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Development of water requirement factors for biomass conversion pathway

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ABSTRACT

Published data were used to develop an integrated spreadsheet-based model to estimate total water requirement for 12 biomass conversion pathways. The water requirement for crop production was attributed only to the grains in the estimates since agricultural residues are produced irrespective of their use for fuel or electricity. Corn stover- and wheat straw-based ethanol production pathways are water efficient, requiring only 0.3 l, whereas biopower production pathways (i.e. direct combustion and bio-oil production) require about 0.8–0.9 l of water per MJ. Wheat- and corn-based ethanol production pathways consume 77 and 108 l of water per MJ, respectively. Utilization of switchgrass for production of ethanol, biopower through the direct combustion, and pyrolysis consume 128, 187 and 229 l of water per MJ, respectively. Biodiesel production from canola seed consumes 124 l of water per MJ. Corn stover- and wheat straw-based conversion pathways are most water efficient.

1. Introduction

The production of biomass and its conversion into energy consumes large amounts of water (Pimentel and Patzek, 2005; Varghese, 2007; King and Webber, 2008; Pfromm, 2008; RFA, 2008; Gerbens-Leenes et al., 2009). Seventy percent of the fresh water utilized by humans withdrawn worldwide is used for agriculture (Pimentel and Patzek, 2005), while about 22% and 8% are used by industry and for direct human consumption, respectively (WEF, 2009).

Only a few studies on the water needed to meet the demand for biofuels have been carried out (Aden, 2007; Varghese, 2007; King and Webber, 2008; Pfromm, 2008). Aden (2007) briefly discussed water requirements for ethanol production from corn and corn stover, and Varghese (2007) discussed the water requirement for corn-based ethanol in the US and sugarcane-based ethanol in Brazil. King and Webber (2008) estimated the water required to produce corn and corn stover-based ethanol including irrigation requirements but excluding water required for fertilizer production. Pfromm (2008) estimated minimum water requirements for ethanol production from corn, assuming 100% water recycling. Some other studies have estimated water requirements specific to various crops such as wheat, barley, corn, rice etc. at specific locations and have included irrigation, but not precipitation (e.g. Gerbens-Leenes et al., 2009). Therefore, there is a need for further analysis of life cycle water requirements (i.e. including production, precipitation and conversion) for various biomass conversion pathways.

In the current study, the total water required (precipitation and irrigation) for production of corn, wheat and switchgrass was calculated and the total life cycle water requirement for various biomass conversion pathways, independent of the place of bioenergy production, was estimated. Literature data were collected on the agricultural production and crop conversion stages. Water requirements for biomass transportation from field to power plant were not evaluated since these are negligible (King and Webber, 2008). Indirect water requirements such as water associated with fossil fuel and fertilizer production were included. The study focused on developing water requirement factors for different commercially established and experimentally successful biofuel and biopower pathways.

2. Methods

The life cycle of bioenergy can be divided into three main stages: biomass feedstock production and harvesting, transportation of biomass to the conversion facility, and conversion of biomass to bioenergy product. To evaluate the life cycle water requirement of bioenergy, this study estimated the requirement of water in agriculture and conversion stages. Data from the literature were collected wherever available and also developed for specific cases. These data were used to develop a spreadsheet based integrated model to evaluate life cycle water requirement for different biomass conversion pathways using various biomass feedstocks. The water requirement for the transportation stage (from field to power plant) was not evaluated as water requirement is negligible for this stage (King and Webber, 2008). This study also estimated the indirect water requirement associated with the life cycle of major input resources such as water associated with the life cycle of fossil fuel production,

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fertilizer required in the agricultural stage etc. This study focuses on developing water requirement factors for different commercially established and experimentally successful biofuel and biopower pathways. Details on selection of biomass feedstocks, biochemical, and thermo-chemical pathways for biofuel and biopower production are given in subsequent sections. Mass and energy balances of the processes were performed to estimate the intermediate parameters required for calculation of total water requirement for a conversion pathway. A spreadsheet-based model was developed to estimate the total water consumption in a biomass conversion pathway by integrating the water consumptions of the unit operations involved in that pathway.

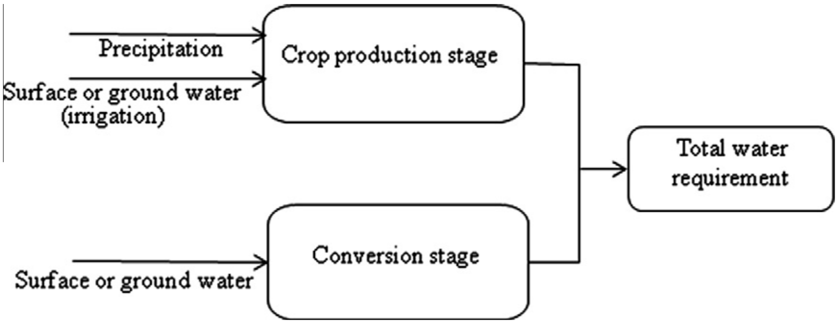

Fig. 1. Water sources for bioenergy production.

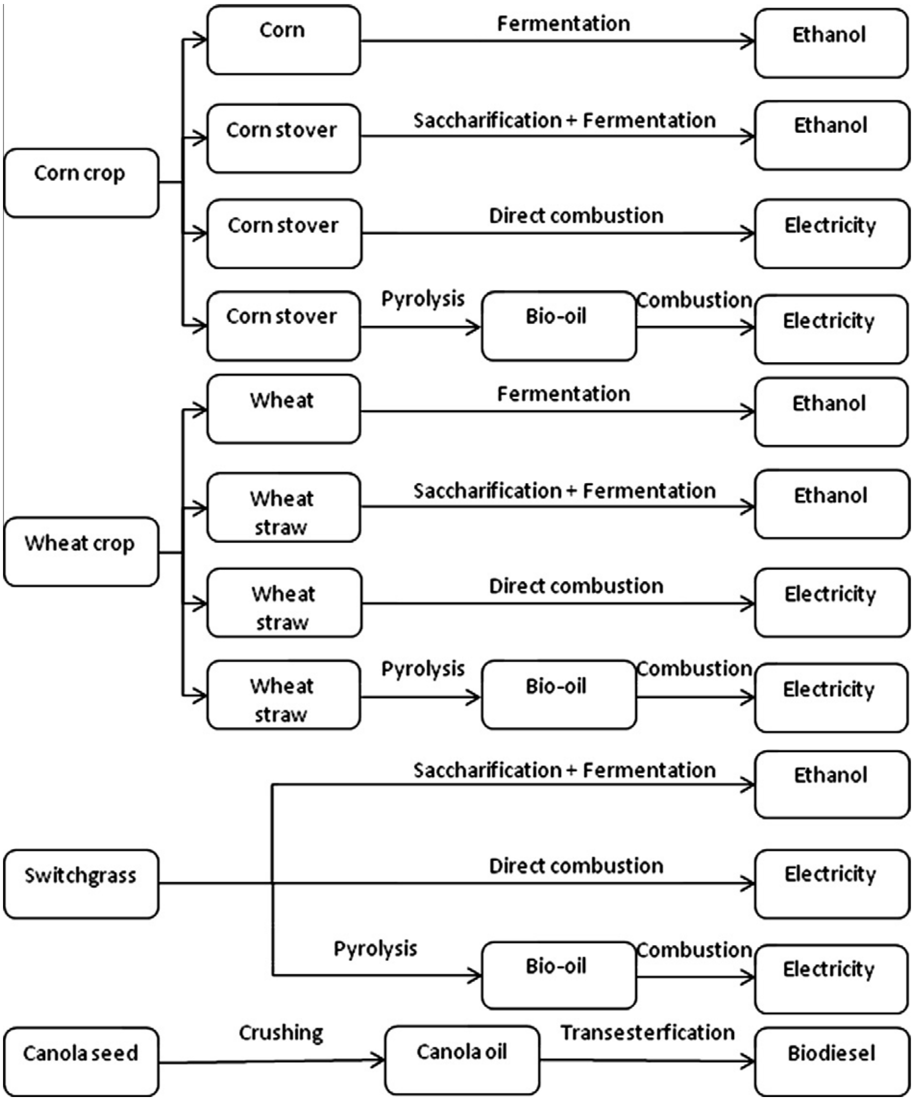

Fig. 2. Twelve biomass conversion pathways.

2.1. Definition of water requirement

Water requirements refer to the total direct and indirect water used to produce biomass and to convert it into biofuel/bioenergy. The sources of direct water are precipitation, and/or surface or ground water (Fig. 1). The direct water requirement for the conversion stage is the make-up water requirement for the conversion process. The source of this water is surface or ground water. The indirect water requirements for both the stages are the water used during the manufacturing of major inputs such as fertilizers, chemicals, and fuels. The source of this indirect water requirement is surface or ground water.

2.2. Selection of biomass feedstocks and biomass conversion pathways

In this study, agriculture-based biomass feedstocks are considered. These include corn, corn stover, wheat, wheat straw, switchgrass and canola. The key idea behind selection of biomass feedstock is to compare the conversion technologies which are commercially available or are near to commercialization. There are different mature pathways available for biomass conversion which produces fuels and electricity and this study compares these in terms of water consumption. Raw biomass is converted into useful biofuels or electricity using thermo-chemical and biochemical processes depending upon the constituents of the biomass. Fig. 2 shows the utilization of different feedstocks in the conversion pathways considered in this study.

3. Results and discussion

Direct and indirect water requirement for the biomass production and conversion stages for each of the pathways are estimated separately. The following sections include descriptions on each unit operation.

3.1. Corn crop based biomass conversion pathways

3.1.1. Direct and indirect water requirements for corn and corn stover production

In the crop production stage of corn, the water supplied to the crop affects its yield. Corn yield data from Canada and the US with their water requirements are shown in Table 1 and the average dry yield and water requirement for production of corn in the North America along with its characteristics are shown in Table 2.

The typical energy and fertilizer requirements of corn used in this study are shown in Table 3. This table also gives the amount of water required to produce a specific quantity of output (for example, 147.7 l of water is required for the production of 55.7 kg diesel). Other inputs like herbicide, lubricants needed for farm vehicles, etc. have been ignored. The life cycle water requirement of these inputs as considered in this study includes water consumption from mining raw materials, manufacturing each input and delivering it to the farm.

Corn stover yield is based on data given in Table 2. It is important to note that corn stover is produced along with corn even if we do not use corn stover for energy or fuel production; therefore, the assumption in this study is that water requirement during growth of corn is only attributed to corn and not to corn stover. A sensitivity analysis was performed by attributing water consumption to corn and corn stover and is discussed later.

3.1.2. Direct and indirect water requirements for conversion of corn to ethanol

To convert corn into ethanol, the dry grind process was considered. The process used in this study is shown in Fig. 3. Water requirement during ethanol production is due to the water loss during distillation and drying processes (Table 5). Based on the data in this table and characteristics of corn (given in Table 2), the average water requirement of the corn ethanol process was estimated (Table 4). Note that direct and indirect water requirements for all the biomass conversion pathways are given in Table 4.

Electricity and natural gas are major inputs of the process of conversion of corn to ethanol. Electricity is used to run auxiliary equipment of the process, and natural gas is used to produce steam for the process. For corn-based ethanol production, 0.52 kWh of electricity and 0.085 kg of natural gas (Franceschin et al., 2008) are required to produce 1 kg of ethanol and 1.76 l of water is needed per kWh of electricity produced and no water is needed to produce natural gas (King and Webber, 2008).

3.1.3. Direct and indirect water requirements for conversion of corn stover to ethanol

Fig. 4 shows the ethanol production process from corn stover as considered in this study. The hemicellulose and cellulose portion of corn stover is used for ethanol production and the solid residue containing lignin is fed into a boiler to produce steam which is partially used to provide heat required by the process, with the remaining steam being utilized for power production.

In this study the assumption was made that water is used in the pretreatment and hydrolyzation of corn stover. This involves cleaning and slurrying of the corn stover for further processing. As steam is used as a heating medium in the whole process, water is lost through vents and traps in the steam distribution system and water is drained off from the boiler to maintain steam quality.

Table 1
Crops yields and water requirements.

Crop	Country	Yield (kg ha^{-1})	Crop water requirement (mm)	Source
Corn	Canada	7533	500	OMAFRA (2009b)
	Canada	8400	533	Manitoba Agriculture (2009)
	Canada	7533	510	McKenzie and Dunn (1997)
	US	13,012	943	Howell et al. (1998)
	US	12,260	793	Howell et al. (1998)
	US	8000	600	Koa and Piccinnib (2009)
	US	10,625	617	Payero et al. (2008)
	US	9970	481	Jia et al. (2007)
	US	13,812	838	Claim (2009)
Wheat	Canada	7416	507	Shock et al. (2005)
	Canada	7406	460	Raddatz and Shaykewich (1998)
	Canada	2251	290	McKenzie and Dunn (1997)
	USA	1179	205	Lenssen et al. (2007)
Canola Seed	Canada	4064	480	McKenzie and Dunn (1997)
	Canada	2463	369	Canada Canola Council (2008)
	Canada	2285	395	Canada Canola Council (2008)
	Canada	1916	351	Canada Canola Council (2008)
	Canada	1776	317	Canada Canola Council (2008)
	Canada	1593	343	Canada Canola Council (2008)
	Canada	1537	282	Canada Canola Council (2008)
	Canada	922	210	Canada Canola Council (2008)

Table 2
Characteristics of biomass feedstocks.

Feedstocks	Values	Comments/remarks
Corn		
• Moisture content (%)	15.4	OMAFRA (2009a)
• Average yield (dry kg/ha)	8568	Calculated based on the values of corn yield for North America as given in Table 1
• Average water requirement for production (mm)	646	Calculated based on the values of water requirement given in Table 1 for North America
Corn stover		
• Moisture content (%)	15	Aden et al. (2002)
• Average yield (dry kg/ha)	2999	Ringer et al. (2006)
• Size of corn stover for bio-oil production (mm)	2	Calculated based on corn stover to grain dry weight ratio of approximately 1 (Perlack and Turhollow, 2003). Corn stover cannot be practically recovered completely from the field because of poor collection efficiency and other field requirements (Aden et al., 2002; Perlack and Turhollow, 2003). It is technically required to leave part of the corn stover in the field to maintain soil nutrient and carbon levels and to control soil erosion (Aden et al., 2002; Perlack and Turhollow, 2003). As a result of the above limitations and requirements, it is assumed that 35% of the produced corn stover can be used for biomass conversion. Based on 35% availability, only 2999 kg of corn stover can be collected per hectare out of 8568 kg of corn stover
• Grinding energy for corn stover (kWh/dry tonne)	23.5	Mani et al. (2004)
• Ash content (%)	7.7	Parikh et al. (2007)
Wheat		
• Moisture content (%)	14.6	Dominion (2009)
• Average yield (kg/ha)	4563	Based on the values of corn yield for North America as given in Table 1
• Average water requirement for production (mm)	364	Calculated based on the values of water requirement given in Table 1 for North America
Wheat straw		
• Moisture content (%)	15	Kerstetter and Lyons (2001)
• Average yield (dry kg/ha)	3161	Based on an average straw to grain ratio of 1.1 (Sokhansanj et al., 2006) and assumption that an average 1125 kg ha^{-1} of wheat straw is left in the field to protect soil (Sokhansanj et al., 2006), the net dry yield of wheat straw is 3161 kg ha^{-1}
• Size of wheat straw for bio-oil production (mm)	2	Ringer et al. (2006)
• Grinding energy for wheat straw (kWh/dry tonne)	52.9	Derived from Mani et al. (2004)
• Ash content (%)	10.2	EERE (2009a)
• Lower heating value (LHV) (MJ/kg)	16.6	Kerstetter and Lyons (2001)
Switchgrass		
• Moisture content (%)	15	
• Average yield (dry kg/ha)	11,700	Calculated based on the values of switchgrass yield for North America as given in Table 1
• Average water requirement for production (cm)	81	Calculated based on the values of water requirement given in Table 1 for North America
• Size of wheat straw for bio-oil production (mm)	2	Ringer et al. (2006)
• Grinding energy for wheat straw (kWh/dry tonne)	64.9	Derived from Mani et al. (2004)
• Ash content (%)	5.7	Larson et al. (2005)
• Lower heating value (MJ/kg)	17.5	Larson et al. (2005)
Canola		
• Average yield (dry kg/ha)	1785	Based on the values of corn yield for North America as given in Table 1
• Average water requirement for production (mm)	324	Calculated based on the values of water requirement given in Table 1 for North America

The process model considered for this study also includes power production using steam; therefore, a large amount of cooling water is required for steam condensation in the condenser. This water is cooled in a cooling tower where it is lost through evaporation, and some of it is drained off intermittently from the system to maintain its quality.

To evaluate the indirect water requirement, only major inputs for conversion of corn stover to ethanol were considered. As shown in Table 5, the indirect water requirement is minimal for all input materials except enzyme. The total water requirement for a 4% solution of cellulosic-hydrolyzing enzymes is 1.37 l per kg of enzyme (Sheehan et al., 2004). In manufacturing sulfuric acid, water is used to absorb SO_3 for the formation of sulfuric acid. Water is also used as cooling water for integrated power generation unit (ESAA, 2000). This power generation unit receives heat from exothermic reactions of the sulfuric acid manufacturing process. A total of 0.22 l of water is used to produce 1 kg of sulfuric acid (ESAA, 2000). Corn steep liquor, a byproduct of the corn wet-milling process, is used as a source of nutrients for microorganisms. The steep liquor is 50% concentrated solutions, i.e. 50% of steep liquor, fed to this process is water (Liggett and Koffler, 1948).

3.1.4. Direct and indirect water requirements for conversion of corn stover to electricity through direct combustion

The water requirement for conversion of corn stover to electricity depends upon the thermo-chemical pathway used for electricity generation. In this study, electricity production was based on steam generation in a corn stover fired boiler and use of this generated steam in a condensing steam turbine as shown in Fig. 5. The water requirement in this type of biomass power plant depends upon type of cooling water system.

In a rankine cycle based power plant, water requirement is governed dominantly by cooling water requirement for steam condensation in a condenser. This cooling water removes heat to the atmosphere through evaporative cooling in a cooling tower. The evaporation and blow down losses of cooling tower creates a demand for make-up water. In this study, closed cooling system (Gerdes and Nichols, 2008) was considered for electricity

Table 3
Major indirect inputs to crop production and their water requirement.

Inputs	Quantity[a] (kg ha^{-1})	Water requirement[b] (l ha^{-1})
Corn		
Diesel	55.7	147.7[d]
Gasoline	22.2	60.4[d]
LPG	23.9	102.9[d]
Electricity	83.0[c]	38.6[d]
Natural gas	9.4	0.0[d]
Nitrogen	178.0	121.6[e]
Phosphorus	113.4	22.0[e]
Potassium	79.0	0.1[e]
Lime	22.2	0.0[f]
Inputs	Quantity[g] (kg ha^{-1})	Water requirement[b] (l ha^{-1})
Wheat		
Diesel	41.4	110.4[d]
Gasoline	7.4	20.1[d]
LPG	1.4	6.0[d]
Electricity	37.1[c]	65.2[d]
Natural gas	0.01	0.0[d]
Nitrogen	68.4	46.7[e]
Phosphorus	24.7	4.8[e]
Potassium	9.0	0.0[e]
Lime	44.8	0.0[f]
Inputs	Quantity[h] (kg ha^{-1})	Water requirement (l ha^{-1})
Canola seed		
Diesel	37.8	100.39[d]
Nitrogen	73.5	50.14[e]
Phosphorus	25.9	5.04[e]
Potassium	5.6	0.01[e]
Sulfur	12.4	8.47[e]

[a] The quantities of inputs are derived from Shapouri et al. (2002).

[b] This water requirement refers to the amount of water required per ha for production of a given quantity of inputs.

[c] The electricity requirement is in kWh ha^{-1}.

[d] Source: King and Webber (2008).

[e] Source: Sheehan et al. (1998).

[f] The lime production cycle involves mining, transportation and grinding (West and Marland, 2001), therefore it is assumed that the water requirement is negligible for production of lime.

[g] The values are derived from Piringer and Steinberg (2006).

[h] These values have been derived from an earlier study by Canada Canola Council (2006).

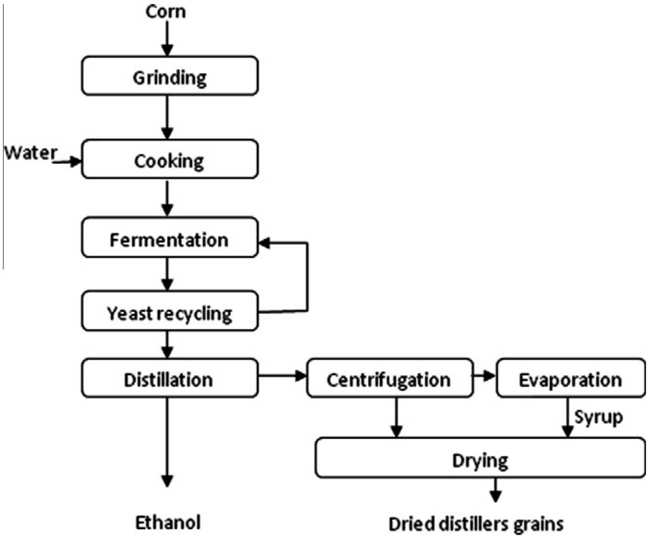

Fig. 3. Dry grind process to convert corn to ethanol [derived from DOE (2008)].

generation. In a power plant, cooling water is also used for plant auxiliaries like compressors, oil coolers, which is about 10% of cooling water requirement in a condenser (Chapman, 1996). The make-up water for cooling system is a major component of the total water requirement. There are also other minor water requirements which include make-up water for steam, feed water cycle and general service water. These were estimated to be approximately 1.5% and 1% of maximum steam flow, respectively (Chapman, 1996).

To evaluate corn stover requirement for production of a kWh of electricity in a direct combustion power plant, wood-based plant model at McNeil Generating Station, Burlington, Vermont (Wiltsee, 2000) was considered. The calculations for study are based on the use of this boiler to burn corn stover. This technology was also assumed for other feedstocks considered in this study. It is assumed that the plant can run with existing auxiliaries using corn stover as feedstock. Elemental analysis and higher heating value (HHV) [as reported by Parikh et al. (2007)] were used to evaluate the boiler heat losses and requirement of biomass feedstock for unit production of electricity to estimate the process stage water requirement. The quantity of corn stover also depends upon net heat rate of the plant. The net heat rate of wood in McNeil power plant is 14,685 kJ kWh^{-1} (Wiltsee, 2000). The boiler heat losses for corn stover and wood were calculated in accordance with ASME Standard PTC 4.1 (ASME, 2008). The net heat rate for corn stover-based power plant was derived from data on wood-based power plant and the calculated value is 12,354 kJ kWh^{-1}. Hence it was estimated that 0.68 kg dry corn stover produces 1 kWh of electricity.

The water requirement in a power plant is related to steam flow to turbine and the quantity of steam flow is independent of feedstock used in the boiler. It is assumed that water requirement for generation of 1 kWh of electricity is same for wood and corn stover-based power plant. The cooling water requirement for McNeil plant to condense steam in a condenser is 176.6 l per kWh net electricity generated. The total cooling water circulation rate in a cooling tower including auxiliary cooling water (which is 10% of condenser cooling water) is 194.3 l. The calculated make-up water requirement, i.e. consumptive water use due to evaporation loss corresponding to this cooling water flow rate in cooling tower is 2.60 l (Perry et al., 1999). About 4.03 kg steam is required per kWh of electricity produced. Make-up water requirement for feed water and steam system is 1.5% of steam flow and is about 0.06 l. Service water requirement is 1% of steam flow and is about 0.04 l (Perry et al., 1999). Total water requirement to generate 1 kWh of electricity is shown in Table 4.

3.1.5. Direct and indirect water requirements for conversion of corn stover to bio-oil through fast pyrolysis

Fig. 6 shows a simplified schematic diagram of the fast pyrolysis process (Dynamotive Energy Systems, 2007; Ringer et al., 2006; Pootakham and Kumar, 2009, 2010; Kumar, 2009; Sarkar and Kumar, 2010) considered in this study. To evaluate production quantity of bio-oil and electricity, the National Renewable Energy Laboratory's (NREL) process model of wood-based fast pyrolysis (Ringer et al., 2006) was considered. As this model used wood containing 50% moisture as feedstock, energy and mass balances were modified based on the chemical properties of corn stover as reported by Parikh et al. (2007) and the products' yields were estimated as shown in Table 6. The fast pyrolysis product yields used in this study for different biomass feedstocks are shown in Table 6. In this study, feedstock is dried to a moisture level of 7% to maximize product yields and to reduce water content in the bio-oil (Ringer et al., 2006). Therefore, 1.45 kg dry corn stover produces 1 kg bio-oil containing 20.6% moisture in this process model.

Net power generation in the process depends on the lower heating value (LHV) of feedstock, bio-oil yield, heat and power requirement of the pyrolysis process. As a result of low LHV, corn stover-based process gets less heat after bio-oil production for power generation. Based on moisture content of corn stover,

Table 4
Water requirement factors for bioenergy conversion pathways.

Biofuel pathways	Dry biomass (kg per kg of biofuel)	Water requirement ($l\ kg^{-1}$)[a]					Product heating value ($MJ\ kg^{-1}$)	Water (l per MJ)
		Agriculture stage[b]		Conversion stage		Total		
		Direct	Indirect	Direct	Indirect			
Corn – ethanol	2.72	2054.31	0.16	4.53	0.91	2059.90	26.7[c]	77.1
Corn stover – ethanol	3.38[e]	0.00	0.00	7.56	0.44	8.00	26.7[c]	0.3
Wheat – ethanol	3.08[f]	2877.84	0.20	5.13	1.03	2884.21	26.7[c]	108.0
Wheat straw – ethanol	3.32[g]	0.00	0.00	7.43	0.43	7.86	26.7[c]	0.3
Switchgrass – ethanol	3.35	3405.40	0.13	7.55	0.43	3413.52	26.7[c]	127.8
Canola seed – biodiesel	2.53	4592.68	0.23	0.30	0.56	4593.78	37.0[d]	124.2
Corn stover – electricity	0.68[h]	0.00	0.00	2.70	0.0	2.70	3.6	0.8
Corn stover – bio-oil – electricity	0.86[h]	0.00	0.00	3.01	0.0	3.01	3.6	0.9
Wheat straw – electricity	0.71[h]	0.00	0.00	2.70	0.0	2.70	3.6	0.8
Wheat straw – bio-oil – electricity	0.88[h]	0.00	0.00	3.10	0.0	3.10	3.6	0.9
Switchgrass – electricity	0.66[h]	669.41	0.03	2.70	0.0	672.13	3.6	186.7
Switchgrass – bio-oil – electricity	0.81[h]	820.66	0.03	2.98	0.0	823.67	3.6	228.8

[a] Liters per kg of ethanol for ethanol production pathways, liters of water per kg of biodiesel for biodiesel production pathway and liters of water per kWh of electricity.
[b] Water requirement is corresponding to dry biomass requirement for production of 1 kg biofuel or 1 kWh of electricity.
[c] Source: Shapouri et al. (2002).
[d] Source: Sheehan et al. (1998).
[e] Derived from Aden et al. (2002)
[f] Based on data from Kim and Dale (2003).
[g] Derived from EERE (2009a, 2009b).
[h] Dry biomass for this pathway is in kg per kWh of electricity.

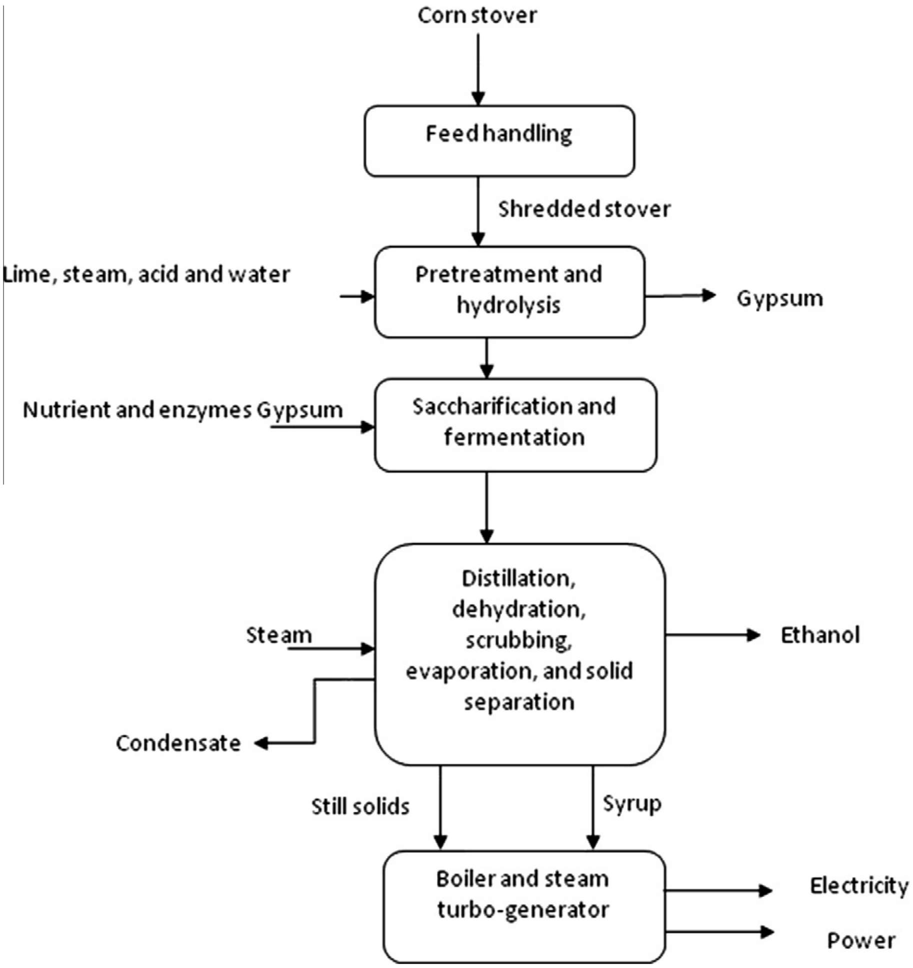

Fig. 4. The corn stover to ethanol conversion process [derived from the Aden et al. (2002)].

Table 5
Make-up water and direct inputs to biomass conversion processes.

Make-up water for dry milling process (l per kg of ethanol)	Corn required (kg per kg of ethanol)	Sources
Corn stover to ethanol process		
5.45	3.08	Franceschin et al. (2008)
3.40	3.20	Johnson (2006)
4.34	3.04	Pfromm (2008)
3.61	3.50	Lurgi (2008)
6.65[a]	–	RFA (2008)
3.80	–	Sobolik (2008)
4.44	–	Aden (2007)
Inputs	Quantity[b] (kg per kg of ethanol)	Water requirement (l)
Corn stover to ethanol process		
Dry corn stover	3.38	–
Enzyme	0.28	0.38[c]
Sulfuric acid	0.13	0.03[d]
Lime	0.10	0.00[e]
Corn steep liquor	0.05	0.03[f]
Inputs	Quantity[g] (kg per kg of canola oil)	Water requirement (l)
Canola seed to canola oil process		
Canola seed	2.44	–
Electricity	0.13[h]	0.24[i]
Natural gas	0.06	0.00[i]
Hexane	0.01	0.00[c]
Inputs	Quantity[g] (kg per kg of biodiesel)	Water requirement (l)
Canola oil to biodiesel process		
Crude canola oil	1.04	–
Sodium methoxide	0.02	0.10[c]
Sodium hydroxide	0.02	0.10[c]
Hydrochloric acid	0.08	0.01[c]
Methanol	0.09	0.15[c]
Electricity	0.03[h]	0.05[c]

[a] RFA (2008) state that 2.5–8.0 gallon of water is required per gallon of ethanol. The average of these values, 5.25 gallon per gallon of ethanol is used in this study. Considering an ethanol density of 0.789 kg per l, 6.65 l of water per kg of ethanol is used in this study.
[b] The quantities of inputs are derived from Aden et al. (2002).
[c] Source: Sheehan et al. (2004).
[d] Source: ESAA (2000).
[e] Source: West and Marland (2001).
[f] Source: Liggett and Koffler (1948).
[g] These values have been derived from an earlier study by Canada Canola Council (2006).
[h] These values are given in kWh.
[i] Source: King and Webber (2008).

grinding energy requirement to reduce its size to 2 mm and ash content as given in Table 2 and 0.17 kWh of electricity is produced for every kg of bio-oil during its fast pyrolysis. This was estimated in this study using energy and mass balance in the process model.

In fast pyrolysis, cooling water is used for different purposes as shown in Table 6. It was assumed that cooling water is used to condense steam in the integrated power plant of fast pyrolysis process and also used in scrubbing to extract bio-oil vapor from the recycled carrier gas. Steam loss of 3% was also considered. The calculated value of water required in the corn stover-based fast pyrolysis process to produce a kg bio-oil is shown in Table 6.

3.1.6. Direct and indirect water requirements for conversion of corn stover derived bio-oil to electricity

The direct combustion of bio-oil through production of steam in a boiler and use of steam in a turbo generator was considered for electricity production. To evaluate the bio-oil requirement for power generation, the McNeil Generating Station, Burlington, Vermont (Wiltsee, 2000) was considered as the process model. This technology was also assumed for combustion of bio-oil from other feedstocks. Although the McNeil plant is wood-based, the major equipments viz. boiler fans, feed pumps, turbine auxiliaries are similar to any oil-based plant except that it has an oil skid assembly instead of a wood conveying system to the boiler. As a result of this difference, auxiliary power requirement for these two cases is slightly different. This difference in auxiliary power would not affect water requirement significantly, hence it is neglected in this study. Based on the characteristics of feedstock and bio-oil as reported in Parikh et al. (2007), Ragland et al. (1991) and Agblevor et al. (1996), net heat rate of the plant for bio-oil combustion plant was estimated to be 12,351 kJ kWh^{-1}. Therefore, 0.66 kg of corn stover derived bio-oil is required per kWh of produced electricity. Water requirement for corn stover-based bio-oil conversion to electricity is the same as for pathway of direct combustion of corn stover for production of electricity.

3.2. Wheat crop based bioenergy conversion pathways

3.2.1. Direct and indirect water requirements for wheat production

To estimate water requirements, different studies related to spring wheat from different regions of Canada and adjacent border states of the USA were considered. Based on the data given in Table 2, the calculated value for average direct water use for wheat is 933.13 l per kg of dry wheat production. Data given in Table 3 were used to estimate average indirect water requirements for each input. Based on an average yield of wheat, the calculated value of indirect water use is 0.07 l per kg of dry wheat production. In this study, water used for the production of wheat crop is attributed to wheat grains only as grains will be produced in any case.

3.2.2. Direct and indirect water requirements for conversion of wheat to ethanol

Based on amount of wheat required to produce one kg of ethanol and the assumption that an equal amount of water is required to process equal amounts of wheat and corn for ethanol production, direct water requirement was calculated (Table 4). Based on the assumption that major inputs required for production of ethanol from wheat are same as corn and wheat, the indirect water requirement was calculated (Table 4).

3.2.3. Direct and indirect water requirements for conversion of wheat straw to ethanol

The process of conversion of wheat straw to ethanol was assumed to be same as that of corn stover. Based on a composition of wheat straw [as reported by Kerstetter and Lyons (2001)], wheat straw required to produce 1 kg of ethanol was estimated. Power generation by combustion of lignin in a boiler is the same as corn stover as the content of lignin is same in both the feedstocks. The direct water requirement for corn stover and wheat straw and other inputs were assumed to be same when processing equal amounts of these feedstocks. Results on water requirements are shown in Table 4.

3.2.4. Direct and indirect water requirements for conversion of wheat straw to electricity through direct combustion

Similar to corn stover case, wheat straw is combusted in a boiler to produce steam and this steam is utilized in the steam turbo generator to produce electricity as shown in Fig. 5. Based on the chemical properties of wheat straw [as reported in EERE (2009a)], the net heat rate of wheat straw-based power plant is 12,373 kJ kWh^{-1} and 0.71 kg of dry wheat straw is required to produce 1 kWh electricity. In this process, water is utilized as cooling water, for production of steam and service water as explained in earlier section. As water requirement in the direct fired power plant is

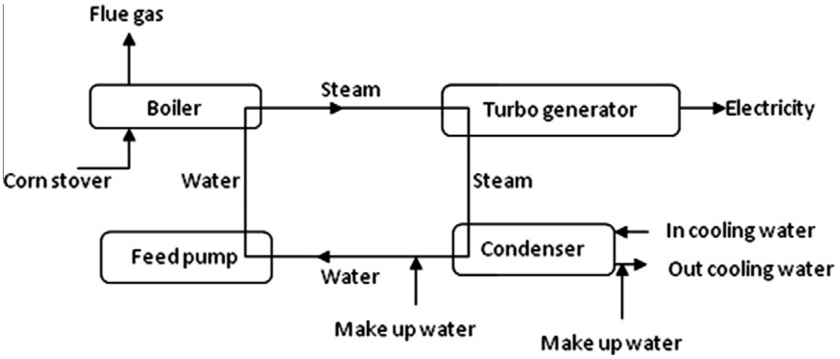

Fig. 5. Power generation using corn stover as feed stock [derived from Wiltsee (2000)].

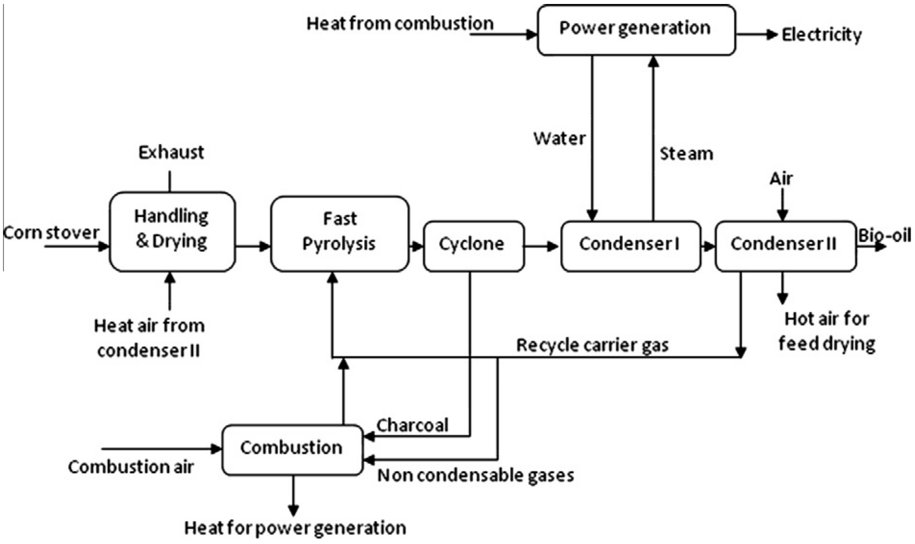

Fig. 6. Fast pyrolysis of biomass [derived from Ringer et al. (2006)].

Table 6
Product yields and make-up water requirements related to fast pyrolysis of corn stover, wheat straw and switchgrass.

Pyrolysis products	Wood[a,f] (% by wt)	Corn stover[b,f] (% by wt)	Switchgrass[c,f] (% by wt)	Wheat straw[d,f] (% by wt)
Product yields				
Gas	13.1	13.2	12.0	12.0
Char	16.2	11.4	15.6	15.6
Water	10.8	6.7	6.0	6.0
Bio-oil	59.9	54.9	54.0	54.0
Purpose	Make-up water (liter per kg of bio-oil)			
	Wood[a]	Corn stover[e]	Wheat straw[e]	Switchgrass[e]
Make-up water requirement				
Bio-oil cooling	0.01	0.01	0.01	0.01
Bio-oil vapor cooling	0.05	0.05	0.05	0.05
Steam condensing	0.50	0.70	0.77	1.02
Steam system	0.03	0.04	0.04	0.05
Ash quenching	0.02	0.18	0.24	0.13
Total	0.61	0.98	1.11	1.27

[a] Source: Ringer et al. (2006).
[b] Source: Agblevor et al. (1996).
[c] Source: Agblevor et al. (1996), Dynamotive Energy Systems (2007).
[d] Derived based on Dynamotive Energy Systems (2007).
[e] Derived on the basis of Ringer et al. (2006) study by performing heat and mass balance.
[f] The moisture content of 'as received' wood, corn stover, wheat straw and switchgrass are 50%, 15%, 15% and 15%, respectively. These feedstocks are dried to 7% moisture before it is introduced in pyrolysis process. Hence the yield of bio-oil is based on feedstock moisture content of 7%.

independent of fuel being fired in boiler, total water requirement is 2.70 l per kWh of electricity produced.

3.2.5. Direct and indirect water requirements for conversion of wheat straw to bio-oil through fast pyrolysis

Similar to corn stover, power and heat integrated fast pyrolysis system is considered for wheat straw. Final products of this process are bio-oil and electricity as shown in Fig. 6. The energy and mass balance of fast pyrolysis mainly depends on bio-oil, charcoal and non-condensable gases yield which is different for different feedstocks. Similar to corn stover, NREL's fast pyrolysis process model was considered. Wheat straw is dried to 7% (Kerstetter and Lyons, 2001) before feeding it to pyrolysis chamber. Using mass and energy balance for the process, 1.48 kg dry wheat straw produces 1 kg of bio-oil containing 20.0% moisture. Based on the LHV, moisture content and grinding energy requirement for size reduction (as given in Table 2), fast pyrolysis of wheat straw produces 0.16 kWh of electricity in addition to 1 kg of bio-oil.

During fast pyrolysis of wheat straw, water is used for steam condensation, vapor condensation, product cooling, make-up water for steam system and water for ash quenching. Water requirement for bio-oil cooling and bio-oil vapor cooling is same as the corn stover case because produced bio-oil quantity is the same. As a wheat straw-based fast pyrolysis plant produces 0.05 kWh more power than a wood-based plant, the water requirement for the steam condensing system is higher than that of a wood-based plant as shown in Table 6. Similarly, water requirement for ash quenching is higher for wheat straw because of its ash content. Hence, wheat straw-based process requires 1.11 l of make-up water to produce 1 kg of bio-oil.

3.2.6. Direct and indirect water requirements for conversion of wheat straw-based bio-oil to electricity

The conversion process of wheat straw-based bio-oil to electricity is shown in Fig. 5. It is assumed that chemical properties of wheat straw derived bio-oil is same as of corn stover-based bio-oil on the basis of similar chemical properties of wheat straw and corn stover [as reported by Parikh et al. (2007), EERE (2009a) and Larson et al. (2005)]. The boiler heat losses and plant net heat rate were calculated for this case accordingly. The net heat rate of wheat straw derived bio-oil-based plant is 12,351 kJ kWh^{-1}. About 0.66 kg of wheat straw derived bio-oil produces 1 kWh of electricity. The water requirement for this pathway is given in Table 4 and is the same as in any other case of electricity production as water requirement is independent of fuel fired in the boiler.

3.3. Switchgrass based bioenergy conversion pathways

3.3.1. Direct and indirect water requirements for switchgrass production

Table 7 gives the yield of switchgrass and the water required, as reported in literature. Based on data in Table 2, the direct water requirement in the production stage is 863.10 l per kg of switchgrass. The nitrogen requirement is a major contributing factor for the switchgrass yield and these values as reported in literature are shown in Table 7. The average requirement of nitrogen is 118 kg ha^{-1}. It was assumed that phosphate and potassium fertilizers do not affect the yield of switchgrass (McLaughlin and Kszos, 2005), these are applied only when the P and K levels in the soil fall below 10 and 90 ppm, respectively (Blade, 2008). The average amount of diesel consumed for field operation is 100 l ha^{-1} based on an earlier study (Pimentel and Patzek, 2005). Thus, the total indirect water requirement in agricultural stage is 0.03 l per kg of switchgrass (Sheehan et al., 1998; King and Webber, 2008).

3.3.2. Direct and indirect water requirements for conversion of switchgrass to ethanol

Due to the compositional differences of switchgrass compared to corn stover (Lee et al., 2007; Ringer et al., 2006), conversion of switchgrass to ethanol process requires 3.35 kg of switchgrass per kg of ethanol production using NREL's model described earlier for ethanol production (EERE, 2009b). The lignin component of switchgrass (19.1%), produces approximately 0.07 kWh additional power for 1 kg of ethanol production.

It was assumed that switchgrass goes through all the stages in a similar manner as corn stover with almost similar input requirements (Spatari et al., 2005). The direct water requirement to process unit mass of switchgrass is almost the same as for the corn stover to ethanol process. The only difference is in the water requirement for generating additional electricity generation. Corresponding to 0.07 kWh of extra generation, direct water requirement for power generation goes up from 0.66 to 0.70 l. After adjusting for the extra water requirement, the switchgrass conversion to ethanol needs 7.55 l of water per kg of ethanol directly. As the input requirement for switchgrass process are same as for corn stover process, 0.45 l of water is used indirectly to produce 1 kg of ethanol.

3.3.3. Direct and indirect water requirements for conversion of switchgrass to electricity through direct combustion

On the basis of chemical composition and heating value of switchgrass (derived from Agblevor et al., 1996), using the electricity production model described earlier for other feedstocks, net

Table 7
Average yields of switchgrass with water and nitrogen requirements.

Switchgrass average yield (kg ha^{-1})	Region	Comments on water requirement	Nitrogen requirement (kg ha^{-1})	Source
13,000	VA, USA	Higher yield with higher precipitation observed	84	Fuentes and Taliaferro (2002)
14,600	USA	Mid season irrigation may double switchgrass yields in dry years	120	McLaughlin and Kszos (2005)
10,300	Italy	400 mm rain fall is not sufficient; therefore, irrigation is required for good establishment	66	Sharma et al. (2003)
13,300	Italy	–	100	Monti et al. (2008)
13,400	Texas, USA	Highest yield with growing season (March–August) rainfall of 676 mm was observed	168	Muir et al. (2001)
6700	Texas, USA	855 mm is optimum water requirement	180	Koshi et al. (1982)
10,900	Nevada, USA	1067 mm of irrigation water is normal	112	Davison (2008)
–	USA	More than 510 mm rain fall is required for high yield	185	Blade (2008)

heat rate of switchgrass based power plant is 12,269 kJ kWh^{-1}. Based on this heat rate, switchgrass power plant requires 0.66 kg dry switchgrass to produce 1 kWh of electricity.

It is considered in this study that similar to other feedstock based direct combustion electricity generation, make-up water is supplied to replenish the cooling water system losses, steam and service water system losses. This make-up water requirement is independent of fuel being fired in boiler (Table 5).

3.3.4. Direct and indirect water requirements for conversion of switchgrass to bio-oil through fast pyrolysis

In the fast pyrolysis process, switchgrass is dried to 7% before pyrolysis chamber. In this process, 1.48 kg of dry switchgrass produces 1 kg bio-oil containing 20.0% moisture. The amount of electricity generation along with 1 kg of bio-oil production depends on the product yields of switchgrass. Fast pyrolysis products of switchgrass are shown in Table 6. Based on the lower heating value of switchgrass, ash content and the grinding energy for size reduction of switchgrass to 2 mm (given in Table 2), the switchgrass based pyrolysis plant produces 0.28 kWh electricity along with 1 kg of bio-oil production.

As shown in Table 6, water requirement for bio-oil cooling and its recovery from volatile gas is same as that of wood because of the equal amount of bio-oil production. But the cooling water requirement for steam condensation is higher than that of wood due to 0.12 kWh more electricity generation. Similarly, make-up water requirement to meet steam system losses is higher in case of switchgrass based bio-oil production. Also quenching water requirement is high in case of switchgrass because of its ash content. Hence, the whole process of conversion of switchgrass to bio-oil requires 1.27 l make-up water to produce 1 kg of bio-oil.

3.3.5. Direct and indirect water requirements for conversion of switchgrass based bio-oil to electricity

Similar to earlier cases of corn stover and wheat straw, heat losses from the boiler is calculated for switchgrass derived bio-oil. Based on chemical properties of switchgrass based bio-oil and plant heat rate (as given in Agblevor et al. (1996)), the net heat rate of plant using switchgrass based bio-oil for electricity production is 12,322 kJ kWh^{-1}. Hence 0.64 kg of switchgrass based bio-oil having HHV of 23,900 kJ kg^{-1} is required to produce 1 kWh of electricity. The water requirement is same as in earlier cases of corn stover and wheat straw (Table 4). This is because the cooling water requirement for condenser and auxiliary is same in all the cases.

3.4. Canola seed based bioenergy conversion pathway

3.4.1. Direct and indirect water requirements for production of canola seeds

Crop water requirement has a strong relationship with the yield of canola seed crop as shown in Table 1. Based on the data of Tables 1 and 2, the direct water requirement in the agricultural stage is 1815 l per kg of canola seed. A typical input requirement for a canola crop is shown in Table 3. Based on these inputs the average indirect water requirement is 0.09 l per kg of production of canola seed. Thus, the total water requirement in the production stage of canola seed is 1815.17 l per kg of canola seed produced.

3.4.2. Direct and indirect water requirements for production of canola oil from canola seed

In this study it is considered that mechanical crushing of canola seeds are followed by solvent extraction method as there is less fugitive emission of solvent, i.e. hexane (Rollefson et al., 2004). This method is considered in this study because of its effectiveness and greater oil extraction efficiency. In this method, canola seeds are graded, cleaned and heated to reduce moisture content for better extraction of oil before crushing. In the seed processing stage, seeds are crushed into flakes and canola oil is extracted partially which is further degummed. After crushing, pressed flakes are treated with hexane to dissolve oil and further oil is separated from hexane by applying heat to solution. Finally, in the degumming stage, oil is washed with water to remove phosphatide content of crude canola oil. This process is described in earlier studies (Sheehan et al., 1998; Rollefson et al., 2004; Canada Canola Council, 2006) and is the basis of this study.

In this process, direct water is used only to separate the gum from the oil and then most of it is recycled. As a result of this set up, make-up water requirement is minimal. The total water used for production of 1 kg of canola oil is 0.01 l (Sheehan et al., 1998). Major inputs of this process are shown in Table 5. About 1.76 l of water is required for 1 kWh of electricity production (King and Webber, 2008). Natural gas is used to supply heat for different stages of the process. The water requirement corresponding to natural gas production is zero (King and Webber, 2008). Hexane is used as the solvent for the process and water requirement corresponding to its production is zero (Sheehan et al., 1998). Hence, the calculated value for the total indirect water requirement of the crushing process is 0.24 l per kg of canola oil using 2.44 kg of canola seed.

3.4.3. Direct and indirect water requirements for production of biodiesel from canola oil

In this study, it is considered that the fatty acid of canola oil is removed by treating it with caustic soda and water. The reaction between refined canola oil and methanol takes place in the presence of a catalyst (sodium methoxide) to produce biodiesel and glycerin. This process is based on detailed description given in Sheehan et al. (1998).

In the biodiesel production process considered in this study, water is used directly in the crude canola oil refining and methyl ester purification stages. In the canola oil refining stage, soaps are formed by a reaction between fatty acid and caustic soda; these are removed by washing oil with water. In the methyl ester purification stage, water is used to separate biodiesel from glycerin and unreacted methanol. Thus, the total water used in the above two stages is 0.29 l for 1 kg production of biodiesel (Sheehan et al., 1998). In this evaluation it is assumed that the water and other input requirements for the production of biodiesel from canola is almost the same as for the soybean to biodiesel process because of the similar chemical compositions of the canola and soybean oils (Przybylski, 2008).

The major inputs required to produce of 1 kg of biodiesel are given in Table 5. The indirect water requirements corresponding to chemicals and electricity used for the process are calculated on the basis of the life cycle water requirement for each input. Hence, the total indirect water requirement of the trans-esterification process is 0.32 l per kg of biodiesel produced using 1.04 kg of canola oil.

3.5. Comparison of total water requirement for different biomass conversion pathways

The water requirement factors for different biomass conversion pathways are shown in Table 4. Among all the bioenergy conversion pathways considered, corn stover to ethanol and wheat straw to ethanol pathways are the most water efficient options based on the calculated values in this study and consume only 0.3 l of water per MJ of ethanol as shown in Table 4. The main reason is that both these biomass feedstocks are residues of food crops and water required in production stage of crop is allocated to the food crop, not residue.

Based on the results, biopower pathways using these agricultural residues are also water efficient options but water requirement of these pathways is little higher than those for ethanol production pathways. The reason is the large amount of cooling water requirement in the biopower pathways (Gerdes and Nichols, 2008) compared to bioethanol pathways.

The switchgrass based pathways consume almost the same amount of water in the conversion process as other lignocellulosic biomass based pathway, but the total water requirement is higher. High water requirement in crop production stage (Fuentes and Taliaferro, 2002; McLaughlin and Kszos, 2005; Muir et al., 2001; Koshi et al., 1982; Davison, 2008; Blade, 2008) makes this pathway water intensive.

Apart from agriculture residue based pathways, the most efficient biofuel pathway is the corn to ethanol pathway for which the water requirement is 77.1 l MJ^{-1} as calculated in this study. Though the wheat to ethanol pathway consumes almost the same amount of water in the conversion stage, this pathway is more water intensive than the corn to ethanol pathway. The first reason for high water requirement in the wheat to ethanol conversion pathway is high dry feedstock consumption for conversion process. As calculated in this study, the corn ethanol process consumes 2.72 kg of dry corn in producing one kg of ethanol while wheat to ethanol pathway consumes 3.08 kg of dry wheat per kg of ethanol production. As water requirement in agriculture stage depends on these quantities, more water is required for wheat. This result shows that the yield of conversion process plays an important role in determining the water requirement of a biofuel pathway. The second reason for high water requirement in wheat to ethanol conversion pathway is water use efficiency of crops. While corn consumes an average of 754 l of water in production for 1 kg of dry corn, wheat consumes an average of 889 l of water in producing of 1 kg of dry wheat (OMAFRA, 2009b; McKenzie and Dunn, 1997; Howell et al., 1998; Payero et al., 2008; Claim, 2009; Shock et al., 2005; Raddatz and Shaykewich, 1998). This result shows that water use efficiency is also dominant factor in determining water requirement for any bioenergy pathway.

Although the conversion stage water requirements are the lowest for canola seed to biodiesel pathway, its total water requirement, i.e. 124 l MJ^{-1} as calculated in this study is almost equal to that of switchgrass to ethanol pathway. The reason for this is canola seed's poor water use efficiency in production stage (i.e. 1815 l of water required to produce 1 kg of canola seed) (McKenzie and Dunn, 1997; Canada Canola Council, 2008). The favorable factor for this pathway is higher LHV of biodiesel which compensates for its poor water use efficiency; without it this pathway would have been worse than the switchgrass to ethanol pathway.

If direct combustion and fast pyrolysis pathways for same biomass feedstocks are compared, water requirement for conversion stage of fast pyrolysis pathway is higher than that of direct combustion pathway. In fast pyrolysis based pathways, water is required for bio-oil vapor scrubbing, bio-oil cooling and ash cooling in addition to water requirement in combustion stage (Ringer et al., 2006). These additional cooling requirements in pyrolysis stage also increases heat loss of this pathway. This is the reason, why more biomass feedstock is required for power generation through pyrolysis. Water requirement of conversion stage was evaluated for specific thermo-chemical conversion pathways. These water requirements may differ depending upon processes of the pathways. For example, bio-oil pathway considers that charcoal is utilized to produce electricity in fast pyrolysis process, in another scenario charcoal may be sold for better commercial viability of the plant. In this case, dry biomass requirement for electricity production will be higher and hence also the water requirement. Similarly in any other model, bio-oil can also be utilized in a gas turbine or a diesel generator to produce electricity instead of its direct combustion in a boiler to produce steam and power (Dynamotive Energy Systems, 2007). If gas turbine or diesel generator is used for bio-oil conversion to electricity, water requirement will be minimal. This will make electricity production from bio-oil pathways more water efficient than direct combustion pathways based on crop residues as there would not be any cooling water requirement for steam condensation. The efficiency of gas turbine or diesel generator will decide the dry biomass feedstock requirement and ultimately the water efficiency.

This study has also evaluated the water requirement associated with the life cycle of major inputs in both stages: the agricultural and conversion stages as shown in Table 3. These requirements are based on typical requirements of fuels and other inputs which may vary substantially in type and quantity depending on location, production technology and process model. As the water requirement associated with these inputs is not significant compared to that of the agricultural stage water requirement, the total water requirement is not affected significantly.

The study considered both grains and their residues for production of fuels and electricity. The water requirement factors evaluated in this study represent the total water requirement for biofuel pathways over the life cycle. These factors also include the direct water requirement for crop production. This direct water requirement is met by precipitation, and/or surface or ground water (through irrigation) and depends on the location. These factors are useful for only comparing the biofuel pathways. These factors do not represent the consumptive use of water for biofuel. The actual consumption can be estimated by subtracting the water available from precipitation and soil moisture from these water requirement factors to grow crop in a specific region.

The yields of different crops assumed in this study are based on an average blended value from the published literature but these are still limited. If more detailed database on the water requirement stage across the North America is developed, the results of this study would be more robust.

In this study agricultural stage water requirements are only allocated to grains. When water requirement to grow crops is allocated on the basis of available corn stover to grain dry weight ratio [1:1 used in this study (Perlack and Turhollow, 2003)] or wheat straw to grain dry weight ratio [1.1:1 used in this study (Arifa et al., 2010; Sokhansanj et al., 2006)], specific water requirement of pathways based on these residues change. The changed water requirements for different biomass conversion pathways are shown in Table 8. Water requirement for corn stover-based pathways would consume more water than switchgrass based pathways. Water consumption for wheat straw-based pathways are still lower than switchgrass based pathways even after allocation of water to wheat straw for agricultural stage.

Dried distillers grain with soluble (DDGS) is a major byproduct of corn to ethanol and wheat to ethanol pathways. In case of corn to ethanol pathways, 100 kg of corn produces 28 kg ethanol along with 32 kg DDGS (Shurshon and Noll, 2005). If water is allocated on the basis of weight ratio, water requirement for ethanol production decreased to 36.3 l per MJ of ethanol. In case of wheat to ethanol process, 100 kg of wheat produces 29 kg ethanol along with 33 kg DDGS (Circle Biodiesel and Ethanol Corporation, 2010). If water is allocated on the basis of weight ratio, water requirement for ethanol production from wheat decreases to 50.7 l per MJ of ethanol.

Lignocellulosic biomass based ethanol production process has electricity as the main byproduct. This electricity is produced mostly by combustion of lignin (Aden et al., 2002). If water requirement during production of electricity from lignin is shared based on the percentage of lignin content in biomass feedstock, water requirement of switchgrass based pathway decreases to 103.4 l per MJ. The water allocation for corn stover and wheat straw will

Table 8
Water requirement factor for bioenergy conversion pathways based upon food crops, if water requirement of agriculture stage is allocated to crop residues.

Biofuel pathways	Dry biomass (kg per kg of biofuel)	Water requirement ($l\ kg^{-1}$)[a]				Product heating value (MJ per kg)[d]	Water (l per MJ)
		Agriculture stage[b]		Conversion stage			
		Direct	Indirect	Direct	Indirect		
Corn – ethanol[e]	2.72	1027.16	0.10	4.53	0.91	26.7[c]	38.7
Wheat – ethanol[f]	3.08	1370.40	0.10	5.13	1.03	26.7[c]	51.6
Corn stover – ethanol[e]	3.38	1272.8	0.12	7.56	0.44	26.7[c]	47.8
Wheat straw – ethanol[f]	3.32	1473.6	0.10	7.43	0.43	26.7[c]	55.5
Corn stover – electricity[e]	0.68[g]	256.6	0.02	2.70	0.0	3.6	72.0
Corn stover – bio-oil – electricity[e]	0.86[g]	323.5	0.03	3.01	0.0	3.6	90.7
Wheat straw – electricity[f]	0.71[g]	315.5	0.02	2.70	0.0	3.6	88.4
Wheat straw – bio-oil – electricity[f]	0.88[g]	462.6	0.03	3.10	0.0	3.6	129.4

[a] Liters per kWh for electricity pathways or liters per kg of ethanol for ethanol production pathways.
[b] Water requirement is corresponding to dry biomass requirement for production of 1 kg biofuel or 1 kWh electricity.
[c] Source: Shapouri et al. (2002).
[d] MJ per kWh for electricity pathways.
[e] Agriculture stage water requirement is allocated to corn and corn stover on the 1:1 corn stover to grain dry weight ratio.
[f] Agriculture stage water requirement is allocated to wheat and wheat straw on the 1.1:1 wheat straw to grain dry weight ratio.
[g] Dry biomass (kg per kWh of electricity).

not change significantly as water requirement without this allocation is only 0.3 l per MJ of ethanol. For biopower pathway, electricity is the only product; therefore, no allocation is required.

4. Conclusions

The life cycle water requirements of twelve biomass conversion pathways were evaluated. Corn stover and wheat straw-based ethanol production pathways are most water efficient followed by biopower production pathways. In this study water consumption is attributed to grains only and not to the agriculture residues. Switchgrass based conversion pathways are less water efficient as compared to pathways based on corn stover and wheat straw. Biodiesel production pathway from canola seed consumes more water per MJ as compared to grain based ethanol pathways. Production of liquid fuels and electricity from corn stover and wheat straw should be considered for future as these are more water efficient.

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