Life Cycle Assessment of Biomass Integrated Gasification Combined Cycle in Cement Industry

Yu Wang, Kiara Winans, Yixin Shao and Joann Whalen* (McGill University, Montreal, Canada)
Darko Matovic (Queen's University, Kingston, Canada)

ABSTRACT: Switching to low carbon fuel will help the cement industry reduce carbon dioxide (CO_2) emissions effectively. One way to decrease the amount of coal burned in the kiln is to generate some "green" electricity to heat the kiln in parallel to coal combustion. A typical integrated gasification combined cycle (IGCC) located on-site would consume biomass fuel to generate 5-30 MW of "green" electricity. Meanwhile, ash from the IGCC can be recycled by blending with Portland cement, which reduces the amount of limestone required to produce an equivalent cementitious material and lowers the CO_2 emitted from limestone decomposition. The objective of this study was to evaluate the environmental impacts of the biomass IGCC with ash recycling, considering the carbon offsets achieved with lower coal and limestone consumption. We used switchgrass as the IGCC fuel, and assessed the life-cycle impacts of replacing 5% and 20% of coal inputs, with or without ash recycling. We found that switchgrass was a competent biomass fuel due to its 17.5 MJ/kg of energy value and good pozzolanic properties in blended cement. Replacing 5% and 20% of coal by IGCC electricity decreased the climate change potential (due to CO, CO_2 and CH_4) by 1.65% and 7.14%, and ash recycling further reduced the climate change potential by 1.04%. Fertilizers and pesticides for cultivating switchgrass increased the photochemical oxidation potential (due to N and P), and switchgrass planting triggered competition for land with agricultural crops. Although producing 1 kg of switchgrass fuel released 0.072 kg of CO_2 from planting, transportation and storage, the entire switchgrass cultivation assimilated a net 1.44 kg of CO_2 from the atmosphere, illustrating the C sequestration possible with this biomass fuel. Compared to a conventional cement plant, if we replaced 20% of coal with "green" electricity from the biomass IGCC, CO_2-equivalent climate change potential decreased by 6.17%, and an additional 0.97% due to ash recycling as cement additive. Hence, applying biomass in an IGCC was a carbon-neutral process if other steps (biomass cultivation, storage, transport, preparation, etc.) could also be powered by carbon-neutral fuel.

INTRODUCTION

Canadian cement manufacturers are estimated to produce 2% of regional CO_2 emissions. Cement manufactured by the calcination process requires a temperature of about 1450 ℃, which is maintained by coal combustion inside the kiln. According to the Portland Cement Association (Marceau et al., 2006), an average-size cement plant consumes 3.06 GJ of coal per 1000 kg of final cement produced, which releases 549 kg of CO_2 from calcination process and another 303 kg from coal combustion. Thus, one effective way to lessen the CO_2 emission is to replace a part of coal by low carbon fuels, e.g. biomass.

Owing to the carbon-neutral property of biomass, a cement plant can set up an independent energy conversion unit to generate "green" energy, which partially supplants coal consumption in the kiln (Khamseh, 2014). Integrated gasification combined cycle (IGCC) is an energy generation system consisting of gasification, syngas cleaning, combustion turbine generation, heat recovery and steam turbine generation. A typical IGCC powered by biomass fuel can generate 5-30 MW of electricity. Moreover, it features superior energy efficiency (due to heat recovery) and low emission performance (due to syngas cleaning) (Lee et al., 2014), making it an ideal technique for biomass energy generation.

Switchgrass (*Panicum vigratum, L.*) is considered a good low carbon fuel especially in Canada and the United States. Switchgrass, a perennial cold-to-warm-season grass, features an excellent calorific value (15-20 GJ/tonne of dry matter), ease of management and high yield. Because ash remaining after switchgrass combustion contains 60-70% of silica, mixing the ash with cement (10:90 ratio) is a feasible technology that does not adversely affect the material properties of the resulting concrete. Recycling ash in cement also reduces the amount of cement produced by calcination, thus leading to lower CO_2 emissions (Zacoo et al., 2014). Despite the promise of these technologies, no previous research has quantified the environmental impact of using biomass fuel in an IGCC, coupled with ash recycling, for the cement industry.

The objective of this study was to evaluate the environmental impacts of an integrated system using biomass fuel in an IGCC and recycling the ash in cement, considering the carbon offsets achieved owing to a reduction in coal and limestone consumption. We used switchgrass as the IGCC fuel, and assessed the life-cycle impacts of replacing 5% and 20% of coal inputs from this energy source, with or without ash recycling.

METHODS

Functional unit and system boundary

Functional unit was 1000 kg of blended cement product (either 100% Portland cement or <1% switchgrass combustion ash plus ≥99% Portland cement). System boundary was described as cradle-to-gate, starting from the acquisition, extraction and cultivation of raw materials, and ending with blended cement product. Four scenarios were compared. As shown in Figure 1, S1 represented conventional Portland cement as the reference material. The S2 scenario replaced 5% of coal and the S3 case replaced 20% of coal by electricity from IGCC with ash recycling (1:99 ash: Portland cement ratio). In S4, 20% of coal was supplanted by IGCC electricity, and no ash recycling occurred. Given the scope of this cradle-to-gate analysis, ash disposal (landfill) was not considered.

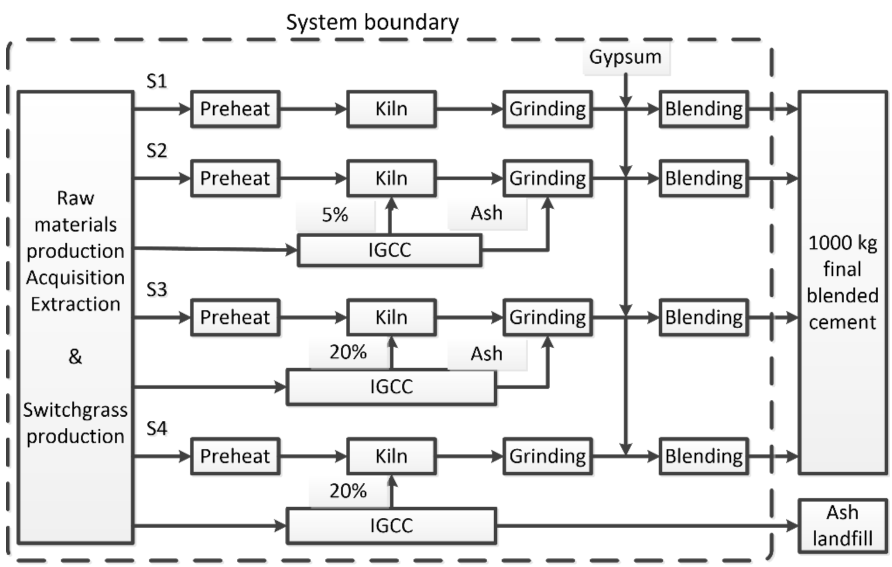

FIGURE 1. Four different scenarios with system boundary in this case study.

Life cycle inventory data

This study considered a simplified conventional cement production process (Figure 2). Data describing the mass balance, energy input and emissions was from the Portland Cement Association (Marceau et al., 2006). We assumed that coal and electricity were the sole energy sources, with equal efficiency, that sustained a temperature of 1450 ℃ in the kiln. Coal combustion generated 0.148 kg of particulate matter (PMs), SO_2 (0.270 kg) and NO_x (2.35 kg) emissions during cement production. In addition, data on extraction of raw materials, e.g. limestone and coal, were obtained from the National Renewable Energy Laboratory (NREL) database of the United States (NREL, 2012).

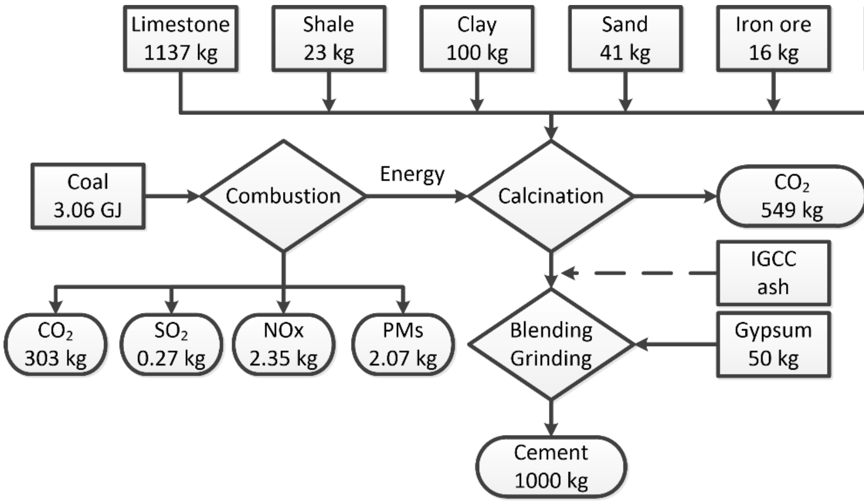

FIGURE 2. Conventional Portland cement production. IGCC ash can be blended with clinker through the dash line.

Data of switchgrass cultivation, harvesting and transport was presented in Table 1. We considered all crop production processes from field preparation to harvesting and baling (Sokhansanj et al., 2009). CO_2, SO_2 and NO_x sequestrated by cultivation completely transformed to the C, N and S content of fresh switchgrass. After harvesting, we assumed that switchgrass was transported by diesel trucks a distance of 90 km from farm to cement plant (Spatari et al., 2005). CO_2 emissions generated from switchgrass drying and storage were also included in the Table 1. Properties of switchgrass and its ash were characterized and reported in Table 2. Switchgrass had a high energy value (17.5 MJ/kg of higher heating value (HHV)), and thus was suitable for energy generation (Demirbas, 2005).

TABLE 1. Critical inputs and outputs in simplified switchgrass cultivation and IGCC models.

Switchgrass production, per 1 kg of switchgrass			**IGCC, per 1 MJ of electricity output**		
Input	**Unit**	**Value**	**Input**	**Unit**	**Value**
CO_2	kg	1.51E+00	Switchgrass	kg	1.94E-01
Energy from solar	MJ	1.53E+01	Transport	kg*km	1.17E+01
Fertilizer	ha	6.76E-05	**Output**		
NO_x	kg	1.97E-02	Electricity	MJ	1.00E+00
Pesticide	ha	6.76E-05	NO_x	kg	3.81E-03
Planting	ha	6.76E-05	SO_2	kg	2.32E-04
SO_2	kg	1.20E-03	CO	kg	2.41E-05
Occupation	ha	6.76E-04	Particulates	kg	4.84E-04
Transformation	ha	6.76E-05	CO_2	kg	2.92E-01
Output			Ash	kg	9.05E-03
Switchgrass	kg	1.00E+00			
CO_2 due to crop production, transport, drying and storage	kg	7.19E-02			

Due to lack of information on switchgrass fuel in an IGCC, we modified a model describing poplar tree as fuel for an IGCC in the light of the switchgrass properties (NREL, 2012). This model summed the energy, ash output, gaseous and particulate emissions from the system infrastructure (Figure 3), as listed in Table 1. According to IEA guideline (IEA, 2007), the IGCC was assumed to have 10 MW of electricity output, with 35% energy efficiency based on the lower heating value (LHV) of switchgrass. The IGCC system had 0.25% unreacted rate, which resulted in PMs. When substituting IGCC electricity for coal, the change in gaseous and particulate emissions (due to coal replacement alone) was proportional to the reduction in coal input.

TABLE 2. Proximate and ultimate analysis, and calorific value of switchgrass, and chemical composition of ash.

Proximate analysis, w.t.%						
Basis	Moisture	Volatile matter	Ash	Fixed carbon		
Air	6.55	80.6	4.69	8.21		
Dry	—	86.2	5.02	8.78		
Ultimate analysis, dry basis, w.t. %					Calorific value, MJ/kg	
C	H	N	S	O	HHV	LHV
41.3	5.86	0.600	0.060	52.2	17.5	15.8
Major mineral oxides in ash, w.t.%						
SiO2	Al2O3	Fe2O3	MgO	CaO	Na_2O	LOI
67.2	0.680	0.310	2.05	12.3	0.110	14.8

We assumed that ash from combusted switchgrass was completely recycled in cement production. We also assumed that ash contained negligible carbon content and alkaline materials that could cause deterioration in concrete. Ash containing amorphous silica and total SiO_2 + Fe_2O_3 + Al_2O_3 greater than 70%, could be blended in cement at a rate of ≤20% ash without any negative impact (Zacoo et al., 2014). Ash was added to clinker before grinding together to make blended cement. Ash replacement rates were 0.14% and 0.55% of the blended cement product when 5% and 20% of coal were supplanted. As less Portland cement was required to make 1000 kg of blended cement, all input and output values for Portland cement production decreased proportionally.

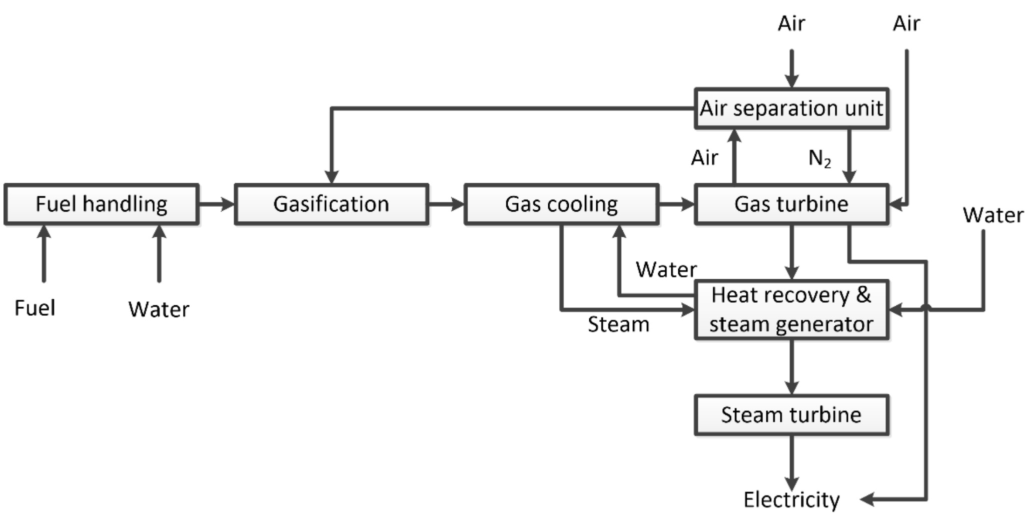

FIGURE 3. Systematic description of integrated gasification combined cycle (IGCC).

Life cycle impact assessment

Life cycle impact was evaluated by pressure-oriented approach. This method restricted the calculation to early stage (midpoint) in the cause-effect chain, with a relatively small uncertainty. To constrain uncertainty, we ran the calculations at the midpoint, conforming to CML 2001 guidelines (Guinée, 2001).

Uncertainty analysis

Uncertainties in the life cycle inventory originated from parameter choice, model adoption, assumptions, spatial and temporal variability. To be credible, we evaluated these uncertainties by Monte

Carlo simulation (Peters, 2007). We assigned normal distribution to each value in the life cycle inventory, with a variability of ±10%. Simulations were performed on 1000 random iterations of each variable, and the LCA impacts were estimated and presented as the mean value with standard deviation.

RESULTS AND DISCUSSION

The pressure-oriented approach estimated the environmental impact of the four scenarios. As shown in Table 3, adopting biomass energy (in S2, S3 and S4) successfully reduced the environmental burden of acidification, climate change (after 100 years), eutrophication and resource depletion. These diminutions were attributed to the carbon-neutral property of biomass, which decreased the gaseous and particulate emissions by substituting biomass energy for coal energy. Recycling ash as cement substitutes likewise lessened the acidification and climate change from 1.54 kg and 799 kg to 1.52 kg and 791 kg (S4 and S3), due to less Portland cement production. This substitution also alleviated the resource depletion from 0.667 kg (S4) to 0.663 kg (S3).

Biomass cultivation induced higher photochemical oxidation (S2, S3 and S4), which was ascribed to the usage of fertilizers and pesticides to sustain high yields and for crop protection. Furthermore, biomass cultivation required agricultural land that would otherwise be used for arable crops, pasture and meadow, and permanent crops. Hence, compared to reference scenario S1 (0 m^2a), the scenarios S2, S3 and S4 needed 166 and 669 m^2a of land transformation. The fields devoted to switchgrass cultivation might have negligible consequences for the current land use for agriculture, forestry, settlements, recreation, and conservation, but this is not known. Thus, we should thoroughly assess the impact of land use to estimate the trade-off between GHG mitigation and competition for land.

Whereas producing 1 kg of switchgrass fuel released 0.072 kg of CO_2 from planting, harvesting, transportation, drying and storage, switchgrass cultivation assimilated a net 1.44 kg of CO_2 from atmosphere due to its carbon neutral property. Compared to the conventional cement plant, if we aggressively replaced 20% of coal by the "green" electricity from switchgrass fuel in an IGCC with ash recycling, the CO_2-equivalent environmental burden decreased by 7.04%, from 852 kg to 792 kg. Therefore, based on the results above, applying biomass fuel in an IGCC was a carbon-neutral process if other steps (biomass cultivation, storage, preparation, transport, etc.) could also be powered by carbon-neutral fuel.

TABLE 3. Life cycle impact by midpoint approach.

Impact	Unit	S1		S2		S3		S4	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Acidification potential	kg SO_2-Eq	1.91E+00	1.37E-01	1.82E+00	1.32E-01	1.52E+00	1.14E-01	1.54E+00	1.10E-01
Climate change 100 yr.	kg CO_2-Eq	8.51E+02	6.86E+01	8.37E+02	6.77E+01	7.91E+02	6.44E+01	7.99E+02	6.64E+01
Eutrophication potential	kg PO_4-Eq	3.05E-01	2.51E-02	2.91E-01	2.41E-02	2.43E-01	2.08E-02	2.45E-01	2.00E-02
Land use – competition	m^2a	0.00E+00	0.00E+00	1.66E+02	1.36E+01	6.68E+02	5.52E+01	6.68E+02	5.52E+01
Photochemical oxidation	kg	0.00E+00	0.00E+00	1.81E-05	1.47E-06	7.22E-05	5.96E-06	7.22E-05	5.96E-06
Resources depletion	kg	8.33E-01	6.88E-02	7.92E-01	6.25E-02	6.63E-01	5.58E-02	6.67E-01	5.43E-02

CONCLUSIONS AND FUTURE RECOMMENDATIONS

To sum up, 1) switchgrass had 17.5 MJ/kg of energy value, thus being an excellent biomass fuel for IGCC; 2) whereas producing 1 kg of switchgrass fuel released 0.072 kg of CO_2 from planting, transportation and storage, the entire switchgrass cultivation assimilated a net 1.44 kg of CO_2 from atmosphere due to its carbon neutral property; 3) compared to the conventional cement plant, if we replaced 20% of coal with “green” electricity from the biomass IGCC, CO_2-equivalent climate change potential decreased by 6.17%, and an additional 0.97% due to ash recycling as cement additive; 4) applying biomass IGCC was a carbon-neutral process if other steps (biomass cultivation, storage, preparation, transport, etc.) could be powered also by carbon-neutral fuel.

However, since this case study contains many assumptions due to lack of real experimental data, some relevant trials (e.g. switchgrass cultivation, switchgrass IGCC, using IGCC electricity for kiln) should be conducted to provide authentic data for more credible LCA results. 2) Meanwhile, the feasibility of using biomass IGCC in the cement industry should be analyzed and proved at a real cement plant.

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