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Comparison of the energy and environmental performances of nine biomass/coal co-firing pathways

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HIGHLIGHTS

- ▶ Life cycle assessment was carried out for co-firing of densified lignocellulosic biomass with coal to produce power.
- ▶ Nine different co-firing-based power production pathways were studied.
- ▶ Life cycle net energy ratio and emission factors were developed for these pathways.

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ABSTRACT

Life cycle energy and environmental performances of nine different biomass/coal co-firing pathways to power generation were compared. Agricultural residue (AR), forest residue (FR), and whole trees (WT) as feedstock were analyzed for direct (DC) and parallel co-firing (PC) in various forms (e.g., chip, bale and pellet). Biomass co-firing rate lies in the range of 7.53–20.45% (energy basis; rest of the energy comes from coal) for the co-firing pathways, depending on type of feedstock and densification. Net energy ratios (NER) for FR-, WT-, and AR-based co-firing pathways were 0.39–0.42, 0.39–0.41, and 0.37–0.38, greenhouse gas (GHG) emissions were 957–1004, 967–1014, and 1065–1083 kg CO_{2eq}/MWh, acid rain precursor (ARP) emissions were 5.16–5.39, 5.18–5.41, and 5.77–5.93 kg SO_{2eq}/MWh, and ground level ozone precursor (GOP) emissions were 1.79–1.89, 1.82–1.93, and 1.88–1.91 kg (NO_x + VOC)/MWh, respectively. Biomass/coal co-firing life cycle results evaluated in this study are relevant for any jurisdiction around the world.

1. Introduction

Life cycle assessment of biomass co-firing is critical for determining the full environmental impacts of this means of energy generation. Previous studies have focused on global warming impact of greenhouse gas (GHG) emissions (CO_{2eq}) (Corti and Lombardi, 2004; Hartmann and Kaltschmitt, 1999); however, environmental impacts including acidification (SO_{2eq}: due to acid rain precursors) and smog formation [(NO_x + VOC): due to ground level ozone precursors] from biomass-based power are also significant concerns (Rafaschieri et al., 1999). Also the focus of earlier LCA studies has been on direct combustion or gasification of biomass (Carpentieri et al., 2005; Corti and Lombardi, 2004; Reichling and Kulacki, 2011) and not on biomass co-firing. The present study was aimed at addressing these issues, using data for the Province of Alberta (a western Province in Canada).

GHG emission is a growing concern in Alberta. With only 10.5% of Canada's population, this Province generates 33.2% (245.7 million tonnes) of Canada's total GHG emission (Environment Canada, 2009). Almost 40% of these emissions come from fossil fuel production and their subsequent use for electricity and heat generation. Coal (81.2%) and natural gas (11.7%) are the major contributors to electricity generation. Since these fossil fuels have a high carbon footprint, GHG emissions from Alberta's power generation sector are one of the major contributors to total GHG missions from the Province. Therefore, in response to the climate change issue, Alberta has planned to mitigate 37 million tonnes of GHG by 2050 by greening its energy sector with renewable resources (Kabir et al., 2012).

A significant part of this mitigation can be achieved by replacing fossil fuels with sustainable biomass feedstock including agricultural residue (AR), forest residue (FR), and whole tree biomass (WT). In case of WT for energy use, it is assumed that sustainable forest management practices will be employed as is currently done by forest industry when harvesting forest for pulp and lumber. The economics of biomass-based power generation in, but potential environmental impacts have not been fully assessed. This study

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employs the life cycle assessment (LCA) methodology to illustrate the environmental implications of green electricity production from processed biomass through co-firing with coal.

Co-firing is a quick option for integrating biomass to the power generation sector since it can be implemented with only minor retrofitting of existing coal-fired power plants (Sebastián et al., 2007). According to the specified gas emitters' regulation of Alberta, any facility that emits more than 100,000 tonnes of GHG (CO_{2eq}) per year has to pay $15 tax for each tonne of excess CO_{2eq} emission (Alberta Environment, 2007). A facility that reduces its emission intensity to below this threshold, may trade its emission credits with other facilities in Alberta (Alberta Environment, 2007). Like CO_{2eq}, SO_{2eq} credits can be traded as well (Mann and Spath, 2001). Co-firing can also offer a near-term solution to reduce NO_x emission and solid waste handling (Mann and Spath, 2001). Most importantly, consumers may choose the power plant companies that include renewable fuel in their portfolio.

Conventionally, agricultural (AR) and forest biomass (FR, WT) resources are utilized for power production in the form of bale and chips, respectively; however, low bulk and energy densities are the main obstacles for utilizing biomass feedstock in these forms and biomass densification should be implemented to save transport and handling costs and to improve the efficiency of the final conversion stage (Uslu et al., 2008). One of the main technologies for biomass densification is pelletization. In addition to improving the biomass volumetric density, pelletization makes storing and shipping easier and improves the conversion efficiency of biomass fuels (Uslu et al., 2008). Pelletization also minimizes dust formation and enables the free flow of biomass fuels, which make loading and unloading operations easier. Since pelletization involves energy- and emission-intensive biomass pretreatments including drying, grinding, and pressing, the benefits of using AR, FR, and WT pellets for producing power must be evaluated from a life cycle point of view.

Another pathway of biomass densification is combined torrefaction and pelletization (TOP). TOP pellets have some added advantages over conventional biomass-based pellets including improved durability, grindability, hydrophobicity, and coal-like combustion (Bergman, 2005). Energy and environmental performances of TOP-based power generation has not yet been analyzed.

In addition to environmental impacts, energy output-input ratios i.e. net energy ratios (NER) are also crucial in assessing renewable energy systems. NER measures the total amount of energy produced by a system corresponding to every unit of energy consumed (Kabir and Kumar, 2011). Evaluating the life cycle NER for a renewable system helps in understanding its effectiveness compared to that of other renewable and fossil-fuel-based systems.

1.1. Biomass feedstocks and densification technologies

In Alberta, more than 90% of the logging operations include cutting of the tree in the stand followed by skidding the tree to the roadside and delimbing of tops and branches. Though the stems are used for pulp and lumber in different plants, the delimbed tops and branches are piled up and burnt to prevent forest fire. These residues (limbs, tops and branches) are the forest harvest residues (FR). Wheat and barley straw are the main sources of agricultural residue (AR) feedstock. Alberta produces about 3.29 million dry tonnes of forest residues and about 6.8, 6.3, and 0.72 million dry tonnes of wheat, barley, and oat straw per year, respectively (Kabir and Kumar, 2011). Since the demand for paper is decreasing, there is prospect for the forest industry to be integrated with the fossil-fuel-based power industry.

The primary densification processes for AR feedstock are baling and chopping and for FR and WT feedstock, it is chipping. These primary densification processes can improve the bulk density of the biomass feedstocks by 1.5–2 times (Sultana and Kumar, 2011a; Sultana et al., 2010); however, further densification is desired, especially for long transportation chains. Pelletization involves compressing dried and ground biomass and extruding it under high pressure to produce cylindrical pieces (bio-pellets). Through pelletization, bulk density can be increased up to 4–10 times (Sultana et al., 2010). Since densified biomass is tenacious and fibrous in nature with a large particle size, they are difficult to grind in a coal-fired power plant using existing coal crusher. In contrast, existing coal crusher can easily disintegrate the bio-pellet since it is composed of ground particles. Bio-pellets absorb moisture, swell and disintegrate resulting in increased dust formation and mechanical strength against crushing. Biological degradation can also occur. Hence, bio-pellets are required to be stored in a dry place, which is hazardous due to the potential for heat generation in the pellet piles. Therefore, there is need to impart hydrophobic property to bio-pellets. The process of combined torrefaction and pelletization imparts this property. During this process, biomass slightly decomposes, retaining 70–80% of the original mass as solid products and releasing the rest as torrefied gas. Note that, the solid and volatile fractions contain almost 90% and 10% of the initial biomass energy content, respectively (Bergman, 2005). Hence, TOP demonstrates a higher energy density compared to that of conventional bio-pellets and primary densified biomass.

2. Methodology

The power generation pathways considered in this study are summarized in Fig. 1. Parallel co-firing pathways are analyzed as a sensitivity case, and the base case of this study concerns direct co-firing pathways. Each pathway was analyzed based on the economic optimum size of the respective biomass densification process. The economically optimum size for an AR-based pellet plant in Alberta is 150,000 dry tonnes/year (Sultana et al., 2010). In contrast, an economically optimum plant size for FR- and WT-based pellet plant is 290,000 dry tonnes/year (Sultana and Kumar, 2011b). The economically optimum size of torrefied pellet plant of any feedstock was assumed to be the same as its corresponding bio-pellet plant. To ensure the comparability of different densification processes, it was assumed that, biomass in the form of chips (FR and WT) and bale (AR) would be supplied to the coal-fired power plant at a rate of 290,000 and 150,000 dry tonnes/year, respectively. Each co-firing pathway was investigated for a hypothetical 450-MW coal-fired power plant that operates 6000 h/year (Singh et al., 2000; Sebastián et al., 2007).

This life cycle study was performed based on the system boundary presented in Fig. 1. The energy and environmental data for coal production, processing, and combustion in Alberta were taken from existing literature (McCulloch et al., 2000), and were not analyzed in the present study. Fig. 1 shows only the processes investigated in the present study. The life cycle of each power generation pathway was divided into the unit processes (UP), biomass production (UP 1), biomass transportation (UP 2), preprocessing (UP 3), transportation to end-user (UP 4), and power production (UP 5). Embodied energy and emission factors for all the material, equipment, and energy flows associated with the system were determined from their respective life cycles. Energy and environmental performance results of a power generation pathway were normalized corresponding to a functional unit (FU). Results were normalized to FU, but inventory data were not normalized. FU is essential for any LCA study since it is considered as a yardstick in comparing the LCA results (ISO 14040, 2006). A FU of 1 MWh electricity production through co-firing of densified biomass was chosen.

NER for the power generation pathways were calculated based on Eq. (1)

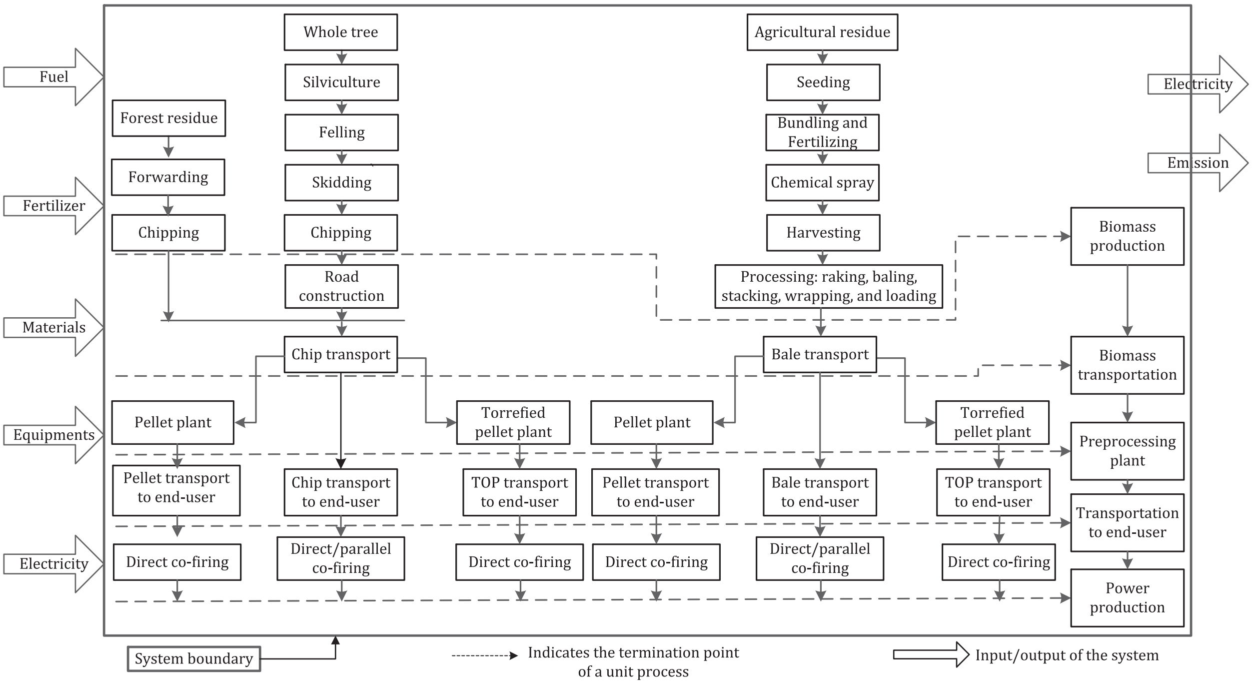

Fig. 1. System boundary of the study.

$$NER = \Sigma E_{out}/\Sigma E_{in} \qquad (1)$$

where ΣE_{in} = total non-renewable primary energy input (MJ$_t$) to the life cycle of a power generation pathway corresponding to the FU, ΣE_{out} = energy (MJ$_e$) available from the FU. An NER value of less than one implies that energy input to the bio-energy pathway is higher than that gained from biomass combustion and vice versa. Net GHG, ARP, and GOP emissions for each power generation pathway were determined based on Eq. (2)

$$Net\ emission = \Sigma \varepsilon_{out} \qquad (2)$$

where $\Sigma \varepsilon_{out}$ = life cycle GHG/ARP/GOP emissions corresponding to the FU. A detailed description of the methodology for evaluating the life cycle NER and environmental emissions has been provided previously (Kabir and Kumar, 2011). It was assumed that coal-fired power plants in Alberta operate with an efficiency of 35% (Kabir and Kumar, 2011). Environmental stressors considered in this study were greenhouse gases (GHG: CO_2, CO, CH_4, and N_2O), acid rain precursors (ARP: SO_2 and NO_x), and ground level ozone precursors (GOP: NO_x and VOC). Weighting factors for the different emission compounds were adopted from Kabir and Kumar (2011). Since biomass absorbs CO_2 during growth, biomass combustion during co-firing was considered as CO_2 neutral; however, other GHG, ARP, and GOP emissions during biomass combustion were included. Energy and environmental performances of each biomass co-firing pathway were compared with those of coal-fired power plant to understand its extent of benefits. The impacts of grid connection, power transmission, and distribution were considered beyond the scope of the current study.

3. Inventory data and assumptions

3.1. Biomass production (UP 1)

FR produced during logging operations is forwarded to the roadside and chipped for transportation to the biomass preprocessing plant. FR are collected and burnt in Alberta and other locations in North America to prevent forest fires. Therefore, irrespective of FR's final use, ash is the only component that goes back to the soil and for this reason the issue of decreasing carbon flux due to the removal of FR from the forest-bed was not considered. Biomass production (UP 1) includes the impacts of FR forwarding and chipping. Therefore, impacts of manufacturing, operation, recycling, and disposal of forwarder and chipper were included in UP 1. Since FR is generated during logging operations, impacts from silviculture were disregarded in UP 1 for this feedstock.

Operations involved with UP 1 of WT feedstock are felling, skidding, and chipping. Hence, life cycle impacts from feller, skidder, and chipper were included. Unlike for FR, impacts of silviculture (fertilizer and pesticide production and spraying) were included in UP 1 for WT feedstock. Nutrients (N, P, and K) removed from the soil due to harvesting of WT were assumed to be replaced by fertilizers; however, impacts from Ca replacement were disregarded since this element is available in abundance in the boreal forest of Alberta (Kumar et al., 2003). A sensitivity case was developed for WT power generation pathways, which excludes silviculture from the system boundary.

The base case of this study considered that no economic value was associated with AR i.e. AR is a by-product. Therefore, production of AR includes straw processing operations like – raking, baling, stacking, wrapping, and loading. AR is transported to the biomass preprocessing plant in the form of bale. A sensitivity case was developed for AR-based power generation pathways, which includes the farming and harvesting operations (cultivation, fertilization, chemical application, and harvesting) within the system boundary. K-fertilizer is not necessary in Alberta's soil to produce barley and wheat (Kabir and Kumar, 2011); hence, its impacts were disregarded. For the sensitivity case, straw to grain mass ratio was considered as 1.1:1 (Kumar et al., 2003). Accordingly, a fraction of energy and environmental impacts from common operations of straw and grain (from cultivation to harvesting) was allocated to straw in the sensitivity case. General inventory data for UP 1 for all the feedstocks (FR, WT, and AR) are provided in Table 1. The equipment inventory data for UP 1 for the feedstocks were adopted from a previous study (Kabir and Kumar, 2011). The life cycle

Table 1
Inventory data for biomass production and transportation.

Properties		AR	FR	WT	Comments/sources
Moisture content (wt.%)		14	45	50	Values presented here refer to the moisture content of as-received biomass feedstock (Kabir and Kumar, 2011; Sultana and Kumar, 2011a)
Higher heating value (GJ/dry tonne)		17.6	20	20	HHV of FR- and WT-based TOP is 24 GJ/dry tonne. In contrast, AR-based TOP has HHV of 21.1 GJ/dry tonne (Pastre, 2002; Kumar et al., 2003; Bergman, 2005)
Ash content (wt.%)		4	3	1	Kabir and Kumar (2011)
Biomass yield (dry tonne/ha)		0.33	0.25	84	The net yield for AR is based on a straw to grain ratio of 1.1:1 and it is determined considering the factors including harvest machine efficiency, straw retained for soil conservation, and straw removed for animal feeding and bedding (Sultana et al., 2010; Kabir and Kumar, 2011). Maintaining soil carbon and nitrogen is crucial for sustainable removal of AR feedstock. It was found that the retention of 0.75–1 tonne of AR per hectare is adequate for soil conservation and maintaining soil carbon and nitrogen (Prairie Practitioners Group, 2008; Stumborg et al., 1996). This study considers the AR retention to be 0.75 t/ha. The net yield for the FR is determined from the net yield of WT biomass based on 100-year rotation of forest growth in Alberta (Kumar et al., 2003)
Plant output (dry tonnes/year)		150,000	290,000	290,000	Sultana et al. (2010) and Sultana and Kumar (2011b)
Plant life (year)		20	20	20	
Operating factor					
	Year 1	0.7	0.7	0.7	These are conventional operating factors for biomass based plants (Kumar et al., 2003)
	Year 2	0.8	0.8	0.8	
	Year 3 onwards	0.85	0.85	0.85	
Material loss (%)		5	5	5	For the combined torrefaction and pelletization plants, material loss (25%) is higher due to mass loss during the process (Bergman, 2005)
Average hauling distance (km)					The average hauling distances for AR-based combined torrefaction and pelletization plant are 42, 45, and 47 km, respectively, for Year 1, Year 2, and Year 3 onwards. In contrast, for FR-based plant these are, respectively, 48, 52, and 53 km. On the other hand, for WT-based plant these are 12.9, 13, and 13 km, respectively
	Year 1	39	44	12	
	Year 2	41	47	12	
	Year 3 onwards	43	49	12	
Biomass collection area (ha)		7,950,595	20,709,775	60,897	The biomass collection area for AR-, FR-, and WT-based combined torrefaction and pelletization plant are 9,465,170, 18,300,188, and 72,504 ha, respectively

energy and emission factors for different raw materials, fuels, electricity, fertilizer, and pesticide input to the system boundary of the study are given in Table 2.

3.2. Biomass transportation (UP 2)

The collection area for AR and forest (FR, WT) biomass was assumed to be circular in shape. Hauling distance for biomass collection is greatly influenced by tortuosity and geometric factors. The tortuosity factor can be defined as the ratio of actual distance travelled to the line of sight distance (Overend, 1982) whereas, On the other hand, geometric factor is a measure to determine the extent of biomass share across the harvesting area. A biomass collection area of circular geometry completely filled with biomass fuel has a geometric factor of one (Overend, 1982). Since transportation does not generally follow straight lines, a tortuosity factor of 1.27 was taken into account (Overend, 1982; Sultana et al., 2010; Kabir and Kumar, 2011). The preprocessing plant was assumed to be located at the center of the circle (Kabir and Kumar, 2011). Inventory data for biomass transportation are presented in Table 1.

It was assumed that FR-chips and AR-bale would be transported by truck to the biomass preprocessing plant using the existing road

Table 2
Life cycle energy and emission factors for materials, fuels, electricity, fertilizer, and pesticide.[a]

Raw materials, fuels, and electricity					Comments/sources
Properties	Recycled-steel	Electricity	Diesel	Natural gas	
HHV (MJ/kg)	–	–	46.03	49.1	Life cycle energy and emission factors of steel, aluminum, concrete, diesel, and natural gas are directly taken from Kabir and Kumar (2011), hence are not presented here. Factors for recycled-steel are normalized for per tonne (t) of material (Kabir et al., 2012). HHV and density of diesel and electricity are taken from Environment Canada (2009). Energy and emission impacts of electricity are corresponding to 1 MWh of grid electricity generation in Alberta (Zhang et al., 2010; Sultana and Kumar, 2011a; Spath et al., 1999; Kabir et al., 2012)
Density (kg/m^3)	–	–	832	0.78	
Energy impact					
GJ/t	9.7	–	–	–	
GJ/MWh	–	2.86			
Pollutants					
kg CO_{2eq}/t	1819	912	–	–	
kg SO_{2eq}/t	15.4	4.2	–	–	
kg (NO_x + VOC)/t	7.02	1.6	–	–	
Fertilizers and pesticide					
Pollutants	N	P	K	Pesticide	
kg CO_{2eq}/kg	3.27	1.34	0.64	24.5	Like other energy and emission factors, these are also determined based on the life cycle of fertilizer/pesticide production (Kabir and Kumar, 2011; Kim and Dale, 2004)
kg SO_{2eq}/kg	0.007	0.001	0.001	0.036	
kg (NO_x + VOC)/kg	0.011	0.002	0.002	0.056	
Energy impact					
GJ/kg	0.05	0.01	0.004	0.12	

[a] N = nitrogen, P = phosphorus, and K = potassium.

network (Kumar et al., 2003; Kabir and Kumar, 2011). Hence, impacts of road construction are disregarded for these two feedstocks under biomass transportation (UP 2), but, impacts of truck manufacturing, operation (loaded/empty), recycling, and disposal were included. Unlike for FR and AR, impacts of primary road construction are included for UP 2 of WT-based power generation pathways. Primary road network is used to transport the WT-chip to the biomass preprocessing plant. Primary road construction required for the whole tree torrefied pellet (WT-TOP) based power generation pathway was estimated to be 350 km and for WT-pellet (WT-P)- and chip (WT-Ch)-based power generation pathways it was 290 km (Kabir and Kumar, 2011). The disparity in the requirement for road construction was predominantly because of the mass loss in the process of combined torrefaction and pelletization. Energy and emission factors of road construction were adopted from Kabir and Kumar (2011). Impacts from secondary road construction were disregarded due to lack of credible data and their negligible lengths compared to those of the primary road network (Kabir and Kumar, 2011). A sensitivity case was developed for WT-based power generation pathways excluding the road construction impacts from the system boundary. Inventory data for the trucks used in transporting different forms of biomass feedstocks are given in Table 3. Transportation of biomass feedstock was constrained by either payload or volumetric capacity of the truck. Whenever a truck carries a load lower than the payload, actual fuel consumption was calculated using Eq. (3) (Sultana and Kumar, 2011a)

$$F_a = F_e + \{(F_f - F_e) \times (L_a/L_p)\} \qquad (3)$$

where F_a = actual fuel consumption by truck while transporting load L_a (L/km), F_e = fuel consumption by the empty truck (L/km), F_f = fuel consumption by a fully loaded truck (L/km), L_a = actual load being carried by the truck (t), and L_p = payload of the truck (t).

3.3. Preprocessing plant (UP 3)

3.3.1. Handling and storage plant

The as-received moisture content of AR, FR, and WT were assumed to be 14, 45, and 50 wt.%, respectively (Sultana and Kumar, 2011a; Kabir and Kumar, 2011). The maximum allowable moisture content for direct co-firing of biomass is 20 wt.% (Sebastián et al., 2007). Hence, feedstock drying is not imperative for power generation pathways that utilize AR-bale. Feedstock preprocessing operations like milling, grinding, etc. are also not required until the AR-bale reaches the power plant. However, FR- and WT-chips are needed to be dried in case of direct co-firing once these feedstocks reach the power plant. Impacts of building the infrastructure (construction, decommissioning, recycling, and disposal) for AR-bale-, FR-chips-, and WT-chips-based handling and storage plants were assumed to be 5% of those of their respective preprocessing plants (discussed in the following sub-sections). Impacts of plant decommissioning were determined based on a previous study (Kabir and Kumar, 2011). The truck used to transport the plant materials for disposal (landfilling), would be similar to the truck used in biomass transportation. Inventory data for the truck are given in Table 3. Impacts of the truck operation for landfilling were evaluated based on the 50-km distance between the plant and landfilling sites. Emissions occurring during landfilling were adopted from Kabir and Kumar (2011). During the decommissioning phase, concrete and aluminum of the plant were considered to be completely landfilled. In contrast, 75% of the plant steel was assumed to be recycled and the rest was landfilled. Inventory data for the raw material, energy, and equipment in-flow to the handling and storage plant (UP 3) of biomass feedstocks are presented in Table SM-1 in Supplementary Material.

3.3.2. Pellet plant

In a pellet plant, biomass feedstocks go through a series of energy-intensive operations including drying, grinding, conditioning, pelleting, cooling, screening, and bagging. FR- and WT-chips have a relatively higher moisture content than AR-bale. To economize the transportation of bio-pellets to the end-user, this study assumed that the moisture level of bio-pellets would be 8 wt.% irrespective of the feedstock. Therefore, a significant amount of energy (natural gas and electricity) is used for drying purpose in a bio-pellet plant. Before pelleting, ground biomass feedstocks must be steam-conditioned to produce durable pellets and minimize dusts. Steam required for the conditioning is produced from natural-gas-fired boiler with an efficiency of 80% (Sultana et al., 2010). Typically, the steam requirement for conditioning is 4% (mass basis) of dry biomass feedstock (Thek and Obernberger, 2004). Total thermal energy requirement for FR-, WT-, and AR-based pellet plant were considered to be 26.9, 33.2, and 2.1 $\mathrm{MW_{th}}$, respectively. Higher thermal energy consumption for the FR- and WT-based plants is driven by the difference in plant size (290,000 and 150,000 dry tonnes pellet/year, respectively, for FR/WT and AR) and the difference in the as-received moisture content (45, 50, and 14 wt.%, respectively, for FR, WT, and AR). This study assumed that all the thermal energy for drying was supplied by burning natural gas.

A pellet plant based on AR-bales, requires 2895 kW including the power requirement for primary grinder, dryer, hammer mill,

Table 3
Inventory data for biomass transportation in different forms.[a,b]

Biomass form	Moisture content, wt.%	Bulk density, kg/m^3	Gross vehicle weight (GVW), t	Truck payload, t	Truck fuel consumption, L/km (empty/full load)	Volumetric capacity of truck, m^3	Weight carried by truck, t	Sources
AR-bale	14	180	38	23	0.24/0.33	70	12.6	Mann and Spath (1997)
AR-pellet	8	600	60	40	0.3/0.48	70	40	Sokhansanj et al. (2010) and Sultana and Kumar (2011a)
AR-TOP	3	800	60	40	0.3/0.48	70	40	Mann and Spath (1997)
FR-chip	45	235	38	23	0.24/0.33	70	16.5	Mann and Spath (1997)
FR-pellet	8	600	60	40	0.3/0.48	70	40	Sokhansanj et al. (2010) and Sultana and Kumar (2011a)
FR-TOP	3	800	60	40	0.3/0.48	70	40	Sokhansanj et al. (2010) and Sultana and Kumar (2011a)
WT-chip	50	250	38	23	0.24/0.33	70	17.5	Mann and Spath (1997)
WT-pellet	8	600	60	40	0.3/0.48	70	40	Sokhansanj et al. (2010) and Sultana and Kumar (2011a)
WT-TOP	3	800	60	40	0.3/0.48	70	40	Sokhansanj et al. (2010); Sultana and Kumar (2011a)

[a] The lifetime of the truck is considered to be 540,715 km. It is assumed that, the truck contains 98% steel on mass basis (Mann and Spath, 2001).

[b] AR = agricultural residue, FR = forest residue, WT = whole tree, and TOP = torrefied pellet.

boiler, pellet mill, cooler, pellet storage, and others (peripheral equipment, lighting, and heating) (Sultana et al., 2010; Campbell, 2007). In contrast, a WT- and FR-based pellet plant consumes 7020 and 6925 kW, respectively (Thek and Obernberger, 2004; Uslu et al., 2008). Energy and environmental impacts of pellet plant construction, decommissioning, recycling, and disposal are also included in this study. Assumptions related to plant decommissioning, recycling, and disposal were stated in Section 3.3.1. Inventory data for the raw materials input to the pellet plant construction corresponding to all feedstocks are provided in Table SM-1 in Supplementary Material. The life cycle energy and emission factors for the raw materials are provided in Table 2.

3.3.3. Torrefied pellet plant

Torrefaction is a mild pyrolysis process performed between 200 and 300 °C at atmospheric pressure in the absence of oxygen (Prins et al., 2006). Torrefaction combined with pelletization improves biomass fuel qualities, and the corresponding inventory data are presented in Table 1. Size reduction of torrefied biomass requires 50–85% less electrical energy than size reduction of fresh biomass (Prins et al., 2006). Torrefied pellet production consists of initial heating, drying, torrefaction, cooling, size reduction, and pelletization. One of the key advantages of this process is that, utility fuel consumption in biomass drying is either eliminated or substantially minimized through the utilization of torrefaction gas (Uslu et al., 2008). The moisture content of torrefied pellets was considered to be 3 wt.%. The torrefied pellet plant fed by AR-bale (150,000 dry tonnes pellet/year) was assumed to 2900 kW. In contrast, plants (290,000 dry tonnes pellet/year) fed by FR and WT feedstocks, respectively, expend 6400 and 6500 kW (Uslu et al., 2008; Thek and Obernberger, 2004; Sultana and Kumar, 2011a). Thermal energy requirements for torrefied pellet plants based on AR, FR, and WT feedstock were considered to be 1.6, 15.3, and 18.7 MW_{th}, respectively (Uslu et al., 2008). The present study assumed that natural gas would be utilized to supply the thermal energy to the torrefied pellet plants. Energy and environmental impacts of torrefied pellet plant construction, decommissioning, recycling, and disposal were included. Impacts of decommissioning, recycling, and disposal were investigated based on the assumptions stated in Section 3.3.1. Inventory data for the material and energy flows for the construction of torrefied pellet plant are provided in the Table SM-1 of Supplementary Material.

3.4. Transportation to end-user (UP 4)

This unit process (UP 4) involves the impacts of the transportation of preprocessed biomass feedstocks to the coal-fired power plant. It was assumed that AR would be collected from the central areas of census division 5 in the Province of Alberta since it was the best yield site for AR (Sultana et al., 2010). Boreal forest comprises almost 48% of the land area of Alberta. This study assumed that forest biomass (FR/WT) would be collected from the regions near Drayton Valley. The distance from these biomass collection areas to the existing coal-fired power plant of Alberta varies in the range of 100–500 km (AMEC, 2006). Therefore, in the base case, the distance between biomass preprocessing plant and coal-fired power plant was considered to be 500 km. However, two sensitivity cases were developed considering other distances. Energy and environmental impacts of truck manufacturing, operation (empty/loaded), recycling, and disposal were taken into account. The impacts from the primary road construction (required for biomass collection) were considered in UP 2. The impacts of road construction were disregarded in UP 4 since it was assumed that the biomass feedstocks would be transported to the power plant from biomass preprocessing plants using the existing road network. Table 3 provides the specifications of the truck used in feedstock transportation to the end user. Methodologies to calculate the actual load carrying capacity and fuel consumption by truck are described in Section 3.2.

3.5. Power production (UP 5)

During direct co-firing, biomass and coal are simultaneously fed into the same boiler. Direct co-firing involves blending of biomass and coal followed by processing of the mixture through coal mills, crushers, pulverizer, and burner. However, this technique can be modified for feedstock in the form of pellet and TOP. Feedstock in these forms is mixed with coal after coal milling since it can be crushed evenly and mixed with the milled coal (Maciejewska et al., 2006). Therefore, biomass feedstocks in the form of pellet and TOP were only analyzed for direct co-firing. Parallel co-firing involves facilitating the power plant with separate biomass pretreatment, feeding, and combustion systems. This technique is relevant to feedstock in the form of chips and bale. Feedstock in the form of bale and chips may make the fuel preparation, feeding, and combustion systems of the power plant complex if the feedstock was directly co-fired due to their higher moisture content, particle size, and non-uniform combustion behavior. Nevertheless, feedstocks in the form of chips and bale were analyzed for direct co-firing as well. Since the maximum allowable moisture content of biomass feedstocks for direct co-firing is 20 wt.%, FR and WT feedstock needed to be dried before direct co-firing. It was assumed that both FR and WT feedstocks would be dried to a moisture content of 18 wt.% from their respective original moisture content of 45 and 50 wt.%. Thermal energy required in evaporating one tonne of water from biomass feedstocks was estimated to be 3600 MJ (Thek and Obernberger, 2004). Electrical energy requirement to dry the FR- and WT-chips for direct co-firing were determined to be 665 and 790 kW, respectively (Thek and Obernberger, 2004). FR- and WT-chips must be pulverized down to 3 mm in size for successful direct co-firing with coal (Sebastián et al., 2007). Biomass feedstock in the form of chips (FR/WT) undergo a single-stage size reduction process whereas feedstock in the form of bale (AR) goes through a two-stage size reduction process. Energy requirement for the former and latter case is 495 and 640 MJ_{th}/tonne of feedstock processed, respectively. Drying and size reduction are not imperative to FR- and WT-feedstock in case of parallel co-firing. Energy and emission impacts associated with coal combustion during co-firing were adopted from the literature. Life cycle emissions from the coal-fired power plant were considered to be 1160 kg CO_{2eq}/MWh, 6.2 kg SO_{2eq}/MWh, and 1.94 (NO_x + VOC)/MWh (McCulloch et al., 2000). The thermal efficiency of the pellet- and TOP-based power generation pathways was assumed at 34%, for other pathways at 33% (Sebastián et al., 2007). However, a sensitivity case was developed to analyze the impact of plant efficiency on the life cycle results.

This study considered biomass combustion as carbon neutral for CO_2 emission only; all other environmental emissions were accounted for. Emission factors for the combustion of different biomass feedstocks are presented in Table 4.

Energy and environmental impacts of power plant retrofitting construction, and associated decommissioning, recycling and disposal (landfilling) were included. It was assumed that impacts from retrofitting would be 5% and 15% of the newly constructed coal-fired power plant (450 MW), respectively, for the direct and parallel co-firing option (Sebastián et al., 2007). The landfilling distance was considered to be 50 km. The impacts of ash disposal, which is a complementary nutrient replacement operation were also considered. In case of direct co-firing, ash produced from the power plant is a mix of coal and biomass ash. In contrast, for parallel co-firing, the ashes from coal and biomass remain separate. The first case limits the utilization of ash to commercial applica-

Table 4
Emission factors for the combustion of biomass in different forms.[a]

Emissions (kg/tonne of biomass)	AR-bale	AR pellet/TOP	Wood (FR/WT) chip	Wood (FR/WT) pellet/TOP	Sources
CO_2	0	0	0	0	Pa et al. (2011) and Pastre (2002)
CH_4	8.92E−02	4.60E−03	1.13E−01	5.82E−03	
N_2O	5.36E−02	3.72E−02	6.99E−02	4.85E−02	
CO	1.07E+01	4.18E+00	3.23E+00	1.26E+00	
VOC	1.13E−02	2.91E−02	1.13E−02	2.91E−02	
NO_x	1.60E+00	1.67E+00	1.38E+00	1.44E+00	
SO_2	2.31E+00	8.39E−01	1.34E−01	4.85E−02	

[a] AR = agricultural residue, FR = forest residue, WT = whole tree, and TOP = torrefied pellet.

tions including construction industry and underground mining (Maciejewska et al., 2006). Therefore, to ensure an identical system boundary, it was assumed that ash produced from the biomass co-firing plants would be utilized for nutrient replacement through landfilling in a biomass area at a distance of 50 km from the plant. Ash would be applied at a rate of 1 tonne/ha using a commercial 40′ fertilizer spreader. The productivity, fuel consumption rate, and lifetime of the spreader was estimated to be 4.4 ha/h, 5 L/h, and 1200 h, respectively (Mann and Spath, 1997). Truck use in the transportation of ash and plant materials for landfilling was assumed to be similar to that for biomass transportation and relevant inventory data are presented in Table 3.

4. Result and discussion

4.1. Life cycle greenhouse gas emissions impact

The life cycle GHG emission impacts of the direct co-firing pathways are shown in Fig. 2. The GHG emissions (Fig. 2) do not include the impacts of coal and only environmental impacts for 1 MWh of biomass-based power generation for all the pathways are shown. From the GHG emission perspective, AR-based power generation is the most favorable option of biomass-based power generation followed by power generation from FR and WT, irrespective of the densification technology (Fig. 2). This outcome is mainly because AR is considered a by-product in the base case and AR is available at a much lower moisture content (14 wt.%) compared to FR (45 wt.%) and WT (50 wt.%). GHG emissions from the WT-based pathways are higher than the FR-based pathways due the higher moisture content of WT feedstock and the inclusion of the impacts of road construction. For any feedstock, TOP performed the best followed by the chip/bale and pellet since energy ingestion in a TOP plant is less compared to its respective pellet plant for any given feedstock and natural gas for feedstock drying is not required (Section 3.3.3). Irrespective of the feedstock, TOP has higher bulk and energy densities compared to pellet/chip/bale, which translates into lower GHG emissions from transportation to end-user (UP 4) and a higher power output from UP 5, respectively. The preprocessing plant (UP 3) is the key player in determining the life cycle emissions of torrefied pellet and pellet-based pathways, since this unit process involves substantial consumption of utilities (natural gas and electricity). For TOP-based pathways, UP 3 contributes 71%, 61%, and 64% of the life cycle GHG emissions, respectively, for FR, WT, and AR. In contrast, for pellet-based pathways, UP 3 shares 78%, 70%, and 66% of the life cycle GHG emissions, respectively. Unlike for pellets and torrefied pellets, for chip/bale based power generation, UP 4 and UP 5 are the major players in determining GHG emission intensities. These two unit processes contribute, respectively, 30% and 58% for FR, 24% and 54% for WT, and 41% and 47% for AR life cycle GHG emissions. Therefore, it is evident that a significant environmental advantage can be achieved through biomass densification. Two-stage size reduction for AR makes UP 5 emission-intensive for the feedstock.

A 290,000 dry tonnes/year plant of FR- and WT-chip could contribute 8932 GWh to a 450 MW coal-fired power plant operating 6000 h/year; this is equivalent to a co-firing rate of 16.54% (energy basis). In contrast, a 150,000 dry tonnes/year plant using AR-bale can supply 4066 GWh at a co-firing rate of 7.53% (energy basis) and a 290,000 dry tonnes/year plant utilizing FR- and WT-pellet could contribute 9203 GWh, equivalent to a co-firing rate of

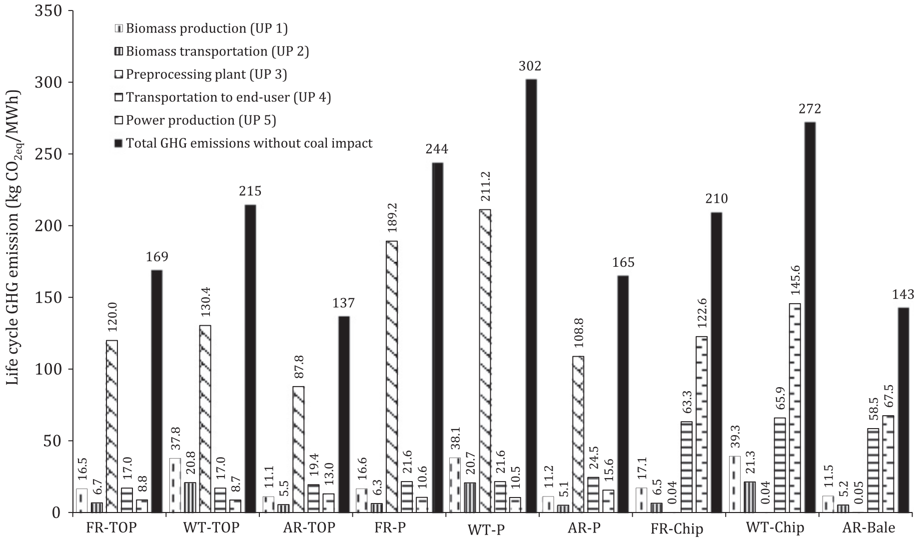

Fig. 2. Life cycle GHG emissions of the biomass direct co-firing pathways (results shown here do not include the impacts of coal). FR = forest residue, WT = whole tree, AR = agricultural residue, TOP = torrefied pellet, and P = pellet.

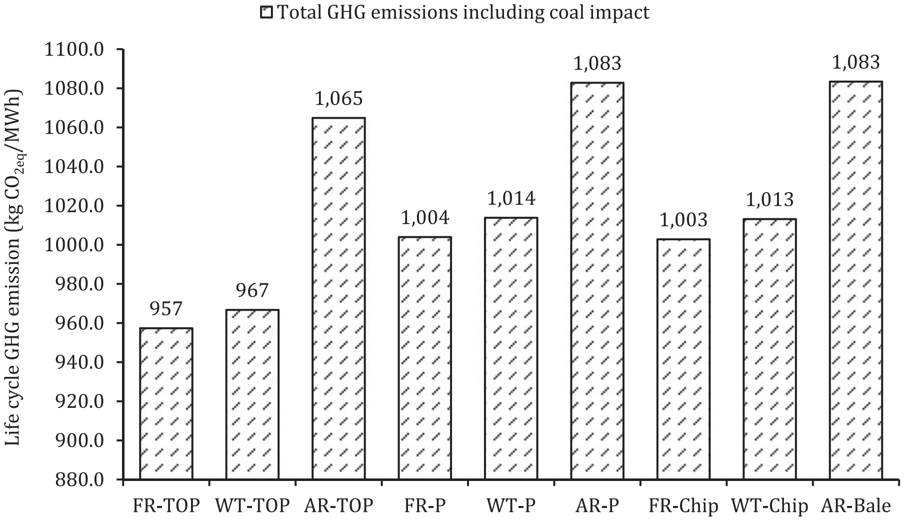

Fig. 3. Life cycle GHG emissions of the biomass direct co-firing pathways (results shown here do include the coal impact). FR = forest residue, WT = whole tree, AR = agricultural residue, P = pellet, TOP = torrefied pellet.

17.04% (energy basis). A torrefied pellet plant of any of these feedstocks (FR/WT) could supply 11,043 GWh at a co-firing rate of 20.45% (energy basis). An AR-pellet and AR-TOP plant of 150,000 dry tonnes/year capacity, could contribute 4189 and 5022 GWh, respectively, at a co-firing rate of 7.76% and 9.3% (energy basis). Fig. 3 shows the net (combining coal and biomass) GHG emissions from the biomass direct co-firing pathways. Net GHG emission for a pathway was determined based on the available co-firing rate (energy basis) from a feedstock. For example, GHG emission for generating 1 MWh electricity from FR-chip was 210 kg CO_{2eq}/MWh; to generate the same amount of electricity coal emits 1160 kg CO_{2eq}/MWh. Therefore, net life cycle GHG emission for the FR-chip-based co-firing pathway is 1003 kg CO_{2eq}/MWh. The same methodology was employed to calculate the other net emission (ARP and GOP) intensities. As shown in Fig. 3, albeit for any given densification technology, AR-based power generation produces the least GHG net GHG emissions for it is highest among the feedstocks. This outcome is because AR provides lowest rate of co-firing among the feedstocks. For any given densification technology, FR was the best among the alternatives from the net GHG emission viewpoint. It is apparent from the Figs. 2 and 3 that, for any given feedstock, the pellet-based power generation pathway is more expensive than the bale/chips-based pathway from the GHG emissions perspective, despite having significant GHG emissions reductions in UP 4 (transportation to end-user) due to densification. The key reason is that pellet plant operations involve extensive consumption of natural gas and electricity (Section 3.3.2).

Overall, FR-based power generation pathways demonstrated life cycle net GHG emissions in the range of 957–1004 kg CO_{2eq}/

Table 5
Net energy ratio and ground level ozone precursor emissions from the biomass co-firing pathways.[a,h]

GJ/MWh									
Unit process	FR-TOP	WT-TOP	AR-TOP	FR-P	WT-P	AR-P	FR-chip	WT-chip	AR-bale
UP 1	0.21	0.44	0.14	0.21	0.44	0.14	0.22	0.45	0.15
UP 2	0.09	0.10	0.07	0.08	0.10	0.07	0.08	0.11	0.07
UP 3	1.70	1.89	1.07	2.86	3.28	1.35	4.39E-04	4.39E-04	5.88E-04
UP 4	0.22	0.22	0.25	0.28	0.28	0.32	0.82	0.85	0.76
UP 5	0.01	0.004	0.01	0.01	0.01	0.01	1.76	2.19	0.41
Total[b]	2.23	2.66	1.55	3.44	4.11	1.89	2.88	3.60	1.38
Total[c]	8.64	8.73	9.47	9.12	9.23	9.63	9.06	9.18	9.62
NER[d]	1.62	1.35	2.33	1.05	0.88	1.90	1.25	1.00	2.60
NER[e]	0.42	0.41	0.38	0.39	0.39	0.37	0.40	0.39	0.37
kg (NO_x + VOC)/MWh									
UP 1	0.10	0.22	0.07	0.10	0.22	0.07	0.11	0.22	0.07
UP 2	0.04	0.07	0.03	0.04	0.06	0.031	0.04	0.07	0.032
UP 3	0.30	0.34	0.17	0.52	0.60	0.22	1.44E-04	1.44E-04	1.93E-04
UP 4	0.10	0.10	0.12	0.13	0.13	0.15	0.39	0.40	0.36
UP 5	0.65	0.65	0.86	0.78	0.78	1.03	1.09	1.17	1.06
Total[f]	1.19	1.37	1.25	1.57	1.79	1.50	1.62	1.87	1.52
Total[g]	1.79	1.82	1.88	1.88	1.91	1.91	1.89	1.93	1.91

[a] FR = forest residue, WT = whole tree, AR = agricultural residue, TOP = torrefied pellet, P = pellet, and NER = net energy ratio.
[b] Total life cycle energy consumption by the co-firing pathways excluding the coal impact.
[c] Total life cycle energy consumption by the co-firing pathways including the coal impact.
[d] Net energy ratio of the biomass co-firing pathways excluding the coal impact.
[e] Net energy ratio of the biomass co-firing pathways including the coal impact.
[f] Total life cycle ground-level-ozone precursor emissions of the co-firing pathways excluding the coal impact.
[g] Total life cycle ground-level-ozone precursor emissions of the co-firing pathways including the coal impact.
[h] Impacts for unit processes are expressed in terms of biomass contribution only.

Table 6
Emission mitigation scenarios and comparison of this study with reference coal system.[a]

Pathways	Net co-firing, % (energy basis)	Bio power generation in 20 years (GWh)	Total power generation in 20 years (GWh)	kg CO_{2eq}/MWh with co-firing[b]	kg SO_{2eq}/MWh with co-firing[b]	kg (NO_x + VOC)/MWh with co-firing[b]	t CO_{2eq} mitigation in 20 years	t SO_{2eq} mitigation in 20 years	t (NO_x + VOC) mitigation in 20 years
Coal[b]	0	0	54,000	–	–	–	0	0	0
FR-TOP	20.45	11043	54,000	957	5.16	1.79	10,962,000	56,160	8100
FR-P	17.04	9203	54,000	1004	5.38	1.88	8,424,000	44,280	3240
FR-chip	16.54	8932	54,000	1003	5.39	1.89	8,478,000	43,740	2700
WT-TOP	20.45	11043	54,000	967	5.18	1.82	10,422,000	55,080	6480
WT-P	17.04	9203	54,000	1014	5.41	1.91	7,884,000	42,660	1620
WT-chip	16.54	8932	54,000	1013	5.41	1.93	7,938,000	42,660	540
AR-TOP	9.30	5022	54,000	1065	5.77	1.88	5,130,000	23,220	3240
AR-P	7.76	4189	54,000	1082.8	5.86	1.906	4,168,800	18,360	1836
AR-bale	7.53	4066	54,000	1083.4	5.93	1.909	4,136,400	14,580	1674

[a] AR = agricultural residue, FR = forest residue, WT = whole tree, P = pellet, and TOP = torrefied pellet.

[b] Life cycle emissions from the 450 MW coal-fired power plant (reference coal system) are 1160 kg CO_{2eq}/MWh, 6.2 kg SO_{2eq}/MWh, and 1.94 (NO_x + VOC)/MWh (McCulloch et al., 2000).

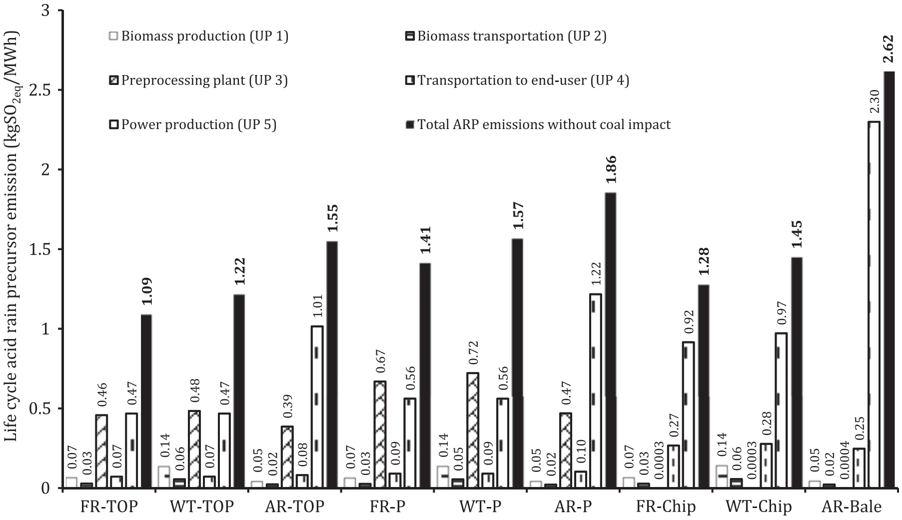

Fig. 4. Life cycle acidification potential of biomass direct co-firing pathways (excluding the coal impact). FR = forest residue, WT = whole tree, AR = agricultural residue, P = pellet, and TOP = torrefied pellet.

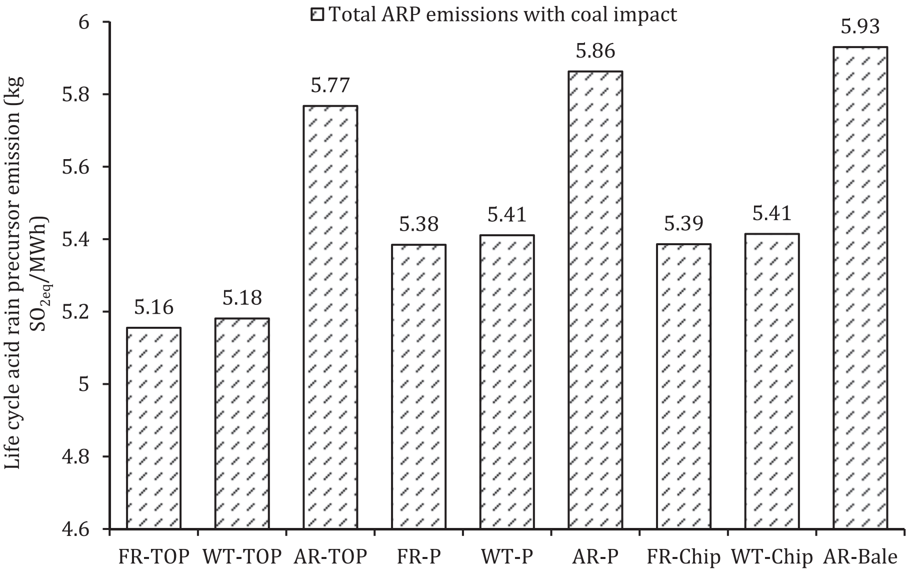

Fig. 5. Life cycle acidification potential of biomass direct co-firing pathways (including coal impact). FR = forest residue, WT = whole tree, AR = agricultural residue, TOP = torrefied pellet, and P = pellet.

MWh. Life cycle GHG emissions from the WT- and AR-based pathways were in the range of 967–1014 and 1065–1083 kg CO_{2eq}/MWh, respectively. The life cycle GHG emission for coal-fired power generation in Alberta is 1160 kg CO_{2eq}/MWh (McCulloch et al., 2000). Therefore, GHG emissions from Alberta's grid can be significantly mitigated employing biomass feedstock for co-firing. The mitigation potentials as calculated with Eq. (4) of the biomass co-firing pathways are illustrated in Table 6.

$$MP = P \times (E_c - E_{co}) \tag{4}$$

where MP = environmental emission (i.e. kg CO_{2eq}, kg SO_{2eq}, etc.) mitigation potential of a co-firing pathway over 20 years, P = total power production (MWh) from the 450 MW power plant over 20 years operating 6000 h/year, E_c = emission factor (kg CO_{2eq}/MWh, kg SO_{2eq}/MWh, etc.) for the coal based power generation, E_{co} = net life cycle emission factor (kg CO_{2eq}/MWh, kg SO_{2eq}/MWh, etc.) for the co-firing pathway.

Some studies have reported life cycle GHG emissions from biomass co-fired power in the range of 665–1100 kg CO_{2eq}/MWh (Liu et al., 2010; Hartmann and Kaltschmitt, 1999; Mann and Spath, 2001; Zhang et al., 2010). However, some of these studies excluded the impacts from operations like biomass farming, fertilizing, and processing from their respective system boundary. In addition, the level of co-firing was different for each study. Lastly, some of these studies considered the power plant to be located very near to the biomass collection area and biomass combustion to be completely GHG emission neutral. For biomass-based power (independent of coal), the life cycle GHG emission factor was in the range of 50–227 kg CO_{2eq}/MWh (Corti and Lombardi, 2004; Rafaschieri et al., 1999; Mann and Spath, 1997; Carpentieri et al., 2005). In most cases, the findings of the present study for the GHG emission intensity of biomass-based power are marginally higher than those found by others, possibly due to non-identical system boundary, temporal and geographical variation, variation in assumptions and inventory data. Therefore, a sensitivity analysis to examine the impact of key sensitivity parameters on the life cycle results was conducted.

4.2. Life cycle acidification impact

The life cycle acidification impacts of the biomass-based power generation pathways are shown in Fig. 4 without the impacts associated with coal utilization during co-firing. For any given densification technology, FR was the best performer from an ARP emission perspective followed by WT and AR. Unlike GHG emissions, ARP emissions were highest for AR among the biomass feedstocks for any given densification technology, mainly because of high SO_x and NO_x emissions during the combustion of AR (Pastre, 2002 and Table 4). Therefore, for the AR-based co-firing pathway, UP 5 contributes 65%, 66%, and 88% of the life cycle ARP emissions for torrefied pellets, pellets, and bales respectively. For generating power from the torrefied pellet/pellet of FR and WT, UP 3 and UP 5 predominated from the life cycle ARP emission point of view. For FR-TOP, these two unit processes contributed 42 and 43% of the life cycle ARP emissions, respectively. In contrast, for WT-TOP they contribute 39% and 38%, respectively. The reasons why these two unit processes were very significant for the life cycle results were explained in Section 4.1. Studies showed that life cycle ARP emissions for biomass-based power varied in the range of 1.6–1.7 kg SO_{2eq}/MWh (Carpentieri et al., 2005; Rafaschieri et al., 1999) and were thus similar to those obtained in the current study.

Fig. 5 depicts the life cycle net ARP emissions of the biomass co-firing pathways. The net ARP emissions were evaluated employing the methodology used for calculating the net GHG emission as in Section 4.1. For any given densification technology, FR was the best among the biomass feedstocks from a net life cycle ARP emission perspective followed by WT and AR. Overall, power generation from FR-based pathways demonstrated net acidification potentials in the range of 5.16–5.39 kg SO_{2eq}/MWh. In contrast, WT- and AR-based pathways showed acidification potentials in the range of 5.18–5.41 and 5.77–5.93 kg SO_{2eq}/MWh, respectively. The life cycle ARP emissions for Alberta's coal-fired power plants are 6.2 kg SO_{2eq}/MWh (McCulloch et al., 2000). Table 6 presents the acidification mitigation scenarios for the co-firing pathways.

4.3. Life cycle ground level ozone emission and energy impact

The life cycle GOP emission and energy impacts for the power generation pathways are given in Table 5. Among the FR-based pathways, power generation from TOP [1.19 kg (NO_x + VOC)/MWh] demonstrated the lowest GOP emission (excluding coal impact), followed by pellets [1.57 kg (NO_x + VOC)/MWh] and chips [1.62 kg (NO_x + VOC)/MWh]. Among these pathways, UP 5 generated the maximum portion of the emissions (55%, 50%, and 67%, respectively, for torrefied pellets, pellets, and chips). The impact of UP 5 was predominant for GOP emissions of other biomass feedstocks and densification technologies. Though the impact of UP 4 (transportation to end-user) was significant for chips/bale-based pathways (21–24%), its impact was trivial for the FR-pellet- and -TOP-based pathways (7–10%) since the transportation emissions were greatly reduced due to biomass densification. GOP emission for biomass-based power was 1.8 kg (NO_x + VOC)/MWh (Rafaschieri et al., 1999) which is very close to what was determined in the present study.

Overall, FR-based power generation pathways exhibited life cycle net GOP emission intensities in the range of 1.79–1.89 kg (NO_x + VOC)/MWh. In contrast, for WT- and AR-based pathways, the intensities were in the range of 1.82–1.93 and 1.88–1.91 kg (NO_x + VOC)/MWh, respectively. The life cycle GOP emission for coal-fired power generation in Alberta is 1.94 kg (NO_x + VOC)/MWh (McCulloch et al., 2000). Like studies (Maciejewska et al., 2006; Baxter, 2005), the present study (in some cases) also found GOP emission intensities for AR-based power close to that of coal-based power, primarily because of emissions associated with AR combustion. Table 6 presents the GOP mitigation potential of all biomass co-firing pathways.

As shown in Table 5, the biomass pathways have net energy ratios equal to or greater than 1 (when the coal impact is excluded i.e. only biomass-based power generation are considered). However, for co-firing, the net energy ratios were found to be less than one. Although AR-based power generation provided the highest NER among biomass feedstocks for any given densification technology, the resultant NERs for the AR-based co-firing pathways were less than those for the respective FR/WT pathways because the rate of co-firing was lower for AR feedstock. Overall, NER for biopower production was in the range of 1–2.6 which is lower than that found with some earlier studies (Liu et al. 2010; Hartmann and Kaltschmitt, 1999). Table 5 shows that when coal impact is considered among the FR-based pathways, TOP (NER: 0.42) proved to be the most energy efficient option followed by chips (0.40) and pellets (0.39). AR-based pathways demonstrated NERs in the range of 0.37–0.38. In contrast, WT-based pathways exhibited NERs in the range of 0.39–0.41. In comparison, NERs for pure coal-based power generation is in the range of 0.31–0.35 (Hartmann and Kaltschmitt, 1999; Heller et al., 2004). Heller et al. (2004) reported that the NER for 10% (energy basis) co-firing of willow biomass with coal was 0.34.

4.4. Sensitivity analysis

The objective of this parametric sensitivity analysis was to understand the effects of some of the key assumptions and param-

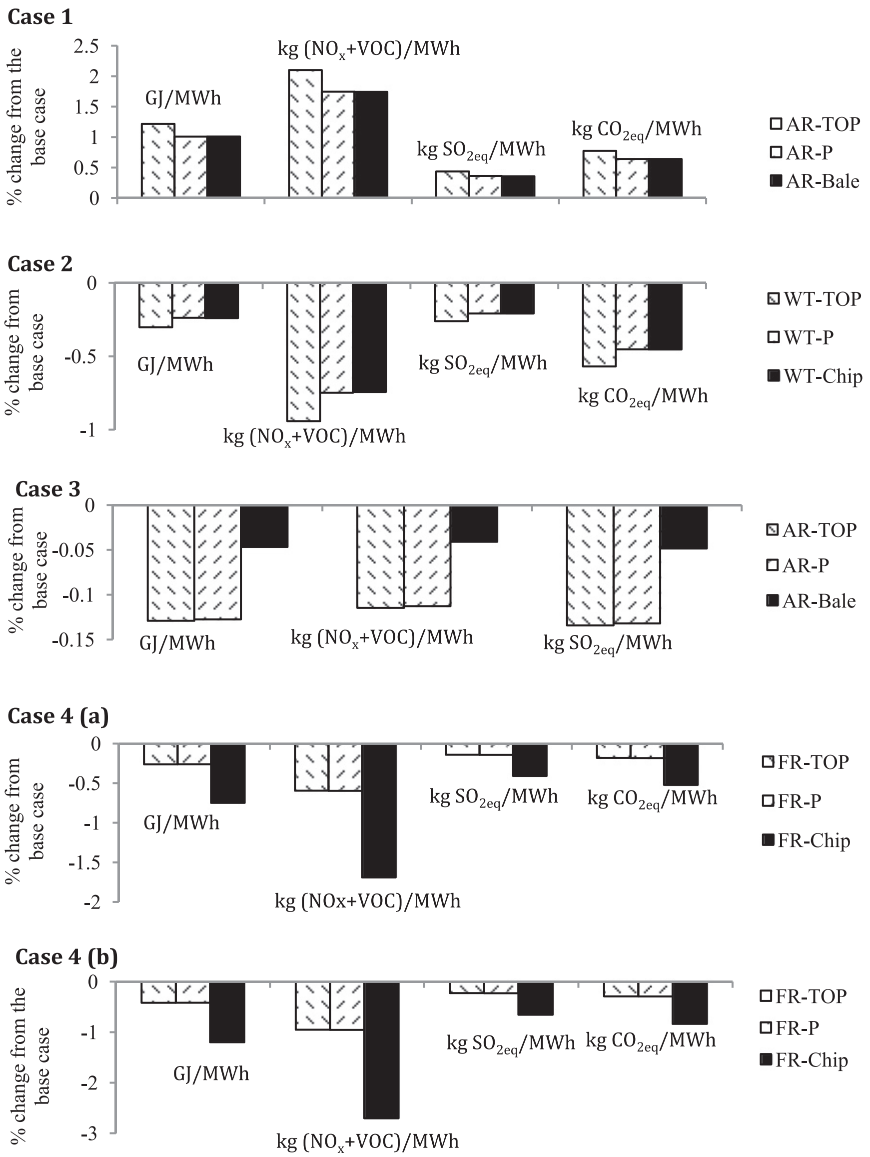

Fig. 6. Impacts of the sensitivity cases over the life cycle results. FR = forest residue, WT = whole tree, AR = agricultural residue, TOP = torrefied pellet, P = pellet, DC = direct co-firing, and PC = parallel co-firing.

eters on the life cycle results. Each sensitivity case was developed independently of other cases to ensure comparability with the base-case. Sensitivity analysis was performed on co-firing cases only, i.e. all sensitivity cases accounted for the coal impact in the life cycle results. Case 1 included the farming operations (Fig. 1) within the system boundary of the AR-based pathways, i.e. this case did not consider AR as a byproduct. Sensitivity of this case is depicted in Fig. 6. Case 2 kept silviculture and road construction out of the boundary of the WT-based pathways. Therefore, impacts were reduced by 0.21–0.94% (Fig. 6). Since Alberta is looking to incorporate green electricity in its grid, a sensitivity case (Case 3) was developed to realize the impacts of grid emissions intensity reduction (20%) on the co-firing pathways. As a result, the emissions intensities of AR-based co-firing pathways were lessened by 0.01–0.13% (Fig. 6). For FR- (0–0.34%) and WT-based (0–0.34%) pathways similar results were obtained. Case 4 analyzed the impact of the distance between biomass preprocessing and co-firing plants by modifying the transportation distances to be (a) 250 km and (b) 100 km, instead of 500 km (in the base-case). Case 4 (a) and 4 (b) causes 0.14–1.74% and 0.23–2.8% reductions in the impacts from the FR-based pathways, respectively (Fig. 6). Similar reductions were found for the WT- (0.14–1.8% and 0.23–2.9%, respectively) and AR-based (0.06–0.7% and 0.1–1.1%, respectively) pathways, hence these data are not shown in Fig. 6. Case 5 considered the power plant thermal efficiency to be 31% and 30%, respectively, for the pellet/TOP- and chip/bale-based pathways. Due to this assumption, a 0.2–0.5% increase in base-case energy and emissions was observed. Since the base case considered direct co-firing technology for the biomass co-firing pathways, a sensitivity case was developed which considered that biomass in the forms of bales/chips would be co-fired using the parallel co-firing technology. This case reduced the GHG emission intensity of FR (chips), WT (chips), and AR (bales) by 1.7%, 2.1%, and 0.2%, respectively, compared to direct co-firing. The extent of reduction in other emission and energy intensities were close to the percentage mentioned for GHG emissions. The sensitivity of biomass yield was also analyzed; however, a ±10% change in biomass yield impacted the life cycle results by less than ±1%. Similarly, the sensitivity of the plant operating factor was analyzed (0.7 for year 1, 0.8 for year 2, and 0.95 from year 3 onwards; 0.65 for year 1, 0.7 for year 2, and

0.75 from year 3 onwards), but the effects of these operating factors on the life cycle results were (less than ±1%), and are thus not presented here.

5. Conclusion

For FR, WT, and AR, maximum net energy ratio (0.42, 0.41, and 0.38, respectively) is found for the feedstock in the form of TOP. The least GHG, ARP, and GOP emissions are obtained from the feedstock in the form of torrefied pellets. It is evident that biomass densification may generate significant energy and environmental advantage. This study investigated the dry torrefaction process only; a scrutiny of wet torrefaction is recommended for future study. The future biomass/coal co-firing life cycle study should also emphasize on the sustainability factors including socio-economic, water use, land use, soil erosion, and biodiversity.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2012.07.106.

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