm Inputs	gal H2O/gal ethanol	3.3[c]	5.1[e]	7.0[d]
Ethanol plant construction	gal H2O/gal ethanol	0.03[f]	0.1[e]	0.18[f]
Ethanol production	gal H2O/gal ethanol	1[g]	4.7[g]	11[g]
Total - Fuel	**gal H2O/gal ethanol**	**43.3**	**168**	**451**
Total - Vehicle	**gal H2O/VMT**	**1.3**	**5.0**	**13**

[a]Derived from USDA 2003; [b]Derived from DOE 2006; [c]Oliveria et. al., 2005, Graboski 2002, Shapouri et.al. and CMUGDI 2008; [d]Pimentel 2005, Graboski 2002 and CMUGDI 2008; [f]USDA 2002, and CMUGDI 2008; [e]Average of low and high values; [g]USDA 2005.

Cellulosic Ethanol

Cellulosic ethanol, while still in its early stages, is set to emerge as a major contender in the biofuels market. Rather than handle and ferment the starches from a plant (for example, corn kernels), the more abundant lignocellulosic stalks and leaves are used for this process. There are several benefits gained from doing so: lignocellulosic product is generally considered waste or animal feed, so this process captures an existing low-grade output stream and turns it toward more productive uses. A wide variety of crops can be processed into ethanol in this manner, many of which are hardier than traditional food crops. And finally, most cellulosic crops have a better net energy balance than corn ethanol (Schmer 2008).

But there are also drawbacks to cellulosic ethanol. Conversion facilities that transform cellulosic biomass into fuel are currently much more expensive than those dealing with corn or soy. Capital costs will likely come down with more research and experience, but right now they pose a formidable barrier to economic production. Lignocellulosic ethanol also requires more water and inputs at the fuel plant.

The process for creating lignocellulosic ethanol from biomass is very similar to that for corn, but requires extra pretreatment of inputs and waste-water treatment. It also includes simultaneous saccharification and co-fermentation.

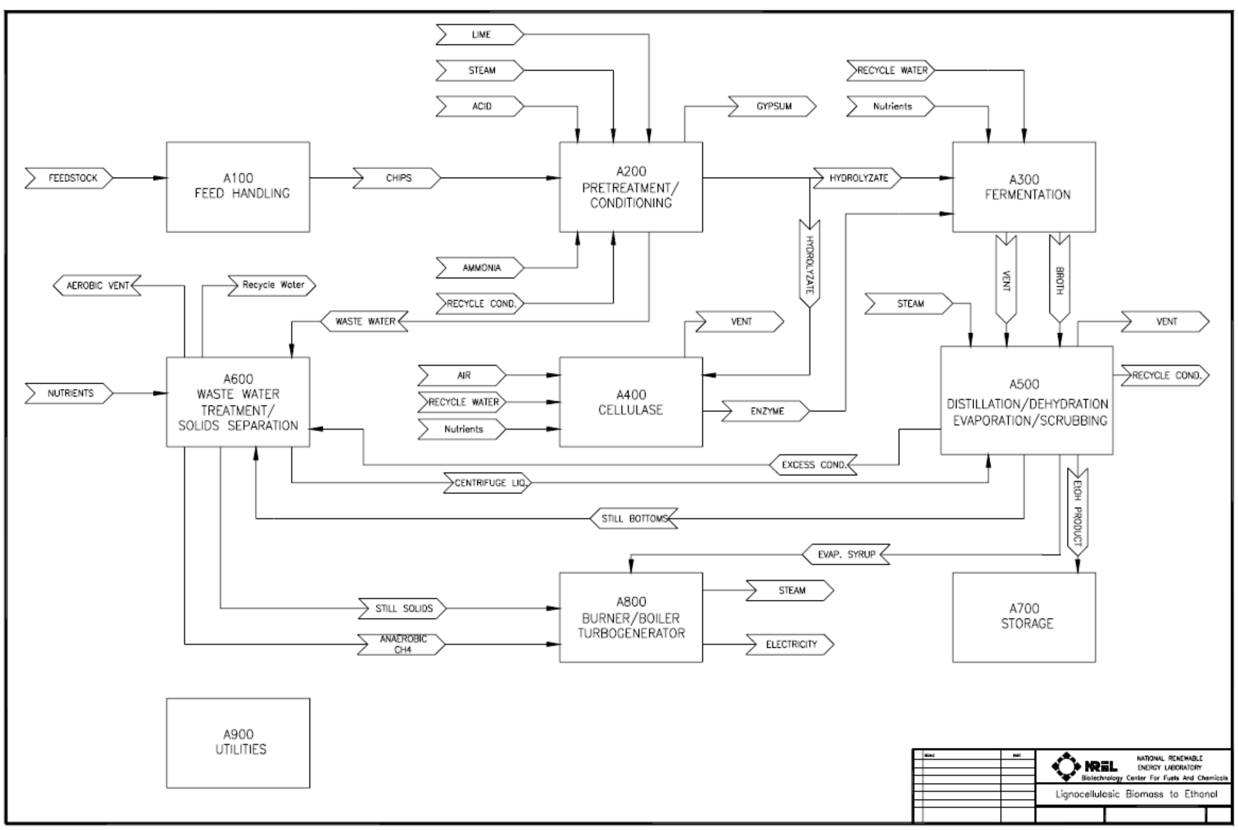

Figure 4. Lignocellulose-to-ethanol process (NREL 2000).

The cellulosic crop considered here is switchgrass, a perennial grass found primarily in the prairie lands of North America. Its habitat ranges from Saskatchewan to the Gulf Coast and there are many different strains adapted to the wide range of climates across the continent. It generally takes two or three years to establish a switchgrass stand and the plant is capable of surviving in relatively harsh conditions.

Processes considered in the creation of ethanol from switchgrass include water usage from: irrigation, other farm inputs (such as fertilizer and gasoline), and ethanol production. No specific data was available for ethanol plant construction so it was assumed the same as corn ethanol. While costs are currently higher for cellulosic ethanol plants, the impacts of construction are unlikely to be significantly different. The results are shown in table 4.

Table 4. Switchgrass cellulosic ethanol lifecycle water use, irrigated crops only

Process	**Unit**	**Low Water Use**	**High Water Use**
Crop Irrigation[a]	gal H2O/gal ethanol	352	411
Farm Inputs	gal H2O/gal ethanol	0.92[b]	3.4[c]
Ethanol Plant Construction[d]	gal H2O/gal ethanol	0.03	0.18
Ethanol Production	gal H2O/gal ethanol	1.9[e]	6[f]
Total - Fuel	**gal H2O/gal ethanol**	**355**	**420**
Total – Vehicle	**gal H2O/VMT**	**11**	**13**

[a]Saurbeck 2008; [b]Mclaughlin and Kszos 2005, Wang 2001 and CMUGDI 2008; [c]Wang 2001, Pimentel 2005, and CMUGDI 2008; [d]No specific data, assumed same as corn ethanol; [e]Ayden 2007; [f]Ayden 2002

The irrigation requirements for switchgrass are not widely published, as the plant usually does not generally require additional water for growth. However, Sauerbeck et. al, in the course of their research, reportedly applied between 210 and 240 mm (8.25 and 9.5 inches, respectively) of water to switchgrass stands in Italy to keep it healthy during a severe drought in 1999 and 2000. Accordingly, a value of roughly 225 mm (8.85 inches) was used to arrive at the numbers in Table 4. These numbers are likely too low for Arizona: totals for precipitation plus irrigation in Italy during the two years observed were between 16 and 20 inches, with evapotranspiration (ET) rates of around 40 inches. Arizona has an ET rate of between 36 and 96 inches/yr depending on location and has relatively little land that receives greater than 20 inches/yr of precipitation.

Since switchgrass does not require much irrigation in most climates, the actual water used to convert it to ethanol in more hospitable areas may be more accurately reflected by a “no irrigation” scenario. Note that since there are no national statistics indicating the proportion of switchgrass crop irrigated in the United States, the following table does not represent a national average but an ideal zero-irrigation case for more temperate climates. However, the values in Table 4 are likely the most applicable to Arizona, though they may be underestimates due to the state’s dry climate.

Table 5. Switchgrass cellulosic ethanol lifecycle water use, no irrigation

Process	**Unit**	**Low Water Use**	**High Water Use**
Crop Irrigation[a]	gal H2O/gal ethanol	0	0
Farm Inputs	gal H2O/gal ethanol	0.92[b]	3.4[c]
Ethanol Plant Construction[d]	gal H2O/gal ethanol	0.03	0.18
Ethanol Production	gal H2O/gal ethanol	1.9[e]	6[f]
Total - Fuel	**gal H2O/gal ethanol**	**2.9**	**9.6**
Total - Vehicle	**gal H2O/VMT**	**0.086**	**0.29**

[a]Assumed to be zero; [b]Mclaughlin and Kszos 2005, Wang 2001 and CMUGDI 2008; [c]Wang 2001, Pimentel 2005, and CMUGDI 2008; [d]No specific data, assumed same as corn ethanol; [e]Ayden 2007; [f]Ayden 2002

Soy Biodiesel

The US is the world's largest soy exporter and planted as many acres of soy as corn in 2007 (USEPA 2007). As such, soy is a well established crop and is very attractive for large-scale fuel manufacturing.

Biodiesel is manufactured via the process of transesterification, where an alcohol/catalyst mix is introduced to a vegetable oil feedstock and heated for several hours at just above the alcohol's boiling point. Glycerin and biodiesel are the end-products of this reaction and are separated out. Excess alcohol is removed and the biodiesel may then go through further cleaning and refining steps. Biodiesel plants are currently up and running around the country, though they are fewer in number and smaller in size than corn ethanol plants—soy plants in the US averaged about 7.5 million gallons per year for output in 2006, whereas corn ethanol plants averaged nearly 67 million gallons (Biofuels Marketplace 2006, Renewable Fuels Association 2005). However, newer biodiesel plants are projected to be in the 60 to 80 million gallon-per-year range (Radich 2004).

Processes considered in the creation of biodiesel from soy included water usage from: irrigation, other farm inputs (such as fertilizer and gasoline), plant construction, and biodiesel production.

Water requirements are extremely high when processing irrigated soy crops, averaging around 6200 gallons of water per gallon of biodiesel output. It is likely that the higher end of the irrigation requirements listed above—9000 gallons of water per gallon of ethanol—will apply to Arizona crops. The biodiesel conversion process is relatively water-efficient compared to that of corn and switchgrass, but the savings here are completely overshadowed by the water needs of the crop and by the relative energy inefficiency of the transesterifiction process—1 bushel of soy produces 1 gallon of biodiesel, whereas 1 bushel of corn produces 2.68 gallons of ethanol (DOE 2006, USDA 2005).

Table 6. Soy biodiesel lifecycle water use, irrigated crops only

Process	Unit	Low Water Use	Average Water Use	High Water Use
Crop Irrigation	gal H2O/gal biodiesel	1600[a]	6200[a]	9000[a]
Farm Inputs	gal H2O/gal biodiesel	33[b]	36[b]	38[b]
Biodiesel Plant Construction	gal H2O/gal biodiesel	0.03[c]	0.05[c]	0.06[c]
Biodiesel Production	gal H2O/gal biodiesel	1[d]	1[d]	1[d]
Total – Fuel	**gal H2O/gal biodiesel**	**1630**	**6240**	**9040**
Total - Vehicle	**gal H2O/VMT**	**28**	**100**	**150**

[a]DOE 2006; [b]Pimentel 2005 and CMUGDI 2008; [c]EIA 2007b and CMUGDI 2008; [d]NREL 1998

Only a very small percentage of soy across the nation is irrigated, so a corrected value that reflects the national average can be derived as shown in table 7.

Table 7. Soy biodiesel lifecycle average water use (includes non-irrigated crops)

Process	Unit	Low Water Use	Average Water Use	High Water Use
Crop Irrigation	gal H2O/gal biodiesel	60[a,b]	239[a]	358[a,b]
Farm Inputs	gal H2O/gal biodiesel	33[c]	36[c]	38[c]
Biodiesel Plant Construction	gal H2O/gal biodiesel	0.03[d]	0.05[d]	0.06[d]
Biodiesel Production	gal H2O/gal biodiesel	1[e]	1[e]	1[e]
Total - Fuel	**gal H2O/gal biodiesel**	**94**	**276**	**397**
Total – Vehicle	**gal H2O/VMT**	**1.6**	**4.6**	**6.3**

[a]Derived from USDA 2003 and USDA 2002; [b]Derived from DOE 2006; [c]Pimentel 2005 and CMUGDI 2008; [d]EIA 2007b and CMUGDI 2008; [e]DOE 2006

Microbial Biodiesel

Biodiesel derived from microorganisms is seen as a major potential source of sustainable transportation fuel. The two most promising categories of microorganism for the production of biodiesel are microalgae and cyanobacteria otherwise known as blue-green algae. Both are phototrophic single celled organisms with microalgae being more complex eukaryotes and cyanobacteria simpler prokaryotes. The simplicity of these organisms makes them easy to genetically engineer, enhancing their potential usefulness as fuel crops. While there are some important differences between these two types of organisms, for the purposes of this analysis they will be treated as equivalent and will be referred to collectively as algae.

The main advantages of algae for fuel production are their fast growth rates, high photosynthetic efficiency, and high lipid content. High lipid content is preferable for biodiesel production as that is the portion of the biomass that eventually becomes fuel. Different strains of algae are known to contain anywhere from 20 to 80% of their mass as lipids with up to 50% expected to be achievable in well controlled industrial production. Photosynthetic efficiencies are orders of magnitude higher than food crops, meaning less land is required to grow them as well. It has been estimated that as little as 1 to 3% of the existing US cropping area would be required to meet 50% of all US fuel needs compared to areas many times the existing crop land for corn and soybean based fuels (Christi 2007). In addition, no actual crop land would have to be used, since algae can be grown on any relatively flat land, including in the desert.

The biggest roadblock in the development of algae based fuels is costs. Unlike traditional agriculture, growing algae is capital intensive. Current costs are still approximately an order of magnitude higher than current market prices for fuel. Even when expected economies of scale are factored in, prices are still too high by a factor of 2 to 5 times (Christi 2007).

This cost challenge applies to both types of reactor systems currently being considered for large scale production. They are enclosed, tubular photobioreactors (PBR) and open raceway ponds. Enclosed systems have the advantage of allowing better control of the system and potentially higher yields at the cost of higher upfront investment. They are necessary if pure cultures are desired or if genetically altered organisms are used. Open ponds are cheaper up front, but they can easily be contaminated by undesirable organisms and generally achieve lower yields. Water use was estimated for both systems.

Because of this, lower system productivities were assumed in the analysis for the open system compared to the enclosed system. Processes considered for the enclosed microbial system were water used to produce the glass reactor, process water extracted with the concentrated biomass, and biodiesel production. Processes considered for the open microbial system were evaporation from the pond surface, process water, and biodiesel production. High and low estimates for each system are shown in tables 8 and 9. All surface evaporation calculations were based upon the range of conditions in Arizona, so these values should be recalculated if these numbers are to be applied to different locations. It is expected that water use would be lower for this system located in milder and more humid climates, although there may be some tradeoff in terms of yield.

Table 8. Enclosed algae photobioreactor biodiesel lifecycle water use

Process	**Unit**	**Low Water Use**	**High Water Use**
Glass Tubes	gal H2O/gal biodiesel	2.5[a]	4.6[a]
Process Water	gal H2O/gal biodiesel	40	57
Biodiesel Plant Construction	gal H2O/gal biodiesel	0.03[b]	0.06[b]
Biodiesel Production	gal H2O/gal biodiesel	1[c]	1[c]
Total - Fuel	**gal H2O/gal biodiesel**	**44**	**63**
Total – Vehicle	**gal H2O/VMT**	**0.73**	**1.0**

[a] Derived from European Commission 2005; [b]EIA 2007b; [c]DOE 2006

Table 9. Open algae photobioreactor biodiesel lifecycle water use

Process	Unit	Low Water Use	High Water Use
Surface Evaporation	gal H2O/gal biodiesel	165[a]	920[a]
Process Water	gal H2O/gal biodiesel	57	80
Biodiesel Plant Construction	gal H2O/gal biodiesel	0.03[b]	0.06[b]
Biodiesel Production	gal H2O/gal biodiesel	1[c]	1[c]
Total - Fuel	**gal H2O/gal biodiesel**	**223**	**1000**
Total – Vehicle	**gal H2O/VMT**	**3.7**	**17**

[a] Derived from AZDWR 2006; [b]EIA 2007b and CMUGDI 2008; [c]DOE 2006

Electric Vehicles

Electric and plug in hybrid vehicles (PHEV) provide a promising alternative to petroleum or biofuels powered vehicles. One advantage is the high efficiency of electric motors which can approach 95% (McCoy et. al. 1993). When running off of electricity vehicles also produce no tail pipe emissions, significantly reducing air pollution in crowded cities. This is not to say electric vehicles are completely clean, they just have a “long tail pipe” as the emissions are associated with producing the original source of electricity. Generally speaking however it is more economical to treat pollution at a single source than at thousands or millions of point sources. In the case of coal power, power plants can be paired with technologies to capture and store carbon dioxide, significantly lowering overall emissions. Electric vehicles can also be charged using clean, renewable energy sources such as solar and wind as well, which reduces the impacts even further.

Arizona has major potential for solar energy as shown in figure 5. The two main types of solar power are photovoltaics (PV) and concentrated solar power (CSP). While photovoltaics are probably the most well known form of solar power, concentrated solar power is gaining a lot of attention for utility scale solar power. CSP operates by using mirrors to direct sunlight onto a fluid which is heated and used to generate steam to drive a turbine instead of converting sunlight directly into electricity like PV. Both of these technologies along with coal power with carbon sequestration were evaluated for their life cycle water consumption.

Table 10 shows a comparison of general characteristics for the three electrical generation technologies. PV panels are typically somewhat more efficient than CSP plants, but they also tend to be more expensive. CSP can incorporate thermal storage into their design which gives the potential to significantly increase capacity factor (the average percentage of their rated capacity generated over a course of a year). This also allows for to shifting of load towards peak hours, which provides a useful benefit for utilities. The combined effects of lower capital costs and higher capacity factor show up in the form of significantly lower levelized cost of electricity production from CSP compared to PV. The added cost of sequestration brings the overall cost of coal up to comparable levels with CSP, but it is unlikely that CSP will completely displace coal for base load capacity. Based upon this, CSP, at least initially, appears like it may be an attractive way for utilities to increase their renewable generation mix.

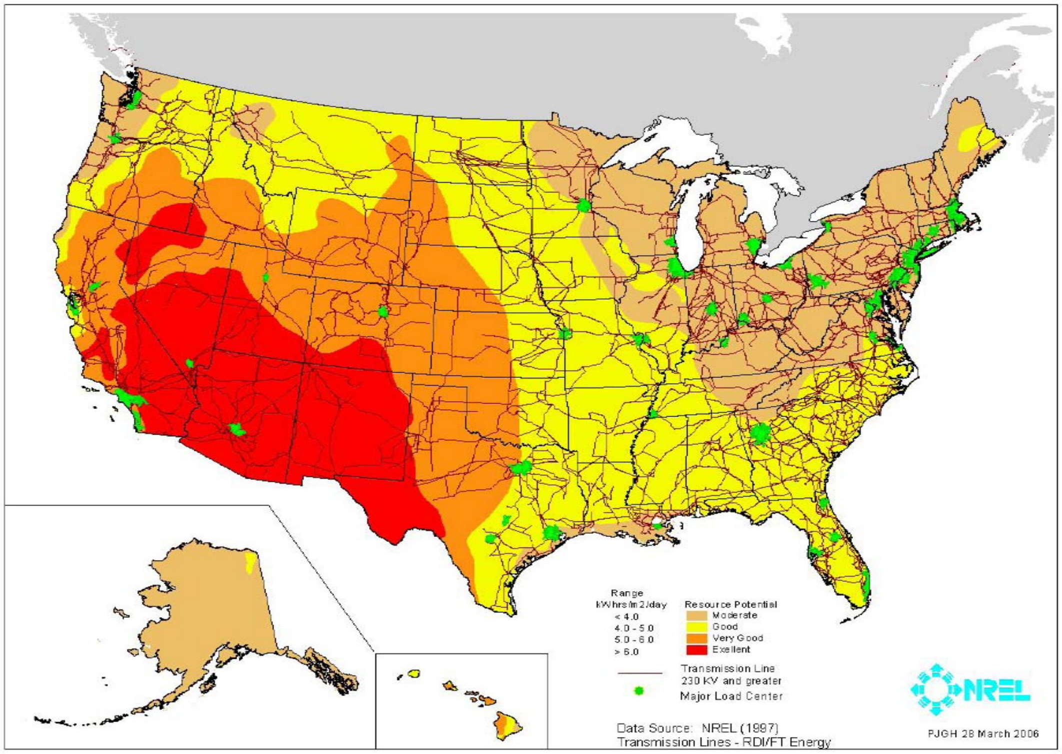

Figure 5. Map of US solar resource availability (NREL 2006)

Table 10. Low-Carbon Electricity Data

	Silicon PV[a]	**Parabolic Trough CSP**[a]	**Coal + Carbon Sequestration**[b]
Efficiency (system)	10-17%	8-16%	24-32%
Capital Cost (\$/kW$_p$)	\$5000-7000	\$2500-4000	\$2400-2900
O&M cost (\$/kWh)	\$0.01-0.02	\$0.01-0.05	\$0.01-0.02[c]
Capacity Factor	23%	22-56%	80-85%
Levelized Cost (\$/kWh)[d]	0.20-0.25	0.06-0.11	0.10-0.12

[a] data aggregated from Tester et. al. 2005, Aabakken 2006, and Price and Kearney 2003; [b]NETL 2007; [c]O&M costs do not include fuel; [d]Present value of lifecycle cost divided by lifecycle energy production

Solar Photovoltaics

The most common types of photovoltaics are based upon silicon, which can be in the form of multiple crystals, a single crystal or amorphous, with each form having its own advantages and disadvantages in terms of cost and efficiency. In addition, there is a wide range of newer technologies utilizing different elements including copper indium selenide, cadmium telluride, and a number of gallium and indium based designs. However, as of 2004, 94% of commercial

PV shipments were still silicon based (Kazmerski 2006). This study focuses only on silicon based Photovoltaics for this reason.

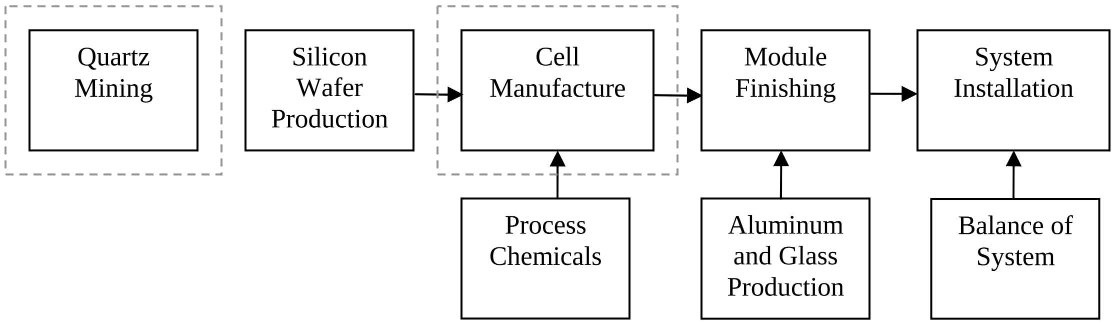

Figure 6. Silicon PV Manufacturing Process Diagram

Water consumption data for solar PV systems is somewhat limited. Figure 6 shows a basic process diagram for PV manufacture. The two processes outlined were the only two processes for which water data were available. The water consumption for the remaining production processes and operations and maintenance were estimating using the EIOLCA methodology. The total water use was also corrected to account for transmission losses from the generation point to the plug. The life cycle water consumption data is shown in table 11.

The limited amount of data results in a significant level of uncertainty that is not truly reflected in the range of the high and low estimates. However, based upon the data available it appears that water consumption for PV based electricity is relatively low. This conclusion seems to fit the conventional wisdom that photovoltacis do not require much water (DOE 2006).

Table 11. Solar PV powered electric vehicle life cycle water use

Process	**Unit**	**Low Water Use**	**High Water Use**
Quartz Mining	gal H2O/kWh	0.0002[a]	0.0008[a]
Cell Manufacture	gal H2O/kWh	0.0080[b]	0.012[b]
IO Correction - Manufacture	gal H2O/kWh	0.05[d]	0.14[d]
IO Correction - O&M	gal H2O/kWh	0.006[d]	0.02[d]
Water at Use Plant	gal H2O/kWh	0.068	0.17
Transmission Losses	fraction	0.09[c]	0.09[c]
Total - Electricity Delivered	**gal H2O/kWh**	**0.07**	**0.19**
Total - Vehicle	**gal H2O/VMT**	**0.016**	**0.044**

[a]Derived from Williams 2000 and Williams 2002;[b] BP 2004; [c]NREL 2003;[d]from cost data in table 10 and CMUGDI 2008

Concentrated Solar Power

Concentrated solar power comes in three main forms. The first and most common form is the parabolic trough. In this configuration, long parabolic mirrors are focused on a tube of liquid running down the center, heating the liquid which is then pumped to a heat exchanger to generate steam. Another configuration is the power tower or central receiver system, where an array of mirrors focuses light onto a central tower where the heat is collected and used to generate steam. The third configuration is known as a disk engine or sterling engine. In this configuration a large disk like mirror focuses light onto a small receiver that both collects the heat and generates electricity in one step, making this configuration better suited for small scale or distributed applications (Tester et. al. 2005). The parabolic trough is the most developed of the three configurations, with nine plants totaling over 300 megawatts of installed capacity operating since the 1980's (Aabakken 2006). The parabolic trough configuration was selected for analysis for this reason.

A parabolic trough CSP plant is made up of three main components: the collector field, the power block, and the optional storage system. For CSP, the largest component of water consumption is evaporation of cooling water during operation. Cooling water consumption is reported to be between 0.77 and 0.92 gal/kWh (DOE 2006). No data was available for water consumption for plant construction, so it was estimated using the EIOLCA methodology. The results for CSP water use are shown in table 12.

As expected, the water use for CSP is dominated by cooling water requirements. Looking at cooling water requirements for the different configurations of CSP plants, power tower systems have been estimated to fall near the bottom of the range for parabolic trough plants. Sterling Engine systems use air cooling and require no cooling water, but are also significantly more expensive than the other two configurations (DOE 2006).

Table 12. CSP powered electric vehicle life cycle water use

Process	**Unit**	**Low Water Use**	**High Water Use**
Cooling Water	gal H2O/kWh	0.77[a]	0.92[a]
IO Correction - Plant Construction	gal H2O/kWh	0.02[c]	0.08[c]
IO Correction - O&M	gal H2O/kWh	0.003[c]	0.02[c]
Water at Use Plant	gal H2O/kWh	0.79	1.02
Transmission Losses	fraction	0.09[b]	0.09[b]
Total - Electricity Delivered	**gal H2O/kWh**	**0.87**	**1.12**
Total - Vehicle	**gal H2O/VMT**	**0.20**	**0.26**

[a]DOE 2006; [b]NREL 2003 [c]from cost data in table 10 and CMUGDI 2008

Coal with Carbon Sequestration

Coal power is one of the oldest forms of electricity generation. It has the advantages of an abundant resource base and the ability to generate power continuously rather than just when the sun is shining or the wind is blowing. Also, a large percentage of our electricity already comes from coal. Because of these advantages it is unlikely it will be replaced completely, at least for a long time. However, the main disadvantage of coal is that it is dirty and produces large quantities of CO_2 (Tester et. al. 2005). One solution that is being proposed to this problem is carbon sequestration. With carbon sequestration, the CO_2 is captured at the stack and transported to a location where it is stored permanently. Storage locations can vary from geological formations, to depleted oil or gas wells, deep under the ocean, or it can be used in the enhanced oil recovery process. The main drawback is that sequestration can add up to 80% to the cost of electricity production from coal and use between 20-30% of the gross electricity produced (Anderson and Newell 2004).

Water consumption in the life cycle for coal plants occurs in coal mining, coal washing, coal transportation, and in plant operation which is generally dominated by cooling water. Two main scenarios were considered for coal plants with carbon sequestration. The first or low case was based upon an integrated coal gasification combined cycle (IGCC) power plant and low end estimates for coal production. The second or high case was based upon a pulverized coal (PC) plant and high end estimates for coal production. The life cycle water consumption for these two scenarios are shown in table 13.

Water consumption at coal plants with carbon sequestration was recently estimated by the National Energy Technology Laboratory by doing detailed modeling of a range of plant designs both with and without sequestration. Average total water consumption for IGCC power plants with carbon sequestration was around 0.5 gallon per kWh and represented a 10-15% increase in water use compared to the baseline without sequestration. Average total water consumption for PC power plants with carbon sequestration was around 1.2 gallons per kWh or about double the water consumption of the baseline power plant. These numbers also incorporated energy penalties of about 30% in the case of IGCC and 20% in the case of PC (NETL 2007).

Table 13. Coal + carbon sequestration powered electric vehicle life cycle water use

Process	**Unit**	**IGCC - Low**	**PC – High**
Coal Mining	gal H2O/kWh	0.01[a]	0.075[a]
Coal Washing	gal H2O/kWh	0[a]	0.025[a]
Coal Transportation	gal H2O/kWh	0[a]	0.07[a]
Plant Operation/Cooling	gal H2O/kWh	0.5[b]	1.2[b]
IO Correction - Plant Construction	gal H2O/kWh	0.013[b]	0.025[b]
Water at Use Plant	gal H2O/kWh	0.52	1.40
Transmission Losses	fraction	0.09[c]	0.09[c]
Total - Electricity Delivered	**gal H2O/kWh**	**0.57**	**1.53**
Total - Vehicle	**gal H2O/VMT**	**0.13**	**0.35**

[a]DOE 2006; [b]NETL 2007 and CMUGDI 2008; [c]NREL 2003

Analysis

A summary of the life cycle water use data is shown numerically in table 14 and graphically in figure 7.

Table 14. Summary of life cycle water use results; gallons per VMT

Technology	**Low**	**Med**	**High**
Traditional Unleaded	0.02	0.035	0.05
Coal +CS	0.13	0.24	0.35
Solar PV	0.016	0.03	0.044
Solar CSP	0.20	0.23	0.26
Switchgrass - Not Irrigated	0.086	0.19	0.29
Switchgrass - Irrigated	11	12	13
Soy National Average	1.6	4.6	6.3
Soy Biodiesel - Irrigated	28	100	150
Corn Ethanol National Average	1.3	5.0	13
Corn Ethanol - Irrigated	5.7	25	67
Microbial Biodiesel - Closed	0.73	0.87	1.0
Microbial Biodiesel - Open	3.7	10	17

The life cycle water use results were used along with data on typical transportation and water demand to determine the impact on Arizona's water resources from scaling up the proposed technologies. Data from the energy information agency indicates that Americans drove approximately 2.3 trillion miles in 2001 (EIA 2005). Dividing this number by the total population from the 2000 census gives an average of 8100 vehicle miles traveled per person. Assuming that driving habits in Arizona do not significantly differ from the national average, the number of miles traveled per year in Arizona was estimated to be 50 billion, based upon the 2006 population estimate (US Census Bureau 2008). This assumption was justified by the fact that the EIA found that VMT statistics for the western region were near the national average (EIA 2005). Total water demand in Arizona is reported to be on the order of 7 million acre feet per year (AZDWR 2008).

Scenarios were analyzed where each technology was scaled up to meet either 10% or 50% of Arizona's total transportation demand. The impact was calculated both in terms of total acre feet of water required and as a percentage of current overall water demand in the state. All calculations for the biofuels were based upon the high estimate for irrigated agriculture, therefore application of these numbers to other states is not recommended. The results of this analysis are shown in table 15.

This analysis shows that the three sources of electricity evaluated and microbial biodiesel based on a closed system design could all meet as much as 50% of Arizona's personal transportation demand while using less than 1% of the current water supply. Photovoltaic based solar power proved to be the most water efficient of all the technologies analyzed with an impact on par with petroleum refining. The remaining biofuels, especially corn and soy based fuels require much more water and would put considerable strain on current supplies if they were produced on a large scale in Arizona. If these fuels are to contribute significantly to our nations energy supply, they should be produced in states with more consistent rain fall or surplus water resources, as irrigation requirements dominate the water consumption for these fuels.

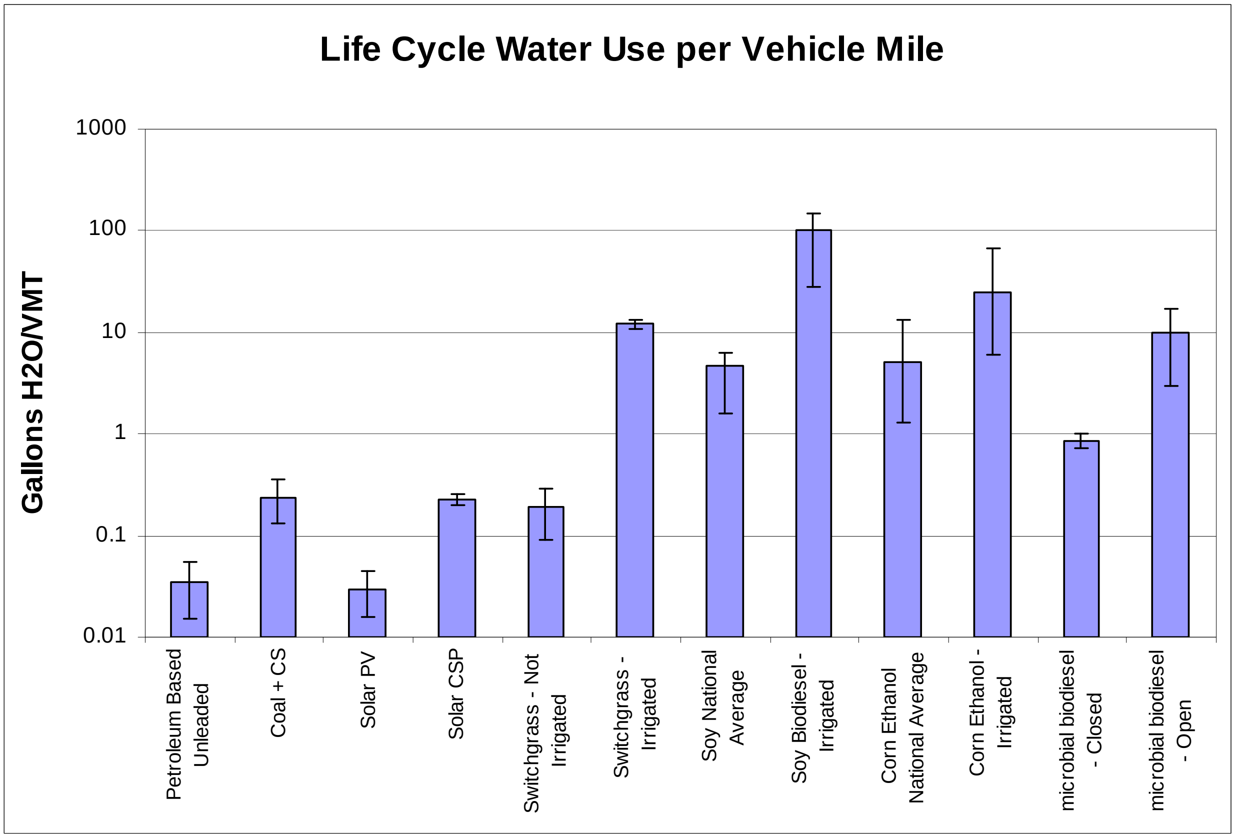

Figure 7. Summary of life cycle water use results

Table 15. Impact of Technology Scale Up on Total AZ Water Demand

	10%		**50%**	
Technology	**Total Acre-ft**	**% AZ demand**	**Total Acre-ft**	**% AZ demand**
Coal +CS	3,700	0.05	18,000	0.26
Solar PV	460	0.01	2,300	0.03
Solar CSP	3,500	0.05	18,000	0.25
Switchgrass - Irrigated	200,000	2.8	1,000,000	14
Soy Biodiesel - Irrigated	2,300,000	33	12,000,000	164
Corn Ethanol - Irrigated	1,000,000	15	5,100,000	73
Microbial Biodiesel - Closed	13,000	0.19	65,000	0.93
Microbial Biodiesel - Open	160,000	2.2	780,000	11

It is important to note that the difficult question of land use change was not considered in this analysis. While it is possible that fuel crops could displace other water intensive agriculture in Arizona leading to net neutral or even a decrease in water demand, the displaced agriculture will most likely relocate in order to continue to meet demand and may result in other environmental impacts such as deforestation. It is also important to recognize that the water consumption results consider the entire life cycle of a fuel process. While the analysis in table 15 assumes that all water consumption would take place in Arizona, it is likely that not all impacts will apply to a specific state or geographical area. For example, coal might be mined in Colorado or Wyoming and transported to Arizona to be burned in a power plant. The water consumption due to the mining process would not directly affect the water resources of Arizona, but the water used in construction and operation of the plant would.

One strategy that may be attractive in Arizona would be to focus on technologies and processes with low water requirements, while importing capital equipment and fuels with high "embodied" water content. PV solar panels or biofuels produced in other states would have virtually no impact on Arizona's water resources since the impacts would occur elsewhere, presumably where water was more abundant.

Conclusions

New forms of low carbon transportation energy will be important if we, as a society, are to successful combat global climate change. However, when considering any new technology it is important to critically and systematically assess it, to ensure that it will not lead to other problems or unintended consequences. Of the technologies explored, only photovoltaic solar power appears to have as low a life cycle water impact as current petroleum based fuels. Unfortunately it is also currently one of the more expensive alternatives. In general though electrical sources of energy were found to use significantly less water than biofuels and are not likely to strain water supplies. Along these lines, Arizona Public Service (APS) has recently announced plans to build at 280 MW CSP plant which could provide enough power to meet up to 10% of Arizona's transportation demand with PHEVs.

It does appear that cellulosic ethanol may be able to compete with the electrical sources as long as its feedstock is not irrigated. It is possible that some amount of cellulosic ethanol could be produced in Arizona from waste biomass. However it is not likely that a dedicated feedstock such as switchgrass can be grown efficiently in Arizona without irrigation. Importation of biofuels from other states may be required if these fuels are to be used to meet a significant portion of Arizona's transportation demand. Microbial biodiesel produced with feedstock grown in closed systems may be the exception. Water use is relatively low, but the technology is not fully developed and costs are currently prohibitive. Improving microbial biofuels technology is active area of research at Arizona State (for more information on this research see the following website - http://biofuels.asu.edu/index.shtml)

In the end water consumption is only one piece of data in a complex, multidimensional decision making process. As with all decisions, there are clearly tradeoffs. For the future of energy in Arizona, the tradeoffs are between cost, carbon, and water.

Appendix A – EIOLCA methodology

To estimate the water use for unknown capital equipment and processes, economic input-output (EIO) data was used. This methodology aggregates all impacts of a given economic sector and allocates them based upon the economic value of the process of interest. The main advantage of EIO data is that it includes both direct and indirect impacts. This means that it considers impacts directly by a specific sector and water used in producing all inputs to that sector as well. In general EIO analysis tends to give more complete accounting of environmental impacts compared to process based analysis which always suffers from cut-off error due to processes and inputs that are not accounted for. This advantage comes at a cost of aggregation which makes it difficult to evaluate specific processes or compare similar technologies.

The specific data set used in this analysis was from the US 1992 benchmark index implemented in the Carnegie Mellon online tool, EIOLCA.net (CMUGDI 2008). This was the only recent EIO data set for the United States that contains water consumption data. In order to correct for the age of the data, all values were converted to 2007 dollars using PPI data (Economagic 2008). The output from this model included water intake, treated discharge and untreated discharge. In order to determine water consumption, both discharge quantities were subtracted from the water intake value. It is quite possible that a significant portion of the water that is discharged untreated may be of diminished quality, but determining what fraction for each sector was beyond the scope of this effort and thus was not accounted for.

The data set also only contains process water consumption from manufacturing processes and does not consider water from energy inputs or agricultural inputs (two of the largest consumers of water). It does provide total energy inputs by type though, so total energy consumption for each sector was corrected by calculating the water consumption for the energy inputs. A high and low estimate of water consumption from energy inputs was estimated and added to the process water requirement. The water consumption values used are shown in table A-1. For most sectors the water requirement for energy accounted for between 10-50% of the total water consumption.

Table A1. Direct water consumption of traditional energy sources

Energy Source	**Unit**	**High**	**Low**
Electricity[a]	gal/kwhr	2	0.47
Coal[b]	gal/MJ	0.0076	0.0019
Oil[b]	gal/MJ	0.0210	0.0083
Natural Gas[b]	gal/MJ	0.0028	0.0028

[a]NREL 2003, for current US electricity mix; [b]DOE 2006

A summary of the total water consumption data for important sectors is shown in table A-2 in units of gallons per 2007$.

Table A-2. Total EIOLCA water consumption data by sector; gallon/$, 2007

Sector	**Low**	**High**
N and P fertilizers	37.19	40.26
Pesticides and agricultural chemicals	4.01	5.01
Lime	5.03	7.24
Industrial inorganic and organic chemicals	6.96	8.19
Glass containers	1.75	3.69
Farm machinery and equipment	5.75	6.61
Motor vehicles (passenger cars and trucks)	1.47	2.50
General industrial machinery and equip	1.06	1.89
Turbine and generator sets	0.89	1.67
Electrical industrial equipment	1.42	2.57
Semiconductors and related devices	0.54	1.14
Storage batteries	1.15	2.36
New construction	0.63	1.10
Other repair and maintenance construction	0.57	1.00
Engineering, architectural and surveying services	0.11	0.25

Appendix B – Biofuels Calculations

Constants and Conversions

Various conversion factors and constants were used during the course of calculations. The following is a list of these, with sources where appropriate:

Table B-1. Conversions for biofuel calculations

Constants		**Source**
1 acre-ft water	325,851 gallons	
1 acre	0.4 hectares	
US avg water consumption for electrical generation	2 gal H2O/kWh	NREL 2003
1 kWh	859.8 kcal	
Soy		
1 bushel soy	1 gallon biodiesel	Pimentel 2005, DOE 2006
US average soy yield	43.6 bushels/acre*	USDA 2002
US low, average, high soy irrigation	0.2, 0.8, 1.2 acre-ft*	USDA 2003
Percentage of US soy irrigated	4%*	USDA 2002
Corn		
1 bushel corn	25 kg	Eaves 2007
1 bushel corn	2.68 gallons ethanol	USDA 2005
US low, average, high corn irrigation	0.3, 1.2, 3.3 acre-ft*	USDA 2003
Percentage of US corn irrigated	15%	Pimentel 2005, Ayden 2007
US average corn yield	139 bushels/acre*	Pimentel 2005
Switchgrass		
1 ton biomass	90 – 104 gallons ethanol	NREL 2005
Average switchgrass yield with irrigation	6.6 tons/acre*	Sauerbeck (available online)
Switchgrass irrigation needs in drought	0.75 acre-ft*	Sauerbeck (available online)

* = calculated from source. Calculations are shown below.

Corn Ethanol, Irrigated (Table 2)

DOE 2006 provides values of 500 gal/bushel (Pennsylvania), 2200 gal/bushel (national avg.), and 6000 gal/bushel (Arizona) for corn crop irrigation. Given 1 bushel of corn = 2.68 gallons of ethanol, this works out to 186 gal H2O/gal ethanol, 820 gal H2O/gal ethanol, and 2240 gal H2O/gal ethanol for the Low, Average, and High scenarios.

A yield of 139 bushels/acre was assumed for corn based upon Table 1 from Pimentel (2005). Yield is listed as 8,655 kg/ha. Since 1 bushel of corn is roughly 25 kg, this translates to about 139 bushels/acre.

Farm inputs included in the analysis were N and P fertilizers, pesticides and lime. Their impacts were calculated using the IO data from table A-2 for the appropriate sectors. Table B-2. shows the masses of the different inputs assumed in the calculations.

Table B-2. Chemical inputs to corn production; kg/ha

Input	Low	High
N and P fertilizers	198[a]	218[b]
Pesticides and ag chem	2.4[c]	9[b]
Lime	17[d]	2959[c]

[a]Oliveria et. al. 2005; [b]Pimentel 2005; [c]Graboski 2002; Shapouri et. al. 2001

Ethanol plant construction calculations assumed a 30 year plant lifetime and an average size of 67 million gallons output per year (average plant size calculated from http://www.ethanolrfa.org/industry/locations/). New plant construction was estimated to be between $1.05 and $3 per gallon of installed capacity in 2002 (USDA 2005). Adjusting to 2007 dollars, these become $1.17 and $3.52, yielding plant costs of between $78.47 and $236.1 million.

Water IO values for new construction and general industrial machinery were taken from table A-2. The processes were each allocated 50% of the total cost—the exact breakdown of the costs is unknown and both numbers are relatively close, so a 50/50 allocation should not bias much one way or another.

Values for water consumption during ethanol fuel production were taken directly from USDA (2005), p. 14.

Corn Ethanol, Average Irrigation (Table 3)

The only difference between this table and the last is in the crop irrigation entry. The new irrigation values were calculated from USDA 2003 with data for low, average, and high irrigation values from DOE 2006. Irrigated corn crops averaged 1.2 acre-ft of water in 2003 and only 15% of corn crops were irrigated. This amounts to an average over all corn crops of 1.2 acre-ft * 0.15 = 0.18 acre-ft.

(0.18 acre-ft) * (325,851 gallons H2O/acre-ft) = 58,653 gal H2O/acre
(58,653 gal H2O/acre) / (139 bushels corn/acre) / (2.68 gal ethanol/bushel corn) = 158 gal H2O/gal ethanol

For the low and high scenarios, simple ratios were first taken to estimate acre-ft of irrigation:

(820 gal H2O/gal ethanol) / (1.2 acre-ft) = (186 gal H2O/gal ethanol) / (X_{low} acre-ft)
X_{low} = 0.3 acre-ft

(0.3 acre-ft) * 0.15 * (325,851 gal H2O/acre-ft) = 14,663 gal H2O/acre
(14,663 gal H2O/acre) / (139 bushels corn/acre) / (2.68 gal ethanol/bushel corn) = 39.4 gal H2O/gal ethanol

(820 gal H2O/gal ethanol) / (1.2 acre-ft) = (2240 gal H2O/gal ethanol) / (X_{high} acre-ft)
X_{high} = 3.3 acre-ft

(3.3 acre-ft) * 0.15 * (325,851 gal H2O/acre-ft) = 161,296 gal H2O/acre
(161,296 gal H2O/acre) / (139 bushels corn/acre) / (2.68 gal ethanol/bushel corn) = 433 gal H2O/gal ethanol

Cellulosic (Switchgrass) Ethanol, Irrigated (Table X3)

Crop irrigation values were difficult to come by for switchgrass, however an example by Sauerbeck et al indicated that between 210 and 240 mm (~0.7 and 0.8 acre-ft) was sufficient to combat severe drought conditions in southern Italy. An average irrigation of 0.75 acre-ft was assumed from Sauerbeck, with an average yield of about 15.4 tonne/ha (~6.61 ton/acre).

(0.75 acre-ft) * (325,851 gal/acre-ft) / (6.61 ton/acre) = 36,973 gal H2O/ton

NREL (2005) report that between 90 and 105 gallons ethanol can be manufactured from one ton of biomass.

(36,973 gal H2O/ton) / (90 gal ethanol/ton) = 411 gal H2O/gal ethanol
(36,973 gal H2O/ton) / (105 gal ethanol/ton) = 352 gal H2O/gal ethanol

Farm inputs included in the analysis were N and P fertilizers and pesticides. There was no data reporting the amount of lime used, if any. Their impacts were calculated using the IO data from table A-2 for the appropriate sectors. Table B-3. shows the masses of the different inputs assumed in the calculations.

Table B-3. Chemical inputs to switchgrass production; kg/ha

Input	**Low**	**High**
N and P fertilizers	50[a]	159.7[b]
Pesticides and ag chem	.04[b]	3[c]
Lime	0	0

[a]McLaughlin and Kszos 2005; [b]Wang 2001; [c]Pimentel 2005

Estimates for water use from cellulosic plant construction were not performed due to a lack of established data. Plant costs are currently higher than those for corn ethanol, but their contribution to the water lifecycle would still be quite small—corn ethanol plants contribute 0.1 gal H2O/gal ethanol in the highest scenario, and cellulosic plants would not be too much past this. Such small numbers have little impact on the total water lifecycle.

Fuel production water use values were taken directly from Ayden (2007 and 2002). The smaller value of 1.9 gallons is the result of a proposed thermochemical process, while the larger is from more established biochemical processes.

Cellulosic (Switchgrass) Ethanol, No Irrigation (Table X4)

The only difference between this table and the irrigated switchgrass table is that here irrigation values are simply assumed to be zero.

Soy Biodiesel, Irrigated (Table X6)

Crop irrigation water use was taken directly from DOE (2006), which states that irrigation is typically between 1600 and 9000 gallons H2O/bushel, with a national average of 6200 gallons H2O/bushel. One bushel of soy is needed to produce one gallon of biodiesel.

Farm inputs included in the analysis were N and P fertilizers, pesticides and lime. Only one source was identified with specific data for soybean inputs, so the high and low scenarios used the same values. The variation between the two was entirely a result of the difference in the high and low impacts from the EIO sector data in table A-2. Table B-4. shows the masses of the different inputs assumed in the calculations.

Table B-2. Chemical inputs to soybean production; kg/ha

Input	**Low**	**High**
N and P fertilizers[a]	41.5	41.5
Pesticides and ag chem[a]	1.3	1.3
Lime[a]	4800	4800

[a]Pimentel 2005

An average yield of 43.6 bushels soy/acre was derived from the following data in USDA (2002):

Percentage of soybean production: 37% (Low), 49% (Mid), 14% (High)
Bushels/acre: 50.4 (Low), 42.2 (Mid), 30.8 (High)

0.37 * 50.4 + 0.49 * 42.2 + 0.14 * 30.8 = 43.6 bushels/acre

Biodiesel plant construction data was treated in the same manner as the ethanol construction data above. A value of $1.04 per gallon of installed capacity was assumed, which translated into $1.22 in 2007 dollars (EIA 2007b). Current average biodiesel plant sizes are around 7.5 million gallons/yr (Biofuels Marketplace 2006). But newer construction averages closer to 70 million gallons/yr and this value was used in the calculations (EIA 2007b). A lifetime of 30 years was assumed, as well as a 50/50 split of costs between construction and construction materials. The resulting value of 0.036 gal H2O/gal biodiesel is tiny compared to the rest of the lifecycle.

Biodiesel fuel production was taken directly from DOE (2006) and is stated as 1 gal H2O for every gallon of biodiesel produced.

Soy biodiesel, Average Irrigation (Table X7)

The percentage of soy production under irrigation was not readily available and was calculated from USDA (2002), which uses data from 1997. The report divided up soy producing farms into low-cost, mid-cost, and high-cost categories and compiled statistics accordingly.

Percent of soybean production (bushels): 37 (Low), 49 (Mid), 14 (High)
Soybean acreage irrigated (percentage): 0 (Low), 3 (Mid), 18 (High)

0.37 * 0 + 0.49 * 0.03 + 0.14 * 0.18 = 0.04, or 4%

From USDA (2003), average irrigation on irrigated soy farms was 0.8 acre-ft, yielding a national average of (0.8 acre-ft) * 0.04 = 0.032 acre-ft. This is equivalent to 10,427 gallon H2O/acre

(10,427 gal H2O/acre) / (43.6 bushels/acre) / (1 gal biodiesel/bushel) = 239 gal H2O/gal biodiesel

For the low and high scenarios, simple ratios were first taken to estimate acre-ft of irrigation:

(6200 gal H2O/gal biodiesel) / (0.8 acre-ft) = (1600 gal H2O/gal biodiesel) / (X_{low} acre-ft)
X_{low} = 0.2 acre-ft

(0.2 acre-ft) * 0.04 * (325,851 gal H2O/acre-ft) = 2,607 gal H2O/acre
(2,607 gal H2O/acre) / (43.6 bushels corn/acre) / (1 gal biodiesel/bushel soy) = 59.8 gal H2O/gal biodiesel

(6200 gal H2O/gal biodiesel) / (0.8 acre-ft) = (9000 gal H2O/gal biodiesel) / (X_{high} acre-ft)
X_{high} = 1.2 acre-ft

(1.2 acre-ft) * 0.04 * (325,851 gal H2O/acre-ft) = 15,641 gal H2O/acre
(15,641 gal H2O/acre) / (43.6 bushels corn/acre) / (1 gal biodiesel/bushel soy) = 358.7 gal H2O/gal biodiesel

Microbial Biodiesel

Two scenarios were developed for evaluating the water use. The first scenario assumed a glass enclosed PBR. The high case assumed a 7% photosynthetic efficiency and 50% lipid yield by weight. The low Case assumed a 5% photosynthetic efficiency and 35% lipid yield by weight. The second scenario assumed an open pond system achieving 5% efficiency and 35% lipid in the high case and 3% efficiency and a 25% lipid in the low case. These yields are somewhat high but likely achievable based upon yields reported in the literature (Janssen et. al. 2003). Both scenarios assume an average incident solar flux of 6 kWh/m2-day (NREL 2006).

Processes considered for the enclosed microbial system were water used to produce the glass reactor, process water extracted with the concentrated biomass, and biodiesel production. The water use for the glass was estimated based on water consumption in glass manufacture of 8 L of water per kg of glass and a 20 year lifetime (European Commission 2005). The process water requirement was based on an assumed 5% concentration of biomass leaving the reactor. This is expected because operators would attempt to minimize water consumption, but higher biomass concentrations would make downstream processing difficult due to the slurry properties. Water use in biodiesel production has been reported as 1 gallon of water per gallon of fuel (DOE 2006).

Processes considered for the open microbial system were evaporation from the pond surface, process water, and biodiesel production. Yearly evaporation in AZ ranges from 3 to 8 feet per year with an average around 5 feet per year (AZDWR 2006). The average evaporation rate for AZ was used to determine evaporative water loss from the open system. The same assumptions about process water and biodiesel production were used for the open and enclosed systems. However, the lower lipid concentration assumed in the open system leads to higher process water requirements.

Appendix C – Electric Vehicle Calculations

Solar PV

Data presented in (Williams 2002) and (Williams 2004) were used to estimate the total water use in mining the quartz required to produce the refined silicon inputs. The basis for these calculations was a data point indicating that 1.3 kg of water is used to mine 1 kg of raw quartz (Williams 2000). This data point was used along with a material input table for PV manufacture and silicon yields for each step of the silicon wafer production process to determine the amount of water required for a given area of PV (Williams 2000, Williams 2002). The total water use was then divided by the expected output of the panel over a 30 year lifetime and assuming a 14% efficiency if the panel was placed in AZ. The resulting water consumption for this process was estimated to be between $2*10^{-4}$ and $8*10^{-4}$ gal/kWh. The lower value assumed silicon processed only to polysilicon and the higher value assumed silicon processed to monocrystaline wafers.

Water consumption for cell manufacture was obtained from a BP Solar environmental statement for their Sidney, Australia manufacturing facility. Water use was reported as 1871 L/kW$_p$ in 2004 and 2844 L/kW$_p$ in 2003 (BP 2004). The lower water use in 2004 was the result of process efficiency improvements implemented at this facility as part of an internal environmental management plan. This facility manufactures solar cells and exports most of them to other facilities for module finishing so the water use was assumed to only apply to the cell manufacturing process. By assuming a 30 year lifetime and a 23% capacity factor the water use from this process was estimated to be $8*10^{-3}$ in 2004 and $12*10^{-3}$ gal/kWh in 2003.

The IO correction factor for PV was calculated using the EIO data presented in appendix A. The capital costs were broken down based on the fractional costs shown in table C1. High and low estimates of the IO correction factors were determined using the upper and lower range of the costs listed in table 10 for capital costs and operations and maintenance. Water consumption for the remainder of the manufacturing process was estimated to be between 0.054 to 0.141 gal/kWh. Water consumption for operations and maintenance was estimated to be between 0.006 and 0.020 gal/kWh. The water use for O&M breaks down to approximately 1 to 2 liters/m2 of water per month, which seems like a reasonable amount of water for rinsing panels in dry, dusty climates.

Table C1. PV System Cost Breakdown

Process	**Fractional Cost[a]**
Inverter	0.11
BOS	0.09
Installation	0.09
Other costs	0.17
Silicon	0.275
Cell Manufacturing	0.11
Module finishing	0.165

[a]Kasmerski 2005

Concentrated Solar Power

A parabolic trough CSP plant is made up of three main components: the collector field, the power block, and the optional storage system. For CSP, the largest component of water consumption is evaporation of cooling water during operation. Cooling water consumption is reported to be between 0.77 and 0.92 gal/kWh (DOE 2006). No data was available for water consumption for plant construction, so it was estimated using the EIO methodology.

Capital cost breakdowns and operating conditions for three separate CSP plants are shown in table 3. The first column has specifications for a plant that has been operating since 1989, while the other two columns represent designs for near (2004) and medium (2010) term power plants modeled based upon known and expected technological improvements. The data from the current and mid-term plants were used for the high and low scenarios assuming a 30 year plant lifetime. Only half of the O&M costs were considered in the EIO calculation as it was assumed that the other half of the O&M costs cover cooling water.

Table 3. CSP Plant Capital Costs and EIO Water Consumption Correction[a]

	SEGS VI	**Near term**	**Mid-term**
Capacity (kW)	30000	50000	100000
Collector field cost ($/kW)	1482	1519	1895
Thermal storage cost ($/kW)	0	0	351
Power block ($/kW)	1022	854	657
Other costs ($/kW)	504	372	512
Total cost ($/kW)	3008	2745	3416
O&M cost ($/kWh)	0.046	0.024	0.01
Capacity factor	22	29	56

[a]Data on plant specifications from Price and Kearney 2003

Coal with Carbon Sequestration

Water consumption in the life cycle for coal plants occurs in coal mining, coal washing, coal transportation, and in plant operation which is generally dominated by cooling water. Two main scenarios were considered for coal plants with carbon sequestration. The first or low case was based upon an integrated coal gasification combined cycle (IGCC) power plant and low end estimates for coal production. The second or high case was based upon a pulverized coal (PC) plant and high end estimates for coal production.

Water use in the various stages of coal production can vary quite a bit. Water use in coal mining is reported to range between 1 and 6 gallons per million BTU's (MMBTU). Coal can be washed to remove sulfur and improve combustion properties. Coals originating in the eastern part of the US are typically washed while coals from the west generally are not. The water use for coal washing typically ranges from 1 to 2 gallons per MMBTU. In addition up to 20% of coal is transported in slurry pipelines. Consumptive water use from these systems can range from 11 to 24 gallons per MMBTU after accounting for the average of 70% of the water that is recycled at the plant (DOE 2006). The upper and lower ends of each of these ranges were used to define the high and low scenarios in table 13 with washing and transport only included in the high scenario.

Water consumption at coal plants with carbon sequestration was recently estimated by the National Energy Technology Laboratory by doing detailed modeling studies of a range of plant designs both with and without sequestration. Average total water consumption for IGCC power plants with carbon sequestration was around 0.5 gallon per kWh and represented a 10-15% increase in water use compared to the baseline without sequestration. Average total water consumption for PC power plants with carbon sequestration was around 1.2 gallons per kWh or about double the water consumption of the baseline power plant. These numbers also incorporated energy penalties of about 30% in the case of IGCC and 20% in the case of PC (NETL 2007).

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