Supporting Information for the manuscript:

The Water Intensity of Transportation

Carey W. King and Michael E. Webber

31 pages total:

Table S1: Fuel energy content for the fuels studied.

Appendix S-A: Calculations for the water consumption for each transportation fuel.

Appendix S-B: Calculations for the water withdrawal for each transportation fuel.

References Supplemental: References used in Supplemental Information but not explicitly mentioned in main text.

Table S1. Values used for energy content of various fuels.

Fuel	Value	Units	Reference
Petroleum Gasoline	**125,000**	**Btu/gal - HHV**	**(27)**
Petroleum Diesel	**138,700 (38.7)**	**Btu/gal (MJ/L) - HHV**	**(27)**
Fischer-Tropsch Diesel (distillate)	**36.9(5.55)**	**MJ/L (MMBtu/BBl) - HHV**	**(S1)**
Fischer-Tropsch naptha	**5.3**	**MMBtu/BBl**	**(S2)**
Fischer-Tropsch butane	**28.7 (4.3)**	**MJ/L (MMBtu/BBl)**	**(S2)**
Hydrogen	**0.114/0.134**	**MMBtu/kg - LHV/HHV**	**(16)/(27)**
Ethanol	**75,700/86,400**	**Btu/gal - LHV/HHV**	**(27)**
Soy Biodiesel	**123,700/126,206**	**Btu/gal - LHV/HHV**	**(27)**

HHV: higher heating value
LHV: lower heating value

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Appendix S-A: Calculations for Water Consumption per Mile (gal/mile)

The calculation of water consumption to propel a light duty vehicle a mile follows a similar approach for each fuel.

Three major categories for tabulating water consumption and withdrawal are considered:

1. *Mining and farming*
2. *Processing and Refining of feedstock to fuel*
3. *Efficiency of use of fuel in vehicle*

Categories neglected in this analysis:

1. *Transport of feedstock from mine/farm to refinery*
2. *Transport of refined fuel to consumer purchase point*
3. *Manufacturing and installation of physical capital*
4. *Water availability (aquifer recharge, river flow, evapotranspiration) for biofuel crops*

Gasoline from U.S. Liquid Petroleum

Oil extraction in U.S.: (*5, 6, 13, S4*)

= (EOR gal H_2O)*(% oil used for gasoline)/(gal gasoline consumed in U.S.)

= (126 Bgal/yr)*(46.6 % into gasoline)/[(9.13 MBBl/day gasoline)(42 gal/BBl)(365 day/yr)]

= **0.42 gal H_2O/gal oil**

Oil Refining to Gasoline: (*6*)

= **1.0 - 2.5 gal H_2O/gal oil product** (~ 1 gal oil)

Gasoline efficiency in automobile:

60% of LDVs are cars averaging 22.3 mpg (*1*)

40% of LDVs are trucks/SUVs averaging 17.7 mpg (*1*)

Composite mpg rating of gasoline LDVs:

= (60% cars)(22.3 mpg) + (40% trucks/SUVs)(17.7 mpg)

= **20.5 mpg for gasoline LDVs** (*5*)

Total water consumption for gasoline driving:

= (extraction + processing/refining)/(automobile fuel efficiency)

= (0.42 gal H_2O/gal oil + 1.0-2.5 gal H_2O/gal gas)/(20.5 miles/gal gas)

= **0.07 - 0.14 gal H_2O/mile**

Gasoline from Tar Sands

Tar Sands Petroleum extraction in Alberta, Canada:

3 m^3 H_2O/m^3 oil – LOW value for "open pit mining" (*12*)

7 m^3 H_2O/m^3 oil – HIGH value for "in situ tar sands mining" (*12*)

Oil Refining to Gasoline:
Same as above for Petroleum Gasoline

Gasoline efficiency in automobile:
Same as above for Petroleum Gasoline.

Total water consumption for gasoline driving:
= (extraction + processing/refining)/(automobile fuel efficiency)
= (3-7 gal H_2O/gal oil + 1.0-2.5 gal H_2O/gal gas)/(20.5 miles/gal gas)
= **0.20 - 0.46 gal H_2O/mile**

Gasoline from Shale Oil

Reserves of U.S. oil shale are estimated at nearly 2 trillion barrels of oil (*9*) primarily in the Green River Formation of Wyoming, Utah, and Colorado. The regulatory and environmental tradeoffs to production of the oil shale have already been expressed in public meetings, with water usage and quality being a top concern (*S3*). Reserves of U.S. tar sands are concentrated in Utah and are much smaller than for oil shale at projected 60-80 billion barrels of oil with approximately 15-25 billion barrels measured (*S13*).

Shale oil extraction and retorting to refinery ready oil: (*S5*)
2 – 5 gal H_2O/gal 'ready' oil from Direct/Indirect Above Ground Retorting and Modified In-Situ processes with and without Above Ground Retorting

Oil Refining to Gasoline:
Same as above for Petroleum Gasoline.

Gasoline efficiency in automobile:
Same as above for Petroleum Gasoline.

Total water consumption for gasoline driving:
= (extraction + processing/refining)/(automobile fuel efficiency)
= (2-5 gal H_2O/gal oil + 1.0-2.5 gal H_2O/gal gas)/(20.5 miles/gal gas)
= **0.15 - 0.37 gal H_2O/mile**

Diesel from liquid petroleum

Oil extraction in U.S.: (*6, 13, S4*)
= (EOR gal H_2O)*(% oil used for DFO)/(gal DFO consumed in U.S.)
= (126 Bgal/yr)*(22.3 % into DFO)/[(4.11 MBBl/day DFO)*(42 gal/BBl)*(365 day/yr)
= **0.45 gal H_2O/gal distillate fuel oil (~ diesel)**

Oil Refining to DFO: (*6*)
= **1.0 - 2.5 gal H_2O/gal oil product** (~ 1 gal oil)

Petroleum Diesel efficiency in automobile:
Assume: (1) 60% of diesel LDVs are cars
(2) 40% of diesel LDVs are trucks/SUVs
(3) diesel vehicles obtain **1.38** better mpg than gasoline cars based upon survey of mileage ratings on www.fueleconomy.gov and http://news.windingroad.com/countriesmarkets/euro/diesel-versus-gasolineby-the-numbers/
(i) Volkswagon Jetta, 2006: Diesel – 41.7 mpg, Gas - 29.1 mpg (*7*)
(ii) Mercedes Benz E320: Diesel 27 mpg, Gas – 20 mpg (*7*)
(iii) BMW 525: 'd'/Diesel – 27.4 mpg , 'i'/Gas – 21.8 mpg (*8*)
(iv) Mercedes Benz: S320 CDI/Diesel – 25 mpg, S350/Gas – 16.9 mpg (*8*)

Composite mpg rating for diesel LDVs:
= 1.38*gasoline mpg = 1.38(20.5 mpg gasoline)
= **28.2 mpg for diesel LDVs**

Total water consumption for petroleum diesel driving:
= (extraction + processing/refining)/(automobile fuel efficiency)
= (0.45 gal H_2O/gal oil + 1.0-2.5 gal H_2O/gal DFO)/(28.2 miles/gal DFO)
= **0.05 - 0.10 gal H_2O/mile**

Electricity derived from U.S. mix

Extraction of fuel used in electric power plants:
0.18 gal/kWh (*5*)

Power Plant Operations and Cooling:
0.465 gal/kWh for U.S. electrical mix (*5*)

Electric vehicle efficiency (electricity 'in' to motor → miles traveled): (*S6*)
30% of LDVs are compact sedans averaging 0.26 kWh/mile
30% of LDVs are mid-size sedans averaging 0.30 kWh/mile

20% of LDVs are mid-size trucks/SUVs averaging 0.38 kWh/mile
20% of LDVs are full-size trucks/SUVs averaging 0.46 kWh/mile

Composite kWh/mile rating = (0.3 compact sedans)(0.26 kWh/mile) + (0.3 mid-size sedans)(0.30 kWh/mile) + (0.2 mid-size trucks/SUVs)(0.38 kWh/mile) + (0.2 full-size trucks/SUVs)(0.46 kWh/mile)
= 0.34 kWh/mile, or 2.98 mile/kWh (includes battery and charger efficiency effects)

Electric vehicle charging cycle efficiency (electricity 'in' to battery → electricity 'out' to motor) that is already accounted for in 0.34 kWh/mile(correction from reference (5)):
87%: efficiency of battery charger (*S6*)
85%: efficiency of battery of round trip charging and discharging (*S6*)
92%: efficiency of transmission and distribution (T&D) grid (*S6*)
68%: total charging efficiency for electric vehicle of plug-in hybrid electric vehicle (i.e. 68% of the electricity at the power plant gets to the car electric motor)

Total water consumption for electric driving on US grid mix: (*5, corrected*)
= (mining + power plant processing/cooling)/(vehicle efficiency)/(charging efficiency)
= (0.18 gal H_2O/kWh + 0.465 gal H_2O/kWh)/[(2.98 mile/kWh)(0.92 for T&D eff.)]
= 0.07 gal H_2O/mile + 0.17 gal H_2O/mile
= **0.24 gal H_2O/mile**

Fuel Cell Vehicle (FCV) – Creating Hydrogen via electrolysis

Fuel extraction used in electric power plants:
Same as above for Electricity

Power Plant Operations and Cooling:
Same as above for Electricity

Fuel Cell Vehicle efficiency:
41%: Amount of energy from electricity to hydrogen to drivetrain of FCV (*17*). Assumes 80% electrolyzer efficiency, 92.5% H_2 compression efficiency, 92% transmission efficiency, and 60% fuel cell efficiency (hydrogen to electricity).

68%: Amount of energy from electricity to battery to drivetrain of EV (*S6*). Assumes 87% battery charger efficiency, and 85% battery discharge efficiency *(already accounted for in 0.34 kWh/mile (correction from reference (5))* in addition to an 8% transmission and distribution loss.

kWh/mile rating for FCV = kWh/mile rating for Electric Vehicle without battery and charger efficiency effects (i.e. use of electricity to motor from the battery)
= (0.34 kWh/mile)(0.85 battery eff.)(0.87 charger eff)

= **0.25 kWh/mile, or 4.0 mile/kWh**

Water as feedstock for H_2:

= (amount H_2 in water)/(miles traveled per kg H_2)

= (2.38 gal H_2O/kg H_2)/[(33.33 kWh/kg H_2 – HHV)(0.60 fuel cell eff.)(4.0 mile/kWh FCV)]

= 0.03 gal H_2O/mile

Total water consumption for electrolysis-based FCV driving:

= (feedstock) + ("mining + power plant processing/cooling" FCV)/[(FCV fueling cycle efficiency)(FCV efficiency)]

= 0.03 gal H_2O/mile + …
[0.18 gal H_2O/kWh + 0.465 gal H_2O/kWh]/[(0.41 FCV fueling eff.)(4.0 mile/kWh)]

= 0.03 gal H_2O/mile + 0.39 gal H_2O/mile

= 0.42 gal H_2O/mile

Fuel Cell Vehicle – Creating Hydrogen via Steam Methane Reforming (SMR)

Water consumption for mining and processing of natural gas feedstock:

6: natural gas processing water consumption ($m^3/10^{12}$ J th) (*6*)
3: natural gas water consumption for pipeline operation ($m^3/10^{12}$ J th) (*6*)
47.5: MJ/kg of natural gas (methane, CH_4) (*17*)

The steam methane reforming reaction is: $\mathbf{CH_4 + H_2O \rightarrow 3H_2 + CO}$
An additional shift reaction produces more H_2: $\mathbf{CO + H_2O \rightarrow CO_2 + H_2}$

Thus, for generating **1 kg H_2**, 0.5 kg of the H_2 comes from both the methane and the water. This mass amounts to **1.25 kg of CH_4** and 2.5 kg of H_2O.

= (water for processing and pipeline $m^3/10^{12}$ J th)(energy content per mass of CH_4)(kg CH_4/kg H_2)/(electric energy per kg H_2)

= (3 + 6 $m^3/10^{12}$ J th)(264.17 gal/m^3)(1 MJ /10^6 J)(47.5 MJ/kg CH_4)/(33.33 kWh/kg H_2 – HHV)

= (3 + 6 $m^3/10^{12}$ J th)(264.17 gal/m^3)(1 MJ/10^6 J)(47.5 MJ/kg CH_4)(1.25 kg CH_4/1 kg H_2)/(33.33 kWh/kg H_2 – HHV)

= (0.112 gal H_2O/kg CH_4)(1.25 kg CH_4/1 kg H_2)/(33.33 kWh/kg H_2 – HHV)

= 0.004 gal H_2O/kWh stored hydrogen

~ 0.00 gal H_2O/kWh – *considered negligible*

Water as feedstock for H_2:

1: gal H_2O consumed to convert methane to 1 kg H_2 (*10*)

= (amount H_2O feedstock for H_2 from methane)/(electric energy per kg H_2)

= (1.0 gal H_2O/kg H_2)/(33.33 kWh/kg H_2 – HHV)

= 0.03 gal H_2O/kWh stored hydrogen

Processing and Cooling water consumption:
3.5: gal H_2O consumed as steam for 1 kg H_2 (*10*)

= (amount H_2O as steam for H_2 from methane)/(electric energy per kg H_2)
= (3.5 gal H_2O/kg H_2)/(33.33 kWh/kg H_2 – HHV)
= 0.105 gal H_2O/kWh stored hydrogen

Fuel cell efficiency converting hydrogen to electricity:
60%: fuel cell efficiency converting hydrogen to electricity (*15*)
0.25 kWh/mile, or 4.0 mile/kWh: FCV vehicle efficiency of converting electricity to movement (assumed same as above for FCVs using electrolysis)

Total water consumption for SMR FCV driving:
= direct feedstock water + indirect processing/cooling water
= (negligible + 0.03 gal H_2O/kWh + 0.105 gal H_2O/kWh)/(.60 fuel cell efficiency)/(4.0 mile/kWh)
= 0.06 gal H_2O/mile

Natural Gas Combustion Vehicle – Compressed Natural Gas (CNG)

NOTE: we assume the fuel efficiency of a natural gas combustion vehicle (NGV) is the same as for gasoline vehicles when 121.5 ft^3 of natural gas is equivalent to 1 gallon of gasoline at 0.124 MMBtu (*7*).

SCF: standard cubic foot (ft^3) of natural gas
0.01 – 0.016: kWh/SCF for natural gas compression with electric compressor (*19*)
91.7: energy efficiency (%) of natural gas compression powered by natural gas compressors (*19*)
5.9: fuel efficiency of NGV (SCF/mile)
- derived as (121.5 SCF/gallon gasoline)/(20.5 mpg of gasoline)

Water consumption for mining of natural gas:
In 2005 in the US, approximately 600 billion cubic feet (Bcf) of natural gas were produced from natural gas shale formations (e.g. Barnett Shale in Texas) and approximately 4,000 billion cubic feet (Bcf) were produced from tight gas sands (much in the Rocky Mountains). These types of unconventional natural gas account for approximately 25% of the 18,200 Bcf (*13*) of US dry natural gas production in 2005.
7,200: ac-ft of water used (injected, recovered, and transported for disposal/treatment) for 350 Bcf of natural gas from Barnett Shale in 2005 (*14*)

= (water for mining shale natural gas ac-ft/SCF)(325851.4 gal/ac-ft)
= (7,200 ac-ft)/(350×10^9 SCF)(325851.4 gal/ac-ft)

= 0.0067 gal H_2O/SCF – for shale gas and tight sands

= (natural gas produced from tight sands and shale in 2005)(water mining rate for tight sands and shale)/(total US natural gas production in 2005)
= (4,600 Bcf from tight sands and shale)(0.007 gal H_2O/SCF)/(18,200 Bcf)
= 0.002 gal H_2O/SCF – average for US natural gas mining

Water consumption for processing of natural gas:
6: natural gas processing water consumption ($m^3/10^{12}$ J th) (*6*)
3: natural gas water consumption for pipeline operation ($m^3/10^{12}$ J th) (*6*)

= (water for processing and pipeline $m^3/10^{12}$ J th)(264.17 gal/m^3)(1056 MJ/MMBtu)(1 MMBtu/10^6 Btu)(0.00103 MMBtu/SCF)
= (3 + 6 $m^3/10^{12}$ J th)(264.17 gal/m^3)(1056 MJ/MMBtu)(1 MMBtu/10^6 Btu)(0.00103 MMBtu/SCF)
= (2.49 gal H_2O/MMBtu)(0.00103 MMBtu/SCF)
= 0.003 gal H_2O/SCF

Electricity for compressing natural gas into vehicle tank (using electric compressors):
= (electricity per standard cubic foot compressed gas)(SCF/mile in NGV)(water consumption for electricity generation)
= (0.01-0.016 kWh/SCF)(0.465 gal H_2O/kWh)
= 0.005 – 0.007 gal H_2O/SCF

Total water consumption for natural gas combustion driving (electric compression):
= (water consumption for natural gas mining + water consumption for natural gas processing + water for electric NG compression)(fuel efficiency of natural gas combustion vehicle)
= (0.002 gal H_2O/SCF + 0.003 gal H_2O/SCF + 0.005-0.007 gal H_2O/SCF)(5.9 SCF/mile)
= 0.06 – 0.07 gal H_2O/mile

Total water consumption for natural gas combustion driving (NG compression):
= (water consumption for natural gas mining + water consumption for natural gas processing)(fuel efficiency of natural gas combustion vehicle)/(energy efficiency of NG compression)
= (0.002 gal H_2O/SCF + 0.003 gal H_2O/SCF)(5.9 SCF/mile)/(0.917)
= 0.03 gal H_2O/mile

E85 Ethanol derived from Corn: Grain and Stover

Important Values
7.3: gallons of water consumed per gallon of ethanol from stover (derived from (*25*))
178: U.S. average corn yield of irrigated farms in 2002 (bushels/acre) (*22*)

1.2: U.S. average amount of water used on irrigated corn (ac-ft/acre/yr) (*22*)
1.17: typical dry mass ratio of corn stover to grain at harvest (thus 54% is grain and 46% is stover) (*21*)
56: lbs of corn grain per bushel
63%: LOW allocation factor for *corn grain* ethanol (fraction of input energy to ethanol process allocated to ethanol versus co-products) (*20*)
80.5%: AVG allocation factor for *corn grain* ethanol (fraction of input energy to ethanol process allocated to ethanol versus co-products) (*20*)
93%: HIGH allocation factor for *corn grain* ethanol (fraction of input energy to ethanol process allocated to ethanol versus co-products) (*20*)
54%: AVG allocation factor for *corn stover* cellulosic ethanol (fraction of input energy to ethanol process allocated to ethanol versus co-products) (*21*)

37.3%: irrigation water consumed or lost in conveyance – New Jersey (*23*)
79.7%: irrigation water consumed or lost in conveyance – US average (*23*)
74.3%: irrigation water consumed or lost in conveyance – Arizona (*23*)

Calculate ethanol output per bushel of corn
2.8: gallons of ethanol per dry bushel of corn grain (*24*)

Gallons of ethanol per equivalent dry bushel corn stover:
= (24,564 kg dry ethanol/98,039 kg wet stover)(1/85% dry % of stover)(1.17*56 lb stover associated with bushel of corn grain)/(6.59 lb/gal of ethanol)
= 2.9 gal ethanol/bushel

Irrigated Farming of Corn Feedstock:
<u>Low</u> gallons of water consumed per gallon of ethanol due to irrigation farming (New Jersey)
= (0.3 ac-ft H_2O/acre/yr)(37.3% irrigation water consumed or lost in conveyance)(325851.4 gal/ac-ft)(1 yr/crop)/ [(158 bushels corn/acre)(2.8 gal ethanol/bushel corn)]
= 82 gal H_2O/gal ethanol– grain only

= (0.3 ac-ft H_2O/acre/yr)(37.3% irrigation water consumed or lost in conveyance) (325851.4 gal/ac-ft)(1 yr/crop)/ [(158 bushels corn/acre)(2.9 gal ethanol/bushel corn)]
= 80 gal H_2O/gal ethanol– stover only

<u>Average</u> gallons of water consumed per gallon of ethanol due to irrigation farming (U.S.)
= (1.2 ac-ft H_2O/acre/yr)(79.7% irrigation water consumed or lost in conveyance) (325851.4 gal/ac-ft)(1 yr/crop)/ [(178 bushels corn/acre)(2.8 gal ethanol/bushel corn)]
= 630 gal H_2O/gal ethanol– grain only

= (1.2 ac-ft H_2O/acre/yr)(79.7% irrigation water consumed or lost in conveyance) (325851.4 gal/ac-ft)(1 yr/crop)/ [(178 bushels corn/acre)(2.9gal ethanol/bushel corn)]

= 600 gal H_2O/gal ethanol– stover only

<u>High</u> gallons of water consumed per gallon of ethanol due to irrigation farming (Arizona)

= (3.4 ac-ft H_2O/acre/yr)(74.3% irrigation water consumed or lost in conveyance) (325851.4 gal/ac-ft)(1 yr/crop)/ [(186 bushels corn/acre)(2.8 gal ethanol/bushel corn)]

= 1600 gal H_2O/gal ethanol – grain only

= (3.4 ac-ft H_2O/acre/yr)(74.3% irrigation water consumed or lost in conveyance) (325851.4 gal/ac-ft)(1 yr/crop)/ [(186 bushels corn/acre)(2.9 gal ethanol/bushel corn)]

= 1500 gal H_2O/gal ethanol – stover only

Energy for corn farming:

<u>Electricity</u>

33.6: electricity used for corn farming (kWh/acre) (*24*)

139.34: bushels of corn per acre in U.S. (used in (*24*))

<u>Gasoline</u>

3.4: gasoline used for corn farming (gal/acre) (*24*)

<u>Diesel</u>

6.85: diesel used for corn farming (gal/acre) (*24*)

Gallons of water consumed due to energy usage during corn farming

= (electricity H_2O/acre + gasoline H_2O/acre + diesel gal H_2O/acre)/(gal ethanol/acre)

= [(33.6 kWh/acre)*(0.18 gal H_2O/kWh mining electricity fuels + 0.465 gal H_2O/kWh power plant) + (3.4 gal gas/acre)*(2.17 gal H_2O/gal gas – *typical*) + (6.85 gal diesel/acre)*(2.20 gal H_2O/gal diesel – *typical*)]/[(139.34 bushels corn/acre)*(2.8 gal ethanol/bushel)]

= [(20.3 + 7.4 + 15.1) gal H_2O/acre]/(390 gal ethanol/acre)

= 0.11 gal H_2O/gal ethanol – grain only

= (electricity H_2O/acre + gasoline H_2O/acre + diesel gal H_2O/acre)/(gal ethanol/acre)

= [(33.6 kWh/acre)*(0.18 gal H_2O/kWh mining electricity fuels + 0.465 gal H_2O/kWh power plant) + (3.4 gal gas/acre)*(2.17 gal H_2O/gal gas – *typical*) + (6.85 gal diesel/acre)*(2.20 gal H_2O/gal diesel – *typical*)]/[(139.34 bushels corn/acre)*(2.9 gal ethanol/bushel)]

= [(20.3 + 7.4 + 15.1) gal H_2O/acre]/(400 gal ethanol/acre)

= 0.11 gal H_2O/gal ethanol – stover only

Corn grain processing to ethanol (starch ethanol):

= 3.5 – 6.0 gal H_2O/gal ethanol (*25*)

Corn stover processing to ethanol (cellulosic ethanol):
= 7.3 gal H_2O/gal ethanol (*26*)

Ethanol (E85) vehicle efficiency
Table B1 shows data for EPA mileage ratings from www.fueleconomy.gov compares same model cars that are flex fuel vehicles when running on gasoline versus E85 fuel.

Table B1. Mileage ratings for various flex fuel vehicles show an approximate 26% drop in miles per gallon rating for using E85 versus gasoline.

Vehicle (2007 model)	Hwy mpg, gas	Hwy mpg, E85	City mpg, gas	City mpg, E85	Avg, gas	Avg, E85	Truck or car?	Car % drop in mpg	Truck % drop in mpg
Chev, Monte Carlo	31	23	21	16	26.0	19.5	car	25.0%	--
Benz, C230	25	18	19	14	22.0	16.0	car	27.3%	--
Mercury, Grand Marquis	25	17	17	13	21.0	15.0	car	28.6%	--
Saturn, Relay FWD	25	19	18	13	21.5	16.0	truck/SUV	--	25.6%
Chev, Avalanche 1500 2WD	21	16	15	12	18.0	14.0	truck/SUV	--	22.2%
GMC, Yukon 1500 2WD	21	16	15	12	18.0	14.0	truck/SUV	--	22.2%
Jeep, Grand Cherokee 2WD	20	14	15	10	17.5	12.0	truck/SUV	--	31.4%
Nissan, Titan 2WD	18	13	14	10	16.0	11.5	truck/SUV	--	28.1%
							average change	**26.9%**	**25.9%**

Composite mpg rating for E85= (20.5 mpg 100% gasoline)(1-74%) **= 15.1 mpg E85**

Irrigated Farming of Corn:
Total water consumption for E85 driving (all ethanol from irrigated corn grain):
= [(irrigation H_2O/ethanol + ethanol processing H_2O/ethanol + farm energy H_2O/ethanol)(85% of fuel is ethanol)(allocation factor) + (water consumption per gallon gasoline)(15% of fuel is gasoline)]/(E85 car miles/gal E85)
= [(82 to 1600 + 3.5 to 6.0 + 0.11)(.85)(0.65 to 0.93) + (1.42-2.92 gal H_2O/gal gas)(0.15)]/(15.1 mpg E85)
= 1.3 – 62 gal H_2O/mile – grain only
= 28 gal H_2O/mile – grain only AVERAGE

Total water consumption for E85 driving (all ethanol from irrigated corn stover):
= [(irrigation H_2O/ethanol + ethanol processing H_2O/ethanol + farm energy H_2O/ethanol)(85% of fuel is ethanol))(allocation factor) + (water consumption per gallon gasoline)(15% of fuel is gasoline)]/(E85 car miles/gal E85)
= [(80 to 1500 + 7.3 + 0.11)(.85)(0.54) + (1.42-2.92 gal H_2O/gal gas)(0.15)]/(15.1 mpg E85)
= 2.7 - 46 gal H_2O/mile – stover only
= 19 gal H_2O/mile – stover only AVERAGE

Because the amount of water consumed for irrigation dominates overall water consumption, there is essentially no difference in water consumption for irrigated cellulosic ethanol versus irrigated starch ethanol from corn.

Mass ratio of ethanol output to corn grain input:

= (density of ethanol)(volume ethanol per dry bushel)/(mass input of bushel)
= (6.59 lb/gal ethanol)(2.8 gal ethanol/bushel)/(56 lbs/bushel corn grain)
= 33 %

Mass ratio of ethanol output to corn stover input (*26*):
= (ethanol output mass flow)/[(plant stover mass input flow)(1-moisture content)]
= (28,564 kg ethanol/hr)/[(98,039 kg stover/hr)(1-15% moisture)]
= 34 %

The mass ratio of ethanol/stover and ethanol/grain is quite similar, so we assume that both have the same mass ratio of 33%.

As noted in Pordesimo et al. (*21*) at typical harvest, above ground dry matter is approximately 54% stover with 0.8 stover(dry):grain(wet) ratio at harvest. Therefore, we assume a dry bushel of corn seed, at 56 lbs/bushel, is associated with 56*(54%/46%) = 66 lbs of stover, or 1.17 times as much mass in stover. Because the mass ratios of ethanol output to feedtock input is roughly the same for corn grain and stover, we can calculate that one bushel of corn grain and its associated stover produce **2.8 + 2.9(1.17) = 6.2 gal ethanol/equivalent bushel.**

Now we can use a conversion of 6.2 gal ethanol/bushel instead of 2.8 and 2.9 for gal ethanol/bushel for corn grain and stover, respectively. Calculating irrigation water per ethanol output now produces a different result for water consumption and withdrawal:

<u>Low</u> gallons of water consumed per gallon of ethanol due to irrigation farming (New Jersey)
= (0.3 ac-ft H_2O/acre/yr)(37.3% irrigation water consumed or lost in conveyance) (325851.4 gal/ac-ft)*(1 yr/crop)/[(158 bushels corn/acre)(6.2 gal ethanol/bushel corn)]
= 37 gal H_2O/gal ethanol – grain and stover to ethanol

<u>Average</u> gallons of water consumed per gallon of ethanol due to irrigation farming (U.S.)
= (1.2 ac-ft H_2O/acre/yr)(79.7% irrigation water consumed or lost in conveyance) (325851.4 gal/ac-ft)(1 yr/crop)/[(178 bushels corn/acre)(6.2 gal ethanol/bushel corn)]
= 280 gal H_2O/gal ethanol – grain and stover to ethanol

<u>High</u> gallons of water consumed per gallon of ethanol due to irrigation farming (Arizona)
= (3.4 ac-ft H_2O/acre/yr)(74.3% irrigation water consumed or lost in conveyance) (325851.4 gal/ac-ft)(1 yr/crop)/[(186 bushels corn/acre)(6.2 gal ethanol/bushel corn)]
= 710 gal H_2O/gal ethanol – grain and stover to ethanol

Total water consumption for E85 driving (<u>ethanol from irrigated corn grain and stover</u>):
= [(irrigation H_2O/ethanol + ethanol processing H_2O/ethanol + farm energy H_2O/ethanol)(85% of fuel is ethanol)(allocation factor) + (water consumption per gallon gasoline)(15% of fuel is gasoline)]/(E85 car miles/gal E85)

= [(37 to 710 + 3.5 to 7.3 + 0.11)(.85)(0.65 to 0.93) + (1.42-2.92 gal H_2O/gal gas)(0.15)]/(15.1 mpg E85)
= 1.6 – 38 gal H_2O/mile - grain and stover to ethanol
= 11 gal H_2O/mile - grain and stover to ethanol AVERAGE

<u>Non-irrigated Farming of Corn:</u>
By neglecting the irrigation water for corn farming in the previous equations, we calculate the water for all other needs for farms that do not irrigate corn.

Total water consumption for E85 driving (<u>all ethanol from non-irrigated corn grain</u>):
= 0.15 – 0.35 gal H_2O/mile

Total water consumption for E85 driving (<u>all ethanol from non-irrigated corn stover</u>):
= 0.24 - 0.25 gal H_2O/mile

Total water consumption for E85 driving (<u>ethanol from non-irrigated corn grain and stover</u>):
= {[(grain ethanol processing H_2O/ethanol)(46% of plant as grain) + (cellulosic ethanol processing H_2O/ethanol)(54% of plant as stover) + (farm energy H_2O/ethanol)](85% of fuel is ethanol)(allocation factor) + (water consumption per gallon gasoline)(15% of fuel is gasoline)}/(E85 car miles/gal E85)
= {[(3.5 to 6.0)(0.46) + (7.3)(0.54) + 0.11](0.85)(0.65 to 0.93) + (1.42-2.92 gal H_2O/gal gas)(0.15)}/(15.1 mpg E85)
= 0.22 – 0.39 gal H_2O/mile

Biodiesel derived from Soy

Irrigated Farming of soybean feedstock:
10.7: refined soy oil per bushel (gal/bushel) (*S7*)
1: biodiesel output from refined soy oil (gal biodiesel/gal soy oil) (*S8*)
37.3%: irrigation water consumed or lost in conveyance – New Jersey (*23*)
79.7%: irrigation water consumed or lost in conveyance – US average (*23*)
91.9%: irrigation water consumed or lost in conveyance – Texas (*23*)
0.18: LOW allocation factor for biodiesel from soybeans (*28*)
0.80: HIGH allocation factor for biodiesel from soybeans (*28*)

<u>Low Irrigation (New Jersey):</u>
0.3: average amount of water used on irrigated soybean (ac-ft/acre/yr) (*22*)
41: U.S. soybean yield of irrigated farms in 2002 (bushels/acre) (*22*)

<u>Average Irrigation (U.S.):</u>
0.8: average amount of water used on irrigated soybean (ac-ft/acre/yr) (*22*)
48: U.S. soybean yield of irrigated farms in 2002 (bushels/acre) (*22*)

<u>High Irrigation (Texas):</u>

0.9: average amount of water used on irrigated soybean (ac-ft/acre/yr) (*22*)
33: U.S. soybean yield of irrigated farms in 2002 (bushels/acre) (*22*)

Low gallons of water consumed per gallon of biodiesel due to irrigation farming -
= (0.3 ac-ft H_2O/acre/yr)(37.3% irrigation water consumed or lost in conveyance)(325851.4 gal/ac-ft)(1 yr/crop)/[(41 bushels soy/acre)(1 gal biodiesel/1 gal refined soy oil)(10.7 gal refined soy oil/1 bushel soy)]
= 83 gal H_2O/gal biodiesel

Average gallons of water consumed per gallon of biodiesel due to irrigation farming -
= (0.8 ac-ft H_2O/acre/yr)(79.7% irrigation water consumed or lost in conveyance)(325851.4 gal/ac-ft)(1 yr/crop)/[(48 bushels soy/acre)(1 gal biodiesel/1 gal refined soy oil)(10.7 gal refined soy oil/1 bushel soy)]
= 400 gal H_2O/gal biodiesel

High gallons of water consumed per gallon of biodiesel due to irrigation farming -
= (0.9 ac-ft H_2O/acre/yr)(91.9% irrigation water consumed or lost in conveyance)(325851.4 gal/ac-ft)(1 yr/crop)/[(33 bushels soy/acre)(1 gal biodiesel/1 gal refined soy oil)(10.7 gal refined soy oil/1 bushel soy)]
= 760 gal H_2O/gal biodiesel

Energy for soybean farming:
Electricity
4.60: electricity used for soybean farming (kWh/acre) (*S9*)

Gasoline
3.11: gasoline used for soybean farming (gal/acre) (*S9*)

Diesel
5.29: diesel used for soybean farming (gal/acre) (*S9*)
0.70: diesel used for "custom operations" in soybean farming (gal/acre) (*S9*)

Natural Gas
0.07: natural gas used for soybean farming (ft^3/acre) (*S9*)

Note:
7.7: density of soybean distillate oil (lb/gal) (*S7*)
0.885: specific gravity of biodiesel (*S9*)

Density of biodiesel = (0.885)(8.321 lb/gal) **= 7.4 lb/gal of biodiesel**

Gallons of water consumed due to energy usage during soybean farming
= (electricity H_2O/acre + gasoline H_2O/acre + diesel gal H_2O/acre)/(gal biodiesel/acre)

= [(4.6 kWh/acre)(0.14 gal H_2O/kWh mining electricity fuels + 0.465 gal H_2O/kWh power plant) + (3.11 gal gas/acre)(2.17 gal H_2O/gal gas – *typical*) + (5.29 gal diesel/acre)(2.20 gal H_2O/gal diesel – *typical*)]/[(48 bushels soy/acre)(10.7 lb soy oil/bushel)(7.4/7.7 lb biodiesel/lb soy oil)(1/7.4 gal biodiesel/lb biodiesel]

= [(2.78 + 6.75 + 11.6) gal H_2O/acre]/(67 gal biodiesel/acre)

= 0.315 gal H_2O/gal biodiesel

Soy processing to biodiesel:

19.35: water consumed for soybean crushing processes (kg/metric ton oil produced) (*S9*)
356: water consumption in converting soy oil to biodiesel (kg/metric ton biodiesel) (*S9*)
7.7: soybean oil density (lb/gal)

Water consumed for soybean crushing processes (gal water/gal oil):

= (19.35 kg/metric tonne soy oil)(1 gal soy oil/gal biodiesel)(7.7 lb/gal soy oil)(4.448 N/lb)(264.17 gal/m^3)/[(9.81 m/s^2)(1000 kg/tonne)(997 kg/m^3 H_2O)

= 0.018 gal H_2O/gal biodiesel

Water consumed for converting soy oil to biodiesel (gal water/gal biodiesel):

= (356 kg/metric tonne biodiesel)(7.36 lb/gal biodiesel)(4.448 N/lb)(264.17 gal/m^3)/[(9.81 m/s^2)(1000 kg/tonne)(997 kg/m^3 H_2O)

= 0.315 gal H_2O/gal biodiesel

Biodiesel vehicle efficiency

126,206: energy content of soy-based biodiesel (Btu/gal - HHV) (*27*)
138,700: energy content of petroleum-based diesel (Btu/gal - HHV) (*27*)

Composite mpg rating for biodiesel LDV –

= (average mpg for petroleum diesel in LDVs)*(energy content biodiesel/energy content petroleum diesel)

= (28.2 mpg petroleum diesel)(126,206/138,700)

= 25.7 mpg

<u>Irrigated Farming of Soybeans:</u>

Total water consumption for biodiesel driving:

= (irrigation H_2O/biodiesel + energy H_2O/biodiesel + processing H_2O/biodiesel)(allocation factor)/(biodiesel car miles/gal biodiesel)

= [(82 to 760 + 0.315 + 0.018 + 0.315) gal H_2O/gal biodiesel](0.18 to 0.80)/(25.7 mpg)

= 0.6 – 24 gal H_2O/mile

= 12 gal H_2O/mile – US Average

<u>Non-Irrigated Farming of Soybeans:</u>

Total water consumption for biodiesel driving:

= (energy H_2O/biodiesel + processing H_2O/biodiesel)(allocation factor)/(biodiesel car miles/gal biodiesel)

= [(0.315 + 0.018 + 0.315) gal H_2O/gal biodiesel](0.18 to 0.80)/(25.7 mpg)

= 0.01 – 0.02 gal H_2O/mile

Fischer-Tropsch Diesel from Coal

F-T Diesel efficiency in automobile:
36.9: energy content of F-T diesel (MJ/L - HHV) (*S1*)
38.7: energy content of petroleum-based diesel (MJ/L -HHV) (*27*)

Composite mpg rating for F-T diesel LDV –
= (average mpg for petroleum diesel in LDVs)(energy content F-T diesel/energy content petroleum diesel)
= (28.2 mpg petroleum diesel)(36.9/38.7)
= 26.9 mpg

Coal mining water consumption:
70-260: water consumed in mining of coal (Mgal/d) (*5*)
10,500: assumed Btu value of coal (Btu/lb)
1133: coal mined in U.S. per year (2005) (million short tons) (*13*)
1056: MJ/MBtu
3.785412: liters per gallon

= (U.S. annual coal mining water consumption)(energy content F-T diesel)/[(U.S. annual coal mined)(energy content of coal)(efficiency of F-T LDV)]
= (70-260 Mgal/d)(365 days/yr)(34.4 energy content F-T diesel MJ/L)(3.79 L/gal)/[(1133 million short tons)(2000 lb/short ton)(10,500 Btu/lb)(1056 MJ/MBtu)]
= 0.131-0.486 gal H_2O/gal F-T diesel

Gasification and F-T processing of coal to F-T Diesel:
5: water consumption for CTL (gal H2O/gal diesel) - LOW, Western Coal (*S5*)
15: water consumption for CTL (gal H2O/gal diesel) – HIGH, Eastern Coal (*S10*)

Total water consumption for driving using F-T diesel from coal:
= (extraction + processing/refining)/(automobile fuel efficiency)
= (0.131-0.486 gal H_2O/gal F-T diesel + 5-15 gal H_2O/gal F-T diesel)/(26.9 miles/gal F-T diesel)
= 0.19 – 0.58 gal H_2O/mile

Fischer-Tropsch Diesel from Natural Gas

F-T Diesel efficiency in automobile:
Same as above for F-T Diesel from coal

Water Consumption for natural gas pipeline mining:

= 0.002 gal H_2O/SCF (see earlier section on Compressed Natural Gas vehicles)

Natural Gas pipeline transport and processing water consumption:
9: water consumption for processing and pipeline transport ($m^3/10^{12}$ J) (*6*)
159: conversion factor, liters per 42 gallon barrel
3.7854: conversion factor, liters per gallon
264.17: conversion factor, gallons in 1 m^3 of liquid

= [(mining water consumption)+(water consumption for pipeline per energy content)](energy of F-T diesel)
= [0.002 gal H_2O/SCF natural gas + (9 $m^3/10^{12}$ J natural gas)(264.17 gal/m^3)(1/10^6 J/MJ)](36.9 MJ/L F-T diesel)(3.7854 L/gal)
= 0.610 gal H_2O/gal F-T diesel

Makeup water for processing of natural gas to F-T Diesel:
114: LOW water consumption for associated gas (Venezuela or Alaskan North Slope) (gal H_2O/BBl F-T product) (*S11*)
455: HIGH water consumption for Southern Illinois pipeline natural gas (gal H_2O/BBl F-T product) (*S11*)

NOTE: The study by Marano and Ciferno (*S11*) assumes a test plant that produces 97.4% and 100% of output energy as F-T distillate in the 'LOW' and 'HIGH' cases above, respectively. Hence the high and low consumption values are:

LOW (*S11*):
= (114 gal H_2O/BBl F-T product)(42 gal/BBl F-T product)*0.974
= 2.6 gal H_2O/gal F-T product

HIGH (*S11*):
= (455 gal H_2O/BBl F-T product)(42 gal/BBl F-T product)*1.0
= 10.8 gal H_2O/gal F-T product

Example gas-to-liquids plant as studied by Choi et al., 1997 (*S12*) with multiple liquid fuel product outputs as well as some electricity.
5.3: Mgal/day of makeup water input
2993: F-T naptha output (BBl/d)
5736: F-T distillate output (BBl/d)
146: butane output (BBl/d)
2018/6880: electric power output (MWh/d)/(MBtu/d)

Plant energy output that is liquid fuels:

= [(2933 BBl/d naptha)(5.3 MBtu/BBl naptha)+(5736 BBl/d distillate)(5.55 MBtu/BBl distillate)+(146 BBl/d butane)(4.3 MBtu/BBl butane)]
≈ 48,000 MBtu/d

Total plant energy output:
≈ 48,000 MBtu/d in liquids + 6,880 Btu/d in electricity
≈ 54,900 MBtu/d

Percentage of plant output that is liquid fuels:
= (energy in liquids)/(total energy of plant)*100
= 87.5 %

Water consumption for natural gas to F-T liquids plant from Choi et al. (*S12*):
= (5.3e6 gal H_2O/d)(87.5% liquids)(5.45 MBtu/BBl average F-T liquid)/[(54,900 MBtu/d)(42 gal/BBl)]
= 11.0 gal H_2O/gal F-T liquid product

Total water consumption for driving using F-T diesel from natural gas:
= (mining consumption + pipeline processing + processing/refining)/(automobile fuel efficiency)
= [0.233 H_2O/gal F-T diesel + 0.330 gal H_2O/gal F-T diesel + 2.6 – 11.0 gal H_2O/gal F-T diesel]/(26.9 miles/gal F-T diesel)
= 0.12 – 0.42 gal H_2O/mile

Appendix S-B: Calculations for Water Withdrawal per Mile (gal/mile)

The calculation of water withdrawal to propel a light duty vehicle a mile follows the same approach as for consumption. Here, withdrawal is equal to the water consumed for each process *plus* additional water that is needed. The withdrawal values in this Appendix inherently include the quantities for consumption calculated in Appendix S-A. The calculation of water consumption to propel a light duty vehicle a mile follows a similar approach for each fuel.

Three major categories for tabulating water consumption and withdrawal are considered:

1. *Mining and farming*
2. *Processing and Refining of feedstock to fuel*
3. *Efficiency of use of fuel in vehicle*

Categories neglected in this analysis:

1. *Transport of feedstock from mine/farm to refinery*
2. *Transport of refined fuel to consumer purchase point*
3. *Manufacturing and installation of physical capital*
4. *Water availability (aquifer recharge, river flow, evapotranspiration) for biofuel crops*

Gasoline from U.S. Liquid Petroleum

Oil extraction in U.S.:
negligible withdrawal on top of consumption
= **0.42 gal H_2O/gal oil** (*5*)

Oil Refining to Gasoline:
= **12.5 gal H_2O/gal oil** (*6*)

Here withdrawal is calculated separately, using the value from Gleick (*6*), from the consumption value in Appendix S-A as done in King and Webber (*5*). Note, that even though approximately 0.40-0.48 gallons of gasoline are produced for every gallon of oil input, we assume the water withdrawal is also apportioned at the same ratio.

Gasoline vehicle efficiency:
Same as calculated in Appendix S-A.

Total water withdrawal for gasoline driving:
= (extraction + processing/refining)/(automobile fuel efficiency)
= (0.42 gal H_2O/gal oil + 12.5 gal H_2O/gal gas)/(20.5 miles/gal gas)
= **0.63 gal H_2O/mile**

Gasoline from Tar Sands

Oil extraction in from tar sands:
negligible withdrawal on top of consumption

= **3-7 gal H_2O/gal oil**

Oil Refining to Gasoline:
Same as above for Petroleum Gasoline

Gasoline vehicle efficiency:
Same as calculated in Appendix S-A.

Total water withdrawal for gasoline driving:

= (extraction + processing/refining)/(automobile fuel efficiency)
= (3-7 gal H_2O/gal oil + 12.5 gal H_2O/gal gas)/(20.5 miles/gal gas)
= **0.76 – 0.95 gal H_2O/mile**

Gasoline from Shale Oil

Oil extraction from shale mining:
negligible withdrawal on top of consumption (same as for consumption)

= **2 – 5 gal H_2O/gal 'ready' oil**

Oil Refining to Gasoline:
Same as above for Petroleum Gasoline

Gasoline vehicle efficiency:
Same as calculated in Appendix S-A.

Total water withdrawal for gasoline driving:

= (extraction + processing/refining)/(automobile fuel efficiency)
= (2-5 gal H_2O/gal oil + 12.5 gal H_2O/gal gas)/(20.5 miles/gal gas)
= **0.71 – 0.85 gal H_2O/mile**

Diesel from liquid petroleum

Here we assume the same withdrawal value as for petroleum gasoline, but use the fuel efficiency of diesel vehicles, as calculated in Appendix S-A, for the water withdrawal per mile calculation.

Oil extraction in U.S.:
negligible withdrawal on top of consumption

Oil Refining to Diesel:

Same as above for Petroleum Gasoline.

Diesel vehicle efficiency:
Same as calculated in Appendix S-A.

Total water withdrawal for petroleum diesel driving:
= (extraction + processing/refining)/(automobile fuel efficiency)
= (0.42 gal H_2O/gal oil + 12.5 gal H_2O/gal DFO)/(28.2 miles/gal DFO)
= **0.46 gal H_2O/mile**

Electricity derived from U.S. mix

Extraction for fuel used in electric power plants:
= 0.18 gal/kWh (*5*)

Power Plant Operations and Cooling:
= 21.2 gal/kWh for U.S. electrical mix (*5*)

Electric vehicle charging cycle efficiency (electricity 'in' to battery → electricity 'out' to motor):
Same as calculated in Appendix S-A:
68%: total charging efficiency for electric vehicle of plug-in hybrid electric vehicle where average of 0.34 kWh/mile from (*S6*) already accounts for battery and charger efficiency, but not transmission and distribution losses of 8% (*S6*)

Electric vehicle efficiency (electricity 'in' to motor → miles traveled):
Same as calculated in Appendix S-A:

Total water withdrawal for electric vehicle driving (*5*)*:*
= (mining + power plant processing/cooling)/(vehicle efficiency)/(charging efficiency)
= (0.18 gal H_2O/kWh + 21.2 gal H_2O/kWh)/[(2.98 mile/kWh)(0.92 for T&D losses)]
= **7.8 gal H_2O/mile**

Fuel Cell Vehicle – Using Hydrogen via electrolysis (U.S. mix electricity)

Here we assume that the electricity used for the electrolysis of water into hydrogen and oxygen is derived from the U.S. average electrical grid mix of power plants, just as for electricity to charge electric vehicles.

Extraction for fuel used in electric power plants:
= 0.18 gal/kWh (*5*)

Power Plant Operations and Cooling:
= 21.2 gal/kWh for U.S. electrical mix (*5*)

Fuel Cell vehicle fueling cycle efficiency (electricity in to electricity to motor):
41%: energetic efficiency of converting electricity to hydrogen (*15*)

NOTE: Mazza and Hammerschlag (*15*) assume 80% electrolyzer efficiency, 92.5% compression efficiency, 92% transmission efficiency (*S6*), and 60% fuel cell efficiency.

Fuel Cell vehicle efficiency (electricity 'in' to motor → miles traveled):
Same as in Appendix S-A

Water as feedstock for H_2:
Same as in Appendix S-A

= 0.03 gal H_2O/mile

Total water withdrawal for electrolysis-based FCV driving:

= (feedstock) + …
("mining + power plant processing/cooling" EV)/[(FCV charging eff.)(fuel cell vehicle efficiency)]

= (0.03 gal H_2O/mile) + …
[(0.18 gal H_2O/kWh + 21.2 gal H_2O/kWh)/[(0.41 FCV fueling eff.)(4.0 mile/kWh)]

= 13 gal H_2O/mile

Fuel Cell Vehicle – Using Hydrogen via steam methane reforming

Water consumption for processing of natural gas feedstock:
Same as for consumption in Appendix S-A.

= 0.00 gal H_2O/kWh stored hydrogen - *negligible*

Water as feedstock for H_2:
Same as for consumption in Appendix S-A.

= 0.03 gal H_2O/kWh stored hydrogen

Processing and Cooling water consumption:
Same as for consumption in Appendix S-A.
4.9: gal H_2O withdrawn for steam and cooling for 1 kg H_2 (*10*)

= (amount H_2O for steam and cooling for H_2 from methane)/(miles traveled per kg H_2)

= (4.9 gal H_2O/kg H_2)/(33.33 kWh/kg H_2 – HHV)

= 0.147 gal H_2O/kWh stored as hydrogen

Fuel Cell vehicle efficiency (electricity 'in' to motor → miles traveled):
Same as in Appendix S-A.

Total water withdrawal for SMR FCV driving:

= direct feedstock water + indirect processing/cooling water
= (0.03 gal H_2O/kWh + 0.147 gal H_2O/kWh)/(.60 fuel cell efficiency)/(4.0 mile/kWh)
= 0.07 gal H_2O/mile

Natural Gas Combustion Vehicle – Compressed Natural Gas (CNG)

NOTE: we assume the fuel efficiency of a natural gas combustion vehicle is the same as for gasoline vehicles when 121.5 ft^3 of natural gas is equivalent to 1 gallon of gasoline at 0.124 MMBtu.

Water withdrawal for mining of natural gas:
Same as for consumption in Appendix S-A.
= 0.002 gal H_2O/SCF

Water withdrawal for processing of natural gas:
Same as for consumption in Appendix S-A.
= 0.003 gal H_2O/SCF

Electricity for compressing natural gas into vehicle tank (using electric compressors):
= (electricity per standard cubic foot compressed gas)(SCF/mile in NGV)(water consumption for electricity generation)
= (0.01-0.016 kWh/SCF)(21.2 gal H_2O/kWh)
= 0.21 – 0.34 gal H_2O/SCF

Total water withdrawal for natural gas combustion driving (<u>electric compression</u>):
= (water withdrawal for natural gas mining + water withdrawal for natural gas processing + water withdrawal for electric NG compression)(fuel efficiency of natural gas combustion vehicle)
= (0.002 gal H_2O/SCF + 0.003 gal H_2O/SCF + 0.21-0.34 gal H_2O/SCF)(5.9 SCF/mile)
= 1.3 – 2.1 gal H_2O/mile

Total water withdrawal for natural gas combustion driving (<u>NG compression</u>):
= (water withdrawal for natural gas mining + water withdrawal for natural gas processing)(fuel efficiency of natural gas combustion vehicle)/(energy efficiency of NG compression)
= (0.002 gal H_2O/SCF + 0.003 gal H_2O/SCF)(5.9 SCF/mile)/(0.917)
= 0.03 gal H_2O/mile

E85 Ethanol derived from Corn Grain and Stover

Irrigated Farming of Corn Feedstock:

Water withdrawn for irrigation is calculated the same as water consumed for irrigation in Appendix S-A except that 100% of irrigation water is considered as withdrawal, not a fraction of that total as considered for consumption in (*23*).

Ethanol from corn grain or stover

Low gallons of water consumed per gallon of ethanol due to irrigation farming (Pennsylvania)

= (0.2 ac-ft H_2O/acre/y)(325851.4 gal/ac-ft)(1 yr/crop)/[(130 bushels corn/acre)(2.8 gal ethanol/bushel corn)]

= 180 gal H_2O/gal ethanol– grain only

= (0.2 ac-ft H_2O/acre/yr)(325851.4 gal/ac-ft)(1 yr/crop)/ [(130 bushels corn/acre)(2.9 gal ethanol/bushel corn)]

= 170 gal H_2O/gal ethanol– stover only

Average gallons of water withdrawn per gallon of ethanol due to irrigation farming (U.S.)

= 780 gal H_2O/gal ethanol– grain only

= 760 gal H_2O/gal ethanol – stover only

High gallons of water withdrawn per gallon of ethanol due to irrigation farming (Arizona)

= 2100 gal H_2O/gal ethanol– grain only

= 2100 gal H_2O/gal ethanol – stover only

Ethanol from corn grain and stover

Low gallons of water withdrawn per gallon of ethanol due to irrigation farming (Pennsylvania)

= 81 gal H_2O/gal ethanol – grain and stover to ethanol

Average gallons of water withdrawn per gallon of ethanol due to irrigation farming (U.S.)

= 350 gal H_2O/gal ethanol – grain and stover to ethanol

High gallons of water withdrawn per gallon of ethanol due to irrigation farming (Arizona)

= 960 gal H_2O/gal ethanol – grain and stover to ethanol

Energy for corn farming:

Same as stated in Appendix S-A.

Gallons of water withdrawn due to energy usage during corn farming

= (electricity H_2O/acre + gasoline H_2O/acre + diesel gal H_2O/acre)/(gal ethanol/acre)

= [(33.6 kWh/acre)(0.18 gal H_2O/kWh mining electricity fuels + 21.2 gal H_2O/kWh power plant) + (3.4 gal gas/acre)(12.5 gal H_2O/gal gas – *typical*) + (6.85 gal diesel/acre)(12.5 gal H_2O/gal diesel – *typical*)]/[(139.34 bushels corn/acre)(2.8 gal ethanol/bushel)]

= [(717 + 43 + 86) gal H_2O/acre]/(390 gal ethanol/acre)

= 2.2 gal H_2O/gal ethanol – grain or stover

Corn processing to Ethanol:
Same as stated in Appendix S-A for consumption for both grain and stover based ethanol.

Ethanol (E85) vehicle efficiency
Same as stated in Appendix S-A.

Irrigated Farming of Corn:
Total water withdrawal for E85 driving (all ethanol from irrigated corn grain):

= [(irrigation H_2O/ethanol + ethanol processing H_2O/ethanol + farm energy H_2O/ethanol)(85% of fuel is ethanol)(allocation factor) + (water withdrawal per gallon gasoline for mining and processing)(15% of fuel is gasoline)]/(E85 car miles/gal E85)

= [(180 to 2100 + 3.5 to 6.0 + 2.2)(.85)(0.65 to 0.93) + (12.9 gal H_2O/gal gas)(0.15)]/(15.1 mpg E85)

= 6.9 – 111 gal H_2O/mile

Total water withdrawal for E85 driving (all ethanol from irrigated corn stover):

= [(irrigation H_2O/ethanol + ethanol processing H_2O/ethanol + farm energy H_2O/ethanol)(85% of fuel is ethanol)(allocation factor) + (water withdrawal per gallon gasoline)(15% of fuel is gasoline)]/(E85 car miles/gal E85)

= [(170 to 2100 + 7.3 + 2.2)*(.85)(0.54) + (12.9 gal H_2O/gal gas)(0.15)]/(15.1 mpg E85)

= 5.6 - 63 gal H_2O/mile

Total water withdrawal for E85 driving (ethanol from irrigated corn grain and stover):

= [(irrigation H_2O/ethanol + ethanol processing H_2O/ethanol + farm energy H_2O/ethanol)(85% of fuel is ethanol)(allocation factor) + (water withdrawal per gallon gasoline)(15% of fuel is gasoline)]/(E85 car miles/gal E85)

= [(81 to 960 + 3.5 to 7.3 + 2.2)(.85)(0.65 to 0.93) + (12.9 gal H_2O/gal gas)(0.15)]/(15.1 mpg E85)

= 3.4 - 51 gal H_2O/mile

Because the amount of water withdrawn for irrigation dominates overall water withdrawal, there is essentially no difference in water withdrawal for irrigated cellulosic ethanol versus irrigated starch ethanol from corn.

Non-irrigated Farming of Corn:
By neglecting the irrigation water for corn farming in the previous equations, we calculate the water withdrawal for all other needs for farms that do not irrigate corn.

Total water withdrawal for E85 driving (<u>all ethanol from non-irrigated corn grain</u>):
= 0.33 – 0.55 gal H_2O/mile

Total water withdrawal for E85 driving (<u>all ethanol from non-irrigated corn stover</u>):
= 0.42 gal H_2O/mile

Total water withdrawal for E85 driving (<u>ethanol from non-irrigated corn grain and stover</u>):
= {[(grain ethanol processing H_2O/ethanol)(46% of plant as grain) + (cellulosic ethanol processing H_2O/ethanol)(54% of plant as stover) + (farm energy H_2O/ethanol)](85% of fuel is ethanol)(allocation factor) + (water withdrawal per gallon gasoline)(15% of fuel is gasoline)}/(E85 car miles/gal E85)
= {[(3.5 to 6.0)(0.46) + (7.3)(0.54) + 2.2](0.85)(0.65 to 0.93) + (12.5 gal H_2O/gal gas)(0.15)}/(15.1 mpg E85)
= 0.41 – 0.59 gal H_2O/mile

Biodiesel derived from Soy

Irrigated Farming of soybean feedstock:
Water withdrawn for irrigation is calculated the same as water consumed for irrigation in Appendix S-A except that 100% of irrigation water is considered as withdrawal, not a fraction of that total as considered for consumption in (*23*).

<u>Low Irrigation Withdrawal (Pennsylvania):</u>
= 150 gal H_2O/gal biodiesel - (same as Appendix S-A without irrigation losses)

<u>Average Irrigation Withdrawal (U.S.):</u>
= 510 gal H_2O/gal biodiesel - (same as Appendix S-A without irrigation losses)

<u>High Irrigation Withdrawal (Colorado):</u>
1.4: average amount of water used on irrigated soybean (ac-ft/acre/yr) (*22*)
51: U.S. soybean yield of irrigated farms in 2002 (bushels/acre) (*22*)

= (1.4 ac-ft H_2O/acre/yr)(325851.4 gal/ac-ft)(1 yr/crop)/[(51 bushels soy/acre)(1 gal biodiesel/1 gal refined soy oil)(10.7 gal refined soy oil/1 bushel soy)]
= 840 gal H_2O/gal biodiesel

Energy for soybean farming:
Same as stated in Appendix S-A.

Gallons of water withdrawn due to energy usage during soybean farming
= (electricity H_2O/acre + gasoline H_2O/acre + diesel gal H_2O/acre)/(gal biodiesel/acre)

= [(4.6 kWh/acre)(0.18 gal H_2O/kWh mining electricity fuels + 21.2 gal H_2O/kWh power plant) + (3.11 gal gas/acre)(12.5 gal H_2O/gal gas – *typical*) + (5.29 gal diesel/acre)(12.5 gal H_2O/gal diesel – *typical*)]/[(48 bushels soy/acre)(10.7 lb soy oil/bushel)(7.4/7.7 lb biodiesel/lb soy oil)(1/7.4 gal biodiesel/lb biodiesel]

= [(98 + 39 + 66) gal H_2O/acre]/(67 gal biodiesel/acre)

= 3.0 gal H_2O/gal biodiesel

Soy processing to biodiesel:

= 1 gal H_2O/gal biodiesel (*10*)

Biodiesel vehicle efficiency

Same as stated in Appendix S-A.

Irrigated Farming of Soybeans:

Total water withdrawal for biodiesel driving:

= (irrigation H_2O/biodiesel + energy H_2O/biodiesel + processing H_2O/biodiesel) (allocation factor)/(biodiesel car miles/gal biodiesel)

= [(150 to 840 + 3.0 + 1) gal H_2O/gal biodiesel](0.18 to 0.80)(/(25.7 mpg)

= 1.1 - 26 gal H_2O/mile

= 15 gal H_2O/mile - Average

Non-Irrigated Farming of Soybeans:

Total water withdrawal for biodiesel driving:

= (energy H_2O/biodiesel + processing H_2O/biodiesel)(allocation factor)/(biodiesel car miles/gal biodiesel)

= [(3.0 + 1) gal H_2O/gal biodiesel](0.18 to 0.80)/(25.7 mpg)

= 0.03 – 0.12 gal H_2O/mile

Fischer-Tropsch Diesel from Coal

F-T Diesel efficiency in automobile:

Same as stated in Appendix S-A.

Coal mining water withdrawal:

Assumed same as consumption in Appendix S-A.

= 0.131-0.486 gal H_2O/gal F-T diesel

Gasification and F-T processing of coal to F-T Diesel:

Assumed same as consumption in Appendix S-A.

Total water withdrawal for driving using F-T diesel from coal:

Assumed same as consumption in Appendix S-A.

= 0.19 – 0.58 gal H_2O/mile

Fischer-Tropsch Diesel from Natural Gas

F-T Diesel efficiency in automobile:
Same as above for F-T Diesel from coal

Natural Gas pipeline transport and processing water withdrawal:
Assumed same as consumption in Appendix S-A.
= 0.330 gal H_2O/gal F-T diesel

Makeup water for processing of natural gas to F-T Diesel:
Assumed same as consumption in Appendix S-A.

LOW:
= 2.6 gal H_2O/gal F-T product (*S11*):

HIGH:
= 10.8 gal H_2O/gal F-T product (*S11*):
= 11.0 gal H_2O/gal F-T liquid product (*S12*)

Total water consumption for driving using F-T diesel from natural gas:
Assumed same as consumption in Appendix S-A.
= 0.11 – 0.42 gal H_2O/mile

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