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Comparing the life cycle impacts of using harvest residue as feedstock for small- and large-scale bioenergy systems (part I)

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ABSTRACT

In part I of our two-part study, we compare the timing-adjusted GHG (greenhouse gas) balance and life cycle impacts of potentially using harvest residue (unmerchantable small-diameter roundwood) in an existing large (211 MW_e) wood pellet-fired (formerly coal-fired) power plant in Ontario, Canada, versus a hypothetical small (250 kW_e) wood chip gasification plant that recovers heat in addition to producing electricity. Although the large, retrofitted power plant has a higher electrical efficiency, the small plant has lower environmental impacts (*TRACI 2.1*), mainly due to the benefits of drying the biomass inputs with recovered heat, having a shorter fuel shipping distance, and reduced biomass processing. The small plant emits 38 g of fossil fuel-derived CO_2 eq./kWh, versus 134 g/kWh from its large-scale counterpart. Although these GHG emissions are insignificant relative to the forest carbon emissions from gasification and combustion (1.3–1.4 kg CO_2/kWh), the harvest residue would have decomposed over time had it been left on the forest floor. After 100 years, forest carbon storage decreases by 3.8–4.1 kg from the sustained production of 1 kWh of electricity per year. The decline in carbon storage delays net GHG mitigation by 4 (small-scale system) to 7 years (large-scale system) when displacing electricity from coal.

1. Introduction

The industrial use of forest biomass for electricity and heat production is expected to increase considerably over the next few decades [1]. While a large portion of the current supply is generated by the pulp and paper sector using mill residues as fuel [2], electrical utilities are expected to produce an increasing share by substituting biomass for coal in retrofitted power plants [1]. Since burning coal emits more GHGs (greenhouse gases) than other fossil fuels [3], replacing coal with biomass is widely considered an effective means of GHG mitigation (e.g., [4–6]). Retrofitting an existing facility also minimizes capital costs, while exploiting the economies of scale afforded by large power plants [7].

Compared to smaller plants, however, large plants (>50 MW_e) have several disadvantages that offset GHG reductions achieved by displacing coal. While large plants are usually more efficient at converting biomass to electricity [8,9], the feedstock must be transported further, and processed to a greater extent, often into wood pellets [6,10,11]. Furthermore, coal-fired power plants retrofitted to use wood pellets (e.g., Atikokan generating station in Canada; Rodenhuize generating station in Belgium) often do not utilize the excess heat generated during combustion. This is mainly due to a lack of sufficient demand for heat in close proximity to large-scale facilities [1]. In contrast, small CHP (combined heat and power) plants (<10 MW_e) are suitable next to small heat sinks, such as kilns for drying lumber, which tend to be more prevalent [1].

Previous studies have quantified the potential GHG benefits of bioenergy, including electricity from retrofitted power plants, assuming that biomass collection and combustion are carbon neutral activities [12,13]. However, many biomass feedstocks, such as harvest residue, do not decompose immediately, thereby negating the carbon neutrality assumption [5]. Collecting and burning harvest residue reduces the amount of carbon stored in forests, an oft-neglected fact that must be considered when assessing net GHG reductions [14–16]. Nevertheless, LCAs (life cycle assessments) have demonstrated that wood pellets can reduce the long-term GHG emissions of large coal-fired power plants, even if there is an initial decline in forest carbon storage (e.g., [5,17]). Yet, there is no net GHG mitigation until the so-called

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"carbon debt" is paid off [12] – once the cumulative non-biogenic GHG reductions fully compensate for the initial decline in forest carbon storage.

The timing of emissions influences their impact on climate, as measured by cumulative radiative forcing [18]. Emissions arising earlier in the life of a project result in greater forcing than those arising later, simply because the GHGs remain in the atmosphere for a longer period within the studied time horizon. Thus, the climate benefits of biomass substitution are overestimated if one assumes that the emission reductions towards the end of a project life are responsible for the same benefits as those at the beginning, as is the case for most bioenergy LCAs [19]. A number of authors [20–23] have emphasized the importance of addressing this timing issue, with Levasseur et al. [22] calling for the use of "dynamic LCA" to characterize both the timing and climatic forcing of GHG emissions. Relative to another LCA methodological issue, bioenergy LCA comparisons commonly (e.g., [5,6]) assume that a bioenergy facility would consume the average electricity mix in its operations, while the electricity added to the grid would displace the marginal source, such as coal or natural gas. The implications of these emissions timing and mixed-method problems on comparative LCA results for bioenergy systems remain inadequately examined.

In light of the potential GHG benefits of bioenergy, various policy instruments have been employed to encourage the use of biomass for electricity as well as heat [24]. However, few studies have quantified the life cycle impacts of small CHP plants that use harvest residue (e.g., [8,25,26]), and none have compared their impacts to those of large, retrofitted power plants using the same feedstock. Thus, it remains uncertain if (and under what circumstances) small CHP plants provide net environmental benefits that meet or exceed those provided by retrofitting large, more electrically efficient, power plants. If they do, the potential benefits of biomass substitution may not be fully realized, particularly in jurisdictions whose policies are skewed towards centralized electricity production, and those (e.g., Ontario, Canada) which lack support for heat recovery. In such a policy context, the net benefits of biomass substitution should be assessed by comparing the life cycle impacts of bioenergy systems which use the same feedstock, but differ both in scale and the utilization of heat.

In this paper, part I of a two-part study, we compare the timing-adjusted GHG balance of two potential biomass conversion pathways in Ontario, Canada: (1) chipping and gasifying harvest residue at a local sawmill that would use a portion of the recovered heat to dry both the residues and lumber in a kiln; and (2) pelletizing, transporting, and firing the residues in an existing large, retrofitted power plant. We also assess the net environmental impacts of the bioenergy options, and compare these impacts at each stage of the life cycle. Electricity generation and GHG mitigation costs from the same two bioenergy conversion pathways are compared in Part II of this study [27].

2. Conversion pathways, geographic context, and policy background

Both potential thermal conversion pathways utilize harvest residues collected from HFWR (Haliburton Forest and Wildlife Reserve), a 30,000 ha privately-owned forest in the GLSL (Great Lakes-Saint Lawrence) forest region of central Ontario. We have chosen HFWR as a case study because it has recently built a new sawmill and kiln, and is considering different means of using residues to generate both heat and electricity locally. If constructed, a small-scale CHP gasification system would supply heat to dry lumber, thus displacing LPG (liquefied petroleum gas), while the electricity would be fed into the power grid under a contract recently awarded to HFWR under Ontario's FIT (Feed-in Tariff) program.

The HFWR sawmill produces 8–10 thousand m^3 of lumber annually, and approximately 16,000 tonnes of woodchips, sawdust, and bark per year. As all of this sawmill residue is currently sold at a reasonable profit, the preferred feedstock for a bioenergy system would be harvest residue, which has been the subject of previous research at HFWR [28,29, Supporting Information, Section S-2.1].

The hardwood forest in HFWR is harvested on a 15–20 year rotation using a partial harvesting method called single-tree selection, which normally leaves behind unmerchantable harvest residue, including small-diameter roundwood, as well as tree crowns and branches, both of which have a low bulk density [29]. The portion that is small-diameter roundwood can be recovered using conventional logging and trucking equipment, then chipped at the sawmill using a 58″ Forano six-knife chipper powered by a 150 horsepower motor. Based on previous research, we assume that 1.18×10^3 dry tonnes of small-diameter roundwood is collected from a different site each year over the course of a 20 year harvest rotation, equivalent to approximately 15% of available downed woody debris [29,30, Supporting Information, Section S-2.1].

Instead of processing the small-diameter roundwood at the sawmill for onsite use, the material could be transported to a local pellet mill, processed, and then shipped to a large power plant in Atikokan, Ontario – the only coal-fired power plant in the province that has been retrofitted to use wood pellets. This retrofit is part of a larger provincial effort to increase the supply of low-emission electricity from renewable sources, and thereby phase out the use of coal [31]. This effort is driven primarily by the Ontario Green Energy and Green Economy Act [32,33], including policy incentives such as the FIT program, which pays a premium for electricity produced from biomass [24]. Supporting policy includes a timber pricing scheme that encourages the use of unmerchantable roundwood from provincial land [34,35]. Previous studies have questioned whether the incentives are sufficient to realize the potential GHG benefits of decentralized bio-electricity production [36]. We believe that the LCA comparison in this paper is an important step in evaluating the potential impacts of these provincial initiatives, as well as similar GHG mitigation policies being considered elsewhere (e.g., [37]).

3. Methods

3.1. LCA scenarios

The net GHG emissions and environmental impacts of two LCA scenarios are assessed using a functional unit of 1 kWh of electricity generated at the gasification/combustion site. In Scenario 1 (S1 – small-scale heat and electricity production), the collected small-diameter roundwood is chipped and gasified next to the sawmill in a hypothetical 250 kW_e fixed bed gasifier. All of the electricity is fed into the grid, while a portion of the potentially recoverable heat is used for the gasification reaction, the drying of the biofuel, as well as the drying of lumber in a kiln with an annual capacity of 1200 m^3 of stacked wood [38]. In Scenario 2 (S2 – large-scale electricity production), the small-diameter roundwood is processed in a local pellet mill, using a portion of the inputs as fuel. The resulting wood pellets are shipped to Atikokan for combustion in its 211 MW_e plant which has been operating well below capacity (8% capacity factor) due to insufficient wood pellet inputs [27].

3.2. System boundaries

The LCA system boundaries encompass the following components: residue recovery; transportation to the sawmill and/or