Modeling and Analysis

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Integration of energy and water consumption factors for biomass conversion pathways

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Abstract. Water consumption is one of the critical factors for bioenergy production. In this study, six biofuel and six biopower production pathways are integrated with their water requirement to develop a new factor combining water consumption and energy efficiency for each pathway. This integrated factor is defined as water requirement for 1 MJ of net energy value (NEV) of biofuel or biopower. Agriculture-residue-based ethanol production pathways consume 51.2–63.6 liters of water per MJ of NEV. These pathways are both water and energy efficient. The biopower production pathways based on agriculture residues consume 27.2–50.6 liters of water per MJ of NEV. Although a switchgrass-based ethanol production pathway is the most energy efficient, this pathway consumes an average of 130 liters of water per MJ of NEV due to poor water efficiency. Corn-to-ethanol and wheat-to-ethanol pathways are neither energy efficient nor water efficient and consume an average of 178 liters and 325 liters of water per MJ NEV, respectively. A rapeseed-to-biodiesel pathway is less energy intensive and lies between corn- and wheat-grain-based ethanol pathways and consumes an average of 211 liters of water per MJ of NEV. © 2011 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: bioethanol; biodiesel; biopower; bio-oil; water consumption; net energy value, energy consumption

Introduction

Bioenergy is renewable but it consumes fossil fuels during its production, hence it is not considered completely carbon neutral. With increased interest in the issue of global warming, the fossil fuel requirement for bioenergy production has become a critical factor. From an environmental perspective, higher fossil fuel requirement for production of bioenergy leads to higher greenhouse gas (GHG) emissions. There are different metrics for presenting the amount of fossil fuel required in the life cycle of bioenergy: life cycle energy efficiency, energy balance, net energy value, or energy ratio. In this study, net energy value (NEV) is used to compare different bioenergy pathways. The NEV reflects the actual energy output from a bioconversion pathway. This is different than gross energy content of a biofuel because gross energy content of a biofuel does not reflect the

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amount of fossil energy consumed in its production. Over the past several years, there has been substantial work done on estimating the NEVs for different bioproducts using different biomass feedstocks.[1–6]

Water requirement is another critical factor in determining the most environmentally efficient bioenergy pathway. Water is used mainly in two stages of bioenergy life cycle: crop production stage and bioconversion stage. Water consumption factors (i.e. liters of water for production of 1 MJ of ethanol or 1 liter of ethanol) for producing bioenergy are calculated in earlier studies.[7–9] These factors help decision-makers find the most water-efficient pathway, but these do not provide information on the energy efficiency of the pathway.

This study proposes a methodology for integration of energy and water consumption factors and develops these integrated factors for different biomass conversion pathways. This study provides a detailed analysis of the NEV and water consumption factors for twelve biomass conversion pathways based on six biomass feedstocks. Some NEV values are not available in the literature, and so were calculated in this study. The water consumption factors for twelve biomass conversion pathways were studied in an earlier study by the authors.[9] Once the NEV and the water consumption factor for each pathway were determined, the NEVs were integrated with the water consumption factors for each of the respective pathways. This resulted in a new integrated factor representing environmental efficiency, which is a combination of energy consumption and water consumption for different bioconversion pathways.

Methodology

In this study, six biomass feedstocks are considered to produce three key bioproducts (bioethanol, biodiesel, and biopower) through twelve bioconversion pathways. Figure 1 shows the twelve pathways including two pathways for fermentation of grain (corn and wheat) into bioethanol; three pathways for conversion of lignocellulosic biomass feedstocks into ethanol through saccharification and fermentation processes; three pathways (corn stover, wheat straw, and switchgrass) into electricity through direct combustion; three pathways (corn stover, wheat straw, and switchgrass) into electricity through conversion to bio-oil and its combustion; and one pathway (rapeseed) into biodiesel through crushing and transesterification processes.

The NEV for any bioenergy production pathway depends on several factors. The main factors which affect the life cycle energy requirement of a bioconversion pathway include types of fuel consumed directly or indirectly over the life cycle, technology used for bioconversion, bioconversion efficiency, byproducts of utilization, and plant capacity. In this study, a range of energy data on conversion of biomass were collected and studied to determine the water consumption factor based on the NEV. The NEV (MJ per unit of bioenergy) for a bioenergy pathway is calculated as follows and is derived from an earlier study:[6]

Net energy value (MJ per unit of bioproduct) = Energy content of bioproduct (MJ per unit of bioproduct) + credits for byproducts (MJ per unit of bioproduct) – direct and indirect fossil fuels input (MJ per unit of bioproduct) (1)

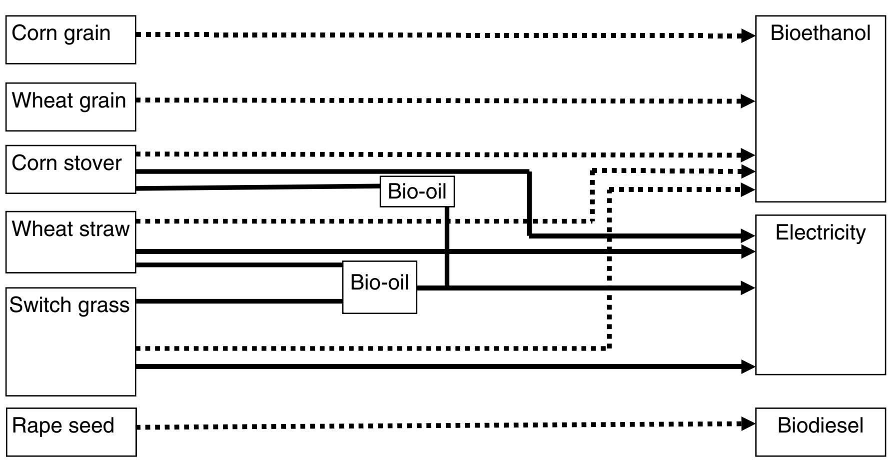

Figure 1. Biomass conversion pathways.

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Energy content of bioproduct is the calorific value of the bioproduct. The total energy content of a biofuel can be considered in terms of its higher heating value (HHV) or lower heating value (LHV).[4] This study considers both the HHVs and the LHVs of biofuels. Energy credit for byproducts is the amount of energy that would have been required to produce that byproduct from any other pathway. Direct and indirect fossil fuel input refers to the input energy for production of the bioproduct.

The water consumption factors are total water requirement per unit production of a bioproduct for a particular bioconversion pathway and these factors are integrated with energy as follows.

Integrated water and energy consumption factor for a bioproduct produced through a particular bioconversion pathway = Water consumption (liters per unit of bioproduct) / Net energy value (MJ per unit of bioproduct) *(2)*

The water consumption factors for twelve different biomass conversion pathways were estimated in an earlier study by the authors.[9] The developed water conversion factors include water requirement in the agriculture stage, water requirement in feedstock transportation stage, and water requirement in the conversion stage. The estimated water requirement for different conversion pathways includes both direct and indirect water use over the life cycle. Agriculture-stage water requirement includes both precipitation and irrigation water. The irrigation water could come from both surface water and groundwater. Similarly, the water for the conversion stage could come from both surface water and groundwater. This study considers both grains and lignocellulosic biomass. Further details on the development of water consumption factors can be found in an earlier study by the authors.[9] For the agriculture stage, water requirements are allocated to grains and residues based on their mass fractions. It is assumed in this study that ratio of corn stover to corn dry weight is 1:1. Similarly, the ratio of wheat straw to wheat dry weight is 1.1:1.

The integrated factor based on water and NEV shown in Eqn (2) is proportional to the water consumption. The water consumption in this integrated factor is the total water consumption to produce a unit of bioproduct and is the sum total of agriculture- and conversion-stage water consumption. The agriculture-stage water could come from precipitation or irrigation and this depends on the place. The integrated factor reflects the total water consumption per unit NEV irrespective of the source of water. The higher value of integrated factor reflects higher water consumption for the particular pathway per unit NEV which is not desirable.

NEV and water consumption factors of bioconversion pathways

NEV and water consumption factor for ethanol produced from corn

Currently, corn is the most popular feedstock for production of ethanol. There has been a lot of discussion on the NEV variation of the corn-based ethanol. As shown in Table 1, the NEV for the corn-to-ethanol pathway varies in a very wide range, mainly because of the type of fuel used in the conversion process.

In the USA, most ethanol plants use natural gas as fuel and the NEV for corn-based ethanol produced using natural gas is approximately 5600 kJ per liter of bioethanol.[10] With increased interest in reduction of greenhouse gas (GHG) emissions and with volatility in the price of natural gas, other alternatives such as DDGS (Distiller's dried grains and soluble), wood chips are being considered as a substitute for natural gas.[10] As reported in different studies, the variation in NEV is also due to differences in assumptions and data on corn yield, fertilizer requirements for the corn crop, the conversion efficiency of the ethanol plant, etc.

Though most researchers reported positive NEVs for corn-based ethanol, the studies by Pimentel reported the NEV of corn-based ethanol as negative, i.e. more energy was consumed through the input of fossil fuel than the amount contained in the bioethanol.[11-13] Many factors contributed to the underestimated Pimentel NEV, such as lower corn yield, higher fertilizer application rate, and lower corn-ethanol conversion rate.[4] Hence, in this study, only positive values for NEVs are considered in evaluating and comparing water consumption factors for different pathways. In this pathway, water is used mainly for corn crop production. Water is also used as process water, cooling water, and steam in the corn-based ethanol plant. Water is also used indirectly for the production of electricity and chemicals used in the pathway.

Table 1. Net energy value and water consumption for different biofuels.

Pathway	Net energy value[a] (kJ liter^{-1})		Water requirement[b] (liters liter^{-1})	Water consumption per unit NEV (liters MJ^{-1})		Sources
	Based on HHV	Based on LHV		Based on HHV	Based on LHV	
Corn – Ethanol	5883	3664	815.81	138.7	222.7	[4]
	8490	6271	815.81	96.1	130.1	[25]
	3978–15446	1759–13227	815.81	205.1–52.8	463.8–61.7	[10]
	8119	5900	815.81	100.5	138.3	[26]
	11701	9482	815.81	69.7	86.0	[2]
	6631	4412	815.81	123.0	184.9	[27]
	8313	6,094	815.81	98.1	133.9	[28]
Average	**8570**	**651**	**815.81**	**110.5**	**177.7**	
Wheat – Ethanol	4337–22767	2,118–20548	1087.57	250.8–47.8	513.5–52.9	[14]
	3490	1271	1087.57	311.6	855.7	[3]
	13044	10825	1087.57	83.4	100.5	[29]
	12895	10676	1087.57	84.3	101.9	[24]
Average	**11307**	**9088**	**1087.57**	**155.6**	**324.9**	
Corn stover – Ethanol	23879	21660	1011.9	42.376	46.717	[5]
	25119	22900	1011.9	40.284	44.188	[26]
	20686	18467	1011.9	48.917	54.795	[30]
	19329	17110	1011.9	52.351	59.141	[16]
	21932	19713	1011.9	46.138	51.332	[17]
Average	**22,189**	**19970**	**1,011.90**	**46.0**	**51.2**	
Wheat straw – Ethanol	19329	17110	1170.44	60.554	68.407	[16]
	22809	20590	1170.44	51.315	56.845	[24]
	20085	17866	1170.44	58.274	65.512	[28]
Average	**20741**	**18522**	**1170.44**	**56.7**	**63.6**	
Switchgrass - Ethanol	22411	20192	2696.68	120.3	133.6	[17]
	23719	21500	2696.68	113.7	125.4	[18]
Average	**23065**	**20846**	**2696.68**	**117.0**	**129.5**	
Rapeseed - Biodiesel	21605	18313	3904.71	180.7	213.2	[24]
	24997	21705	3904.71	156.2	179.9	[29]
	18253	14961	3904.71	213.9	261.0	[3]
	23806	20514	3904.71	164.0	190.3	[19]
Average	**22165**	**18873**	**3904.71**	**178.7**	**211.1**	

[a] Based on higher heating value (HHV) of ethanol: 23 403 kJ per liter, lower heating value (LHV) of ethanol: 21 184 kJ per liter, biodiesel (HHV) of 35 931 kJ per liter, and biodiesel (LHV) of 32 639 kJ per liter.[1,4]
[b] The water consumption factors are derived from an earlier study by the authors.[9] The water consumption factors are based an average yield of the biomass feedstocks in North America.

The total water requirement is found to be 815.81 liters for 1 liter of ethanol produced.

NEV and water consumption factor for ethanol produced from wheat

As with the corn-to-ethanol pathway, the net energy value for this pathway also varies widely depending on the heat and power supply for the ethanol plant. Punter *et al.* reported a net energy value of 4337 kJ per liter of ethanol with natural gas and imported electricity as input fuels for the ethanol plant.[14] In this study, a net energy value is reported as high as 22 767 kJ per liter of ethanol when a wheat straw-based CHP (combined heat and power) plant is considered for the heat and power production for the ethanol plant in place of a fossil-fuel-based power plant (Table 1). In wheat-to-ethanol conversion pathway, water is used for the same purposes as for the corn-to-ethanol pathway and the total water requirement is 1087.57 liters per liter of ethanol produced.

NEV and water consumption factor for ethanol produced from corn stover

Unlike corn- and wheat-based ethanol, corn-stover-based ethanol shows little variation in NEV. The reason is that heat and power requirements for a lignocellulosic-biomass-based

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ethanol plant are fulfilled by an integrated power plant. The integrated power plants use residue (i.e. a lignin-rich byproduct) as input fuel.[5,15,16] In a study by Sheehan *et al.* on ethanol produced from corn stover, the reported figure for the NEV is greater than the HHV of ethanol (23 403 kJ liter^{-1})[5]. In this study, the byproduct energy credit has greater energy value than the fossil fuel energy used in this bioconversion pathway. In this pathway, water requirement in agriculture stage is shared equally between corn and corn stover based on dry weights. Water is consumed in the bioconversion stage as process water, cooling water, and steam. The total water requirement is found as 1011.90 liters per liter of ethanol produced.

NEV and water consumption factor for ethanol produced from wheat straw

The net energy value for producing ethanol from wheat straw varies from 19 329 kJ per liter of ethanol to 22 809 kJ per liter of ethanol as shown in Table 1. For the studies considered in Table 1, the process for production of ethanol from wheat straw is similar to that for producing it from corn stover. Water requirement for this pathway in conversion stage is for the same purposes as for corn-stover-to-ethanol pathway. The total consumption is 1170.44 liters of water per liter of ethanol produced.

NEV and water consumption factor for ethanol produced from switchgrass

Switchgrass is another lignocellulosic biomass which is processed like corn stover and wheat straw to produce ethanol. The energy required for the process is supplied by burning the byproduct (i.e. lignin) of the ethanol plant.[17,18] The fertilizer required to produce switchgrass is lower than annual crops.[18] As a result, the average NEV for the switchgrass conversion pathway is higher than those of other lignocellulosic-biomass-based ethanol production pathways. Unlike other lignocellulosic-biomass-feedstock-based pathways, this pathway consumes a large amount of water in the crop-production stage. Though conversion-stage requirement is almost same as for other lignocellulosic-biomass-based pathways, the total water requirement is 2697 liters per liter of ethanol produced.

NEV and water consumption factor for biodiesel produced from rapeseed

In this bioconversion pathway, fossil-fuel-based energy is used directly and indirectly during different stages of rapeseed production, oil extraction, and transesterification. The net energy consumption depends on climatic conditions and the technologies used for agricultural options and the conversion plant.[19] The values shown in Table 1 for the biodiesel production pathway depend on the assumptions and data considered in calculating fossil energy use. The average range of NEV for the rapeseed-to-biodiesel pathway is 18 873–22 165 kJ per liter of biodiesel. In this pathway, water is used mainly for crop production. In the conversion stage, a little amount of water is used for oil purification purpose. The total water requirement is 3905 liters per liter of biodiesel production.[9]

NEV and water consumption factors for biopower production pathways

The biopower production pathways can be divided into three stages: feedstock production, transportation, and conversion. This study considers two pathways for the production of biopower: direct combustion of biomass feedstocks in a boiler, and combustion of bio-oil produced through fast pyrolysis of biomass feedstocks. Both pathways are self-reliant regarding heat and power requirements because these use power and heat generated in the integrated power plant.[9] The fossil-fuel-based energy required for both the pathways is only for transportation of ash from the power plant to the field. This study considers the direct and indirect fossil energy requirement for production and transportation of feedstock and ash.

Fossil-fuel-based energy input for producing biomass and transporting it to a biopower plant

The energy required during the production and transportation stages of three biomass feedstocks (corn stover, wheat straw, and switchgrass) are shown in Table 2. Feedstock production requires direct energy such as diesel for farming activities, i.e. baling. It also requires indirect energy such as that used to produce fertilizer. The transportation stage involves loading, trucking, unloading, and stacking. The energy required per unit of biomass for trucking varies with trucking distance. This trucking distance depends on the capacity of the plant, the yield of biomass feedstock, land utilization factor, and road winding factor.[20]

In this study, capacity of the biopower plant is 50 MW.[9] For a plant of this size, direct combustion and fast pyrolysis

Table 2. Fossil energy input in producing biomass and transporting it to a biopower plant.

Biomass feedstock	Stage	Input energy (kJ kg^{-1})	Comments/Sources
Corn stover	Production stage[a]	589	[26]
		850	[17]
	Production & transportation[b]	1,143	[5]
Wheat straw	Production stage[a]	1,070	[24]
		820	[17]
Switchgrass	Production stage[a]	662	[18]
		670	[17]
		436	[25]
	Transportation[c,d]	569	Derived from Kumar (2007) for 800 dry tonnes capacity plant.
		589	Derived from Kumar (2007) for 1000 dry tonnes capacity plant.

[a] Feedstocks production requires producing fertilizer, handling and baling of the feedstock.
[b] The value is adjusted for a 1000 dry tonnes plant for transportation.
[c] Transportation involves loading, trucking, unloading and stacking biomass feedstock. The energy input for trucking is adjusted according to biopower plant capacity.
[d] It is assumed in this study that the input energy for transportation is same for corn stover, switchgrass, and wheat straw.

pathways require approximately 800 and 1000 dry tonnes of biomass feedstock per day. The energy requirement for trucking is derived from an earlier study by Kumar and Sokhansanj[20] and has been adjusted for the size of the plants. It is assumed that the energy requirement during the transportation stage is the same for all biomass feedstocks. The energy required for the size reduction of feedstock is also included in this study.

Biomass feedstocks and the fossil-fuel-based energy required to generate electricity through the direct combustion and fast pyrolysis pathways

The quantities required per unit of electricity generated through direct combustion and fast pyrolysis are shown in Table 3 for different biomass feedstocks. The amount of biomass feedstocks required for direct combustion is lower than that required for fast pyrolysis because heat losses in the conversion stage are lower. Energy requirements corresponding to the quantity of feedstocks are shown in Table 3 for the feedstock production, transportation, and ash transportation stages. The ash contents of corn stover, wheat straw, and switchgrass are 7.7%,[21] 10.2%,[22] and 5.7%,[23] respectively. In this study, it is considered that the total ash recovered from pyrolysis and combustion stages is returned to the field to reduce fertilizer consumption and prevent soil erosion.[24]

It is also assumed that transportation of ash consumes energy at the same rate (i.e. MJ tonne^{-1} km^{-1}) as does the transportation of biomass feedstock.[24] The NEV for each pathway is shown in Table 3. This NEV is calculated by subtracting all energy inputs from the energy value of 1 kWh i.e. 10 800 kJ, based on an assumption that one kWh thermal equal to 0.33 kWh electrical.

Water required to generate electricity through the direct combustion and fast pyrolysis pathways

In the conversion stage of direct combustion pathway, water is utilized as cooling water for production of steam and service water. The make-up water for these systems is independent of type of biomass feedstock fed into the boiler. The type of biomass decides the quantity of biomass feedstock required to produce one kWh of electricity and accordingly agriculture-stage water requirement. Agriculture residues consume less water than switchgrass in the agriculture stage based on the assumption that water is shared with grains. The total water requirements for corn-stover- and wheat straw-based biopower pathways are 259.38 and 318.30 liters per kWh, respectively. The switchgrass based pathway consumes 672.13 liters of water per kWh of electricity produced.[9]

In a fast-pyrolysis-based pathway, water is used in pyrolysis process as cooling water for bio-oil cooling, bio-oil scrubbing, ash quenching, and steam condensing. The quantity of cooling water varies with the type of biomass feedstock. Water is also used in power-production stage as cooling water and steam. The total water requirements are 326.59 liters, 465.80 liters, and 823.67 liters per kWh of electricity

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Table 3. Net energy value and water consumption for biopower produced using different biomass feedstocks.

Pathway	Biomass requirement[a] (dry kg kWh^{-1})	Energy input for biopower production ($kJ\ kWh^{-1}$)		Net energy value[c] ($kJ\ kWh^{-1}$)	Water requirement[b] (liters kWh^{-1})	Water consumption per NEV (liters MJ^{-1})
		Biomass production and transportation	Ash transportation[b]			
Corn stover – Electricity	0.68	1234	30	9536	259.38	27.20
Corn stover – Bio-oil – Electricity	0.86	1254	39	9507	326.59	34.35
Wheat straw – Electricity	0.71	1515	41	9244	318.30	34.43
Wheat straw – Bio-oil – Electricity	0.88	1534	53	9213	465.8	50.56
Switchgrass – Electricity	0.66	1159	21	9620	672.13	69.87
Switchgrass – Bio-oil – Electricity	0.81	1178	27	9595	823.67	85.84

[a] It is considered that ash generated by the plant will be sent back to the field at the same rate of energy consumption i.e. MJ per tonne per km.[24]
[b] Source: Singh and Kumar.[9]
[c] Estimated by subtracting all energy inputs from the total energy content i.e. 10800 kJ per kWh of electricity. This is based on an assumption that 1 $kWh_{thermal}$ = 0.33 $kWh_{electrical}$.

produced for corn-stover, wheat straw- and switchgrass-based pathways, respectively.

Results and discussion

Table 1 shows the NEV and water consumption for six pathways using six biomass feedstocks. Water requirements for these pathways include the amount of water used directly or indirectly over the life cycle of biofuel production. The NEV for biofuel or biopower can be expressed as a percentage of the total energy content of the biofuel or biopower. The heating values for bioethanol and biodiesel are considered as total energy contents.

Similarly, the NEV for the corn-to-ethanol pathway is the lowest at 37%. This NEV refers to ethanol plants which use natural gas as fuel; most existing plants are based on this technology.[10] The NEV for the corn-to-ethanol pathway can be improved to 66% by using other biomass (e.g. wood chips) as a source of heat and by importing electricity.[10] The NEV for this pathway can be improved further, to over 90%, if corn stover is used in the CHP plant, but the water requirement of this pathway will remain much higher than that of agricultural-residue-based pathways. As a result, water requirement cannot be reduced to the water requirement for crop residue.

The NEV for the wheat-to-ethanol pathway is the second lowest at about 48%. The NEV for grain-based ethanol depends mainly on the heat and power sources for the conversion process.[10] About 15% of the NEV is for existing ethanol plants where natural gas is used as fuel for heat and electricity is imported from the grid.[14] This low NEV can be improved to a maximum of 97% by utilizing wheat straw in a CHP plant that supplies energy to an ethanol plant. The energy efficiency of the wheat-to-ethanol-based pathway can be improved. As a result, water requirement can be reduced from 325 to 161 liters per MJ of NEV.

The NEV for the switchgrass-to-ethanol pathway is the highest at 99%, primarily because of its low nutrient requirements as a crop and its sufficient byproduct (electricity) production during conversion. These two factors reduce the fossil energy required in the crop production and transportation stages. Among the lignocellulosic-biomass-based ethanol production pathways, the switchgrass-to-ethanol pathway has the highest NEV followed by the corn-stover-to-ethanol and wheat straw-to-ethanol pathways at 95% and 89%, respectively. Though corn stover and wheat straw are both agricultural residues, the NEV for wheat straw is lower than that of corn stover because more energy is required to replenish nutrients in the agriculture stage for wheat straw. Though the switchgrass-based ethanol production pathway is better than other conversion pathways from an energy consumption point of view, it consumes 130 liters of water for each MJ of NEV produced.

Based on water consumption per unit NEV, the most efficient pathway is corn stover to ethanol, followed by wheat straw to ethanol. Wheat to ethanol has the highest water consumption per unit NEV among all the ethanol production pathways. For biopower pathways, corn stover to electricity is the best, followed by wheat straw. The switchgrass-to-electricity pathway has the highest water consumption per unit NEV.

In the biopower production pathway, the cooling water requirement is higher than that of the ethanol production pathway for any given lignocellulosic biomass feedstock. This means more heat is lost from the system in the biopower production pathway. For this reason, biopower production is not as energy efficient as ethanol production for lignocellulosic biomass. In biopower production, the switchgrass-based pathway is better than the agricultural-residue-based pathway due to switchgrass's low nutrients requirement. The NEV for biopower production through direct combustion is slightly higher than that for biopower production through combustion of bio-oil from fast pyrolysis. This is due to additional heat losses in fast pyrolysis.

The NEV for biodiesel production is 62%. This value is higher than that for existing grain-based ethanol production pathways due to low energy consumption in the conversion stage. Though the NEV for this biofuel is sufficiently high, this pathway is not water efficient because growing rapeseed requires high water consumption. As a result, this pathway is water intensive, consuming 211.1 liters of water.

Tables 4 and 5 show the aggregated water requirement values for different pathways. These tables show the integrated water consumption and NEV factors for agriculture and conversion stages separately for different pathways. The integrated water and NEV factors have been calculated by estimating the water consumptions and NEVs separately for the two stages. These aggregated NEV for biofuel pathways are based on biomass energy content, input energy (as given in Table 2), average values based on HHV (as given in Table 1), and water requirement factors presented in the earlier study.[9] The aggregated net energy value for biopower pathways were calculated from data in Table 3 and biomass net energy content. The average biomass heating value was assumed to be 16 GJ per tonne[33].

Biofuel production pathways could be compared to fossil-fuel-based liquid fuel pathways. The ethanol production pathways are compared to the gasoline production pathway from fossil fuel. The water consumption for gasoline over life cycle including exploration, production, and refining for conventional crude oil is reported in the range of 2.8 to 6.6 liters of water per liter of gasoline.[31] Based on a gasoline heat content of 34.86 MJ per liter,[4] the average water consumption for gasoline is 0.135 liters per MJ. This value is significantly lower compared to biofuel production pathways. The comparison here is based on energy content of fuel and not on the net energy value. Further investigation is required in water consumption level of gasoline.

Table 4. Aggregated water consumption and NEV for biofuels pathways.

Pathway		Agriculture Stage		Conversion Stage	
		Direct	Indirect	Direct	Indirect
Corn–Ethanol	Water consumption (liters liter^{-1})	811.45	0.06	3.58	0.72
	NEV (kJ liter^{-1})	13652		5082	
	Water consumption per NEV (liters MJ^{-1})	59.4		0.846	
Corn stover–Ethanol	Water consumption (liters liter^{-1})	1005.51	0.06	5.97	0.35
	NEV (kJ liter^{-1})	39621		17432	
	Water consumption per NEV (liters MJ^{-1})	25.4		0.363	
Wheat–Ethanol	Water consumption (liters liter^{-1})	1082.62	0.08	4.05	0.81
	NEV (kJ liter^{-1})	16389		5082	
	Water consumption per NEV (liters MJ^{-1})	66.1		0.956	
Wheat straw–Ethanol	Water consumption (liters liter^{-1})	1164.14	0.08	5.87	0.34
	NEV (kJ liter^{-1})	37920		17179	
	Water consumption per NEV (liters MJ^{-1})	30.7		0.361	
Switchgrass–Ethanol	Water consumption (liters liter^{-1})	2690.27	0.10	5.96	0.34
	NEV (kJ liter^{-1})	39203		16138	
	Water consumption per NEV (liters MJ^{-1})	68.63		0.39	
Canola seed– Biodiesel	Water consumption (liters liter^{-1})	3628.22	0.18	0.24	0.44
	NEV (kJ liter^{-1})	34880		12715	
	Water consumption per NEV (liters MJ^{-1})	104		0.053	

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Table 5. Aggregated water consumption and NEV for biopower pathways.

Pathway		Agriculture Stage		Conversion Stage	
		Direct	Indirect	Direct	Indirect
Corn stover–electricity	Water consumption (liters kWh^{-1})	256.6	0.08	2.70	0.00
	NEV (kJ kWh^{-1})	9646		10770	
	Water consumption per NEV (liters MJ^{-1})	26.61		0.251	
Corn stover–bio-oil–electricity	Water consumption (liters kWh^{-1})	323.5	0.08	3.01	0.00
	NEV (kJ kWh^{-1})	12506		10761	
	Water consumption per NEV (liters MJ^{-1})	25.87		0.279	
Wheat straw–elecrticity	Water consumption (liters kWh^{-1})	315.5	0.10	2.70	0.00
	NEV (kJ kWh^{-1})	9845		10759	
	Water consumption per NEV (liters MJ^{-1})	32.06		0.251	
Wheat straw–bio-oil–electricity	Water consumption (liters kWh^{-1})	462.6	0.10	3.10	0.00
	NEV (kJ kWh^{-1})	12546		10747	
	Water consumption per NEV (liters MJ^{-1})	36.88		0.288	
Switchgrass–electricity	Water consumption (liters kWh^{-1})	669.41	0.03	2.7	0.00
	NEV (kJ kWh^{-1})	9401		10779	
	Water consumption per NEV (liters MJ^{-1})	71.21		0.25	
Switchgrass–bio-oil–electricity	Water consumption (liters kWh^{-1})	820.66	0.03	2.98	0.00
	NEV (kJ kWh^{-1})	11782		10773	
	Water consumption per NEV (liters MJ^{-1})	69.66		0.277	

For biopower pathways, the water consumption level is compared to a thermoelectric power plant. The amount of water consumed by thermoelectric power plants per kWh of end use energy for the entire United States is calculated as 1.8 liters.[32] The metric was calculated by taking the total consumptive water use divided by the total power output. Again this value is very low compared to biopower production pathways. The comparison here is not based on the NEV. Further investigation is required in water consumption level of thermoelectric power production.

This paper developed a methodology for combining energy and water consumptions factors for production of different biofuels and biopower through different pathways. The results show the environmental efficiency of the various bioconversion pathways.

Conclusion

The grain-based ethanol production pathways using existing technology are the least energy efficient and water efficient. The ethanol production pathways based on lignocellulosic biomass feedstocks (corn stover, wheat straw, and switchgrass) are the most energy efficient. The corn-stover- and wheat straw-based ethanol production pathways are also the most water efficient consuming only about 51–64 liters of water for 1 MJ of NEV. Due to water inefficiency, switchgrass-based ethanol pathway consumes 130 liters of water for 1 MJ of NEV. The NEVs for biopower production pathways based on lignocellulosic feedstocks are lower than that for ethanol production pathways based on the same feedstock; the corn-stover- and wheat straw-based biopower production pathways consume 27–51 liters of water for 1 MJ of NEV. The NEV for rapeseed-based biodiesel is higher than that for grain-based ethanol, but this pathway is water intensive and consumes about 211 liters for 1 MJ of NEV.

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