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

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A B S T R A C T

In part II of our two-part study, we estimate the nominal electricity generation and GHG (greenhouse gas) mitigation costs of using harvest residue from a hardwood forest in Ontario, Canada to fuel (1) a small-scale (250 kW_e) combined heat and power wood chip gasification unit and (2) a large-scale (211 MW_e) coal-fired generating station retrofitted to combust wood pellets. Under favorable operational and regulatory conditions, generation costs are similar: 14.1 and 14.9 cents per kWh (c/kWh) for the small- and large-scale facilities, respectively. However, GHG mitigation costs are considerably higher for the large-scale system: \$159/tonne of CO_2 eq., compared to \$111 for the small-scale counterpart. Generation costs increase substantially under existing conditions, reaching: (1) 25.5 c/kWh for the small-scale system, due to a regulation mandating the continual presence of an operating engineer; and (2) 22.5 c/kWh for the large-scale system due to insufficient biomass supply, which reduces plant capacity factor from 34% to 8%. Limited inflation adjustment (50%) of feed-in tariff rates boosts these costs by 7% to 11%. Results indicate that policy generalizations based on scale require careful consideration of the range of operational/regulatory conditions in the jurisdiction of interest. Further, if GHG mitigation is prioritized, small-scale systems may be more cost-effective.

1. Introduction

The high cost of producing electricity from biomass is widely considered to be a primary impediment to increasing bioenergy supply and realizing associated economic and environmental benefits [1–3]. To overcome this economic barrier, many governments offer subsidies to encourage investment in bioenergy technologies. However, effective policy design is challenged by the considerable variation in bioenergy generation costs resulting from numerous operational and regulatory conditions that are specific to individual projects and jurisdictions, including conversion efficiency, fuel supply and subsequent capacity factor, financing costs, expected returns, and differing regulatory requirements [4]. Yet, there is one cost consideration that consistently determines the level of subsidization: bioenergy production costs, outside of the cost of feedstock, tend to decrease with scale, or the rated capacity of the system (e.g., [5–7]). Thus, supply-side subsidy programs often provide greater financial support for smaller-scale projects within a given technology class.

FIT (Feed-in tariff) programs, which offer fixed payment rates for the production of renewable electricity, demonstrate considerable inter-jurisdictional variability in the number of technology classes, scales, and related provisions that are taken into account. In a comparison of the FIT programs of Ontario (Canada) and Germany, Mabee et al. [8] noted that the Ontario program differentiates between two bioenergy scales, whereas the German program differentiates between four scales. A number of provisions ("adders") are available through the German program for specific aspects of bioenergy projects that result in desirable auxiliary benefits (e.g., waste heat utilization) [8]. There are also differences in the treatment of the contract over time: in Ontario, an annual FIT rate escalation is present, but not fully indexed to inflation [8], whereas the FIT rate for bioenergy facilities under the German program does not change throughout the lifetime of the contract [9]. These program details can have important consequences for attracting investment in bioenergy capacity. Studies have shown that the rates offered for bioenergy are often misaligned with actual generation costs, including those of Ontario's FIT program [4]. The Ontario FIT rate for bioenergy projects smaller than 500 kW_e has recently been

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increased from 13.8 to 15.6 cents/kWh (c/kWh), whereas projects larger than 500 kW_e are now ineligible for FIT subsides, which have been replaced with a bidding/auction mechanism for large projects [10,11]. Previously, bioenergy projects larger than 10 MW_e commanded a FIT of 13.0 c/kWh [11]. Relative to scale, German FITs for biomass technologies have differed to a much greater extent, starting at 0.08 €/kWh for a plant $\leq$ 20 MW_e, and reaching 0.12 to 0.22 €/kWh for small-scale plants 150 kW_e and under [8].

Most bioenergy subsidization initiatives acknowledge that generation costs, and subsidy requirements per unit of electricity generated, decrease as the rated electrical capacity of bioenergy facilities increases. However, unlike fossil fuel-based electricity generation projects, fuel procurement costs for bioenergy systems rise rapidly with scale, a function of the relatively low spatial distribution density, energy density, and bulk density of biomass [7,12,13]. These unfavorable properties of biomass have constrained the scales of bioenergy facilities in North America since the 1980s to an average of approximately 20 MW_e [14]. With the exception of a few recent co-firing projects in northwestern Europe, supply constraints have reduced co-firing rates to an average of 2.8% [15]. In Ontario, initial plans to retrofit coal-fired generating stations to combust wood pellets included a provision that all wood pellet inputs must be derived from in-province biomass supplies. This further constrains biomass supply opportunities and has limited the capacity factor (the ratio of actual output to potential output, based on the nameplate capacity of the facility) of a retrofitted coal-fired generating station in the province to 8% [16].

As bioenergy sectors grow, low cost biomass supplies such as sawmill residue will become fully utilized, requiring procurement of higher cost biomass sources [17,18]. The contribution of forest-origin biomass (including roundwood and harvest residue), to total biomass supply is expected to increase in jurisdictions with active forest sectors, as has been observed in Finland and Sweden [19]. Harvest residue (stem tops, branches, and small-diameter unmerchantable trees) is the lowest cost source of biomass that can be procured from forest operations because the fixed costs of the machinery used in these operations are already borne by the recovered merchantable roundwood, and there are usually no alternative economic uses for the residue. However, the amount of residue generated per hectare is equivalent to only a small portion of roundwood production, requiring a larger theoretical procurement radius relative to roundwood, for a given facility scale. Hence, with harvest residue as the main supply source, small-scale systems (e.g., <500 kW_e), when appropriately sited, could have lower generation costs than large-scale systems because the lower annual biomass demand can maintain procurement costs within acceptable limits. Given the additional GHG (greenhouse gas) benefits of utilizing harvest residue for energy [20,21], future iterations of bioenergy subsidy programs would benefit from a better understanding of the relative costs of small- and large-scale bioenergy facilities utilizing harvest residue as the main fuel source.

In addition to biomass supply constraints, there are additional context-sensitive factors that can also serve to reduce the subsidy requirements of small-scale systems relative to large-scale systems. Small-scale CHP (combined heat and power) facilities that are co-located with industrial facilities or district heating networks can have potential revenue advantages relative to large-scale facilities, which tend to lack proximal heat demand [22]. For example, costs of electricity generation fall from 18 to 11 c/kWh when taking into account the economic value of heat recovered in small-scale biomass gasification CHP systems [23]. With regard to GHG mitigation costs, large-scale systems tend to have higher supply chain emissions, such as those from additional feedstock transportation and processing [24–26]. While electricity generation costs may still be larger for small-scale systems, GHG mitigation costs can drop below those of larger-scale systems due to the improved GHG savings. When considering the potential revenues on carbon markets, the relative subsidy amount required for small-scale systems may further decrease. Conversely, small-scale systems may have larger subsidy requirements in jurisdictions like Ontario, which has a regulation mandating the continual presence of an operating engineer [27], even though unnecessary for certain system designs [4,28].

In this paper, part II of a two-part study (Part I: [29]), we compare the life cycle costs of using harvest residue procured from a hardwood forest in Ontario in a small- and a large-scale bioenergy facility. The small-scale bioenergy facility is a hypothetical wood chip-fueled CHP gasification system (250 kW_e unit) (System 1), whereas the large-scale bioenergy facility is a coal-fired generating station retrofitted to combust wood pellets that is currently operational in Ontario (211 MW_e unit) (System 2). Our analysis estimates the cost of electricity production, and hence the FIT rates that would be necessary to allow bioenergy to compete with lower cost electricity from coal and other fossil fuels. GHG mitigation costs are also estimated in order to assess which system meets this policy objective at lower cost. The sensitivity of the results to capacity factor, operating expenses, and FIT escalation rates is explored for each system through the use of two scenarios representative of different operational and regulatory conditions in the province. Results are further qualified using sensitivity analysis, and discussed in relation to Ontario's FIT policy.

2. Methods

2.1. Study area, scenarios, and system boundary

As in Part I of our study which pertains only to life cycle GHG emissions and impacts, the LCC (life cycle costing) is based on the use of harvest residue collected from the HFWR (Haliburton Forest and Wildlife Reserve), a privately-owned forest located in the Great Lakes-Saint Lawrence forest region of southern Ontario. The residue would be collected via the modification of a conventional single-tree selection operation, producing an average of 1.9 dry tonnes of biomass per hectare (dt/ha) in the form of small-diameter roundwood [30]. The collected residue would be processed and supplied to either (1) a hypothetical 250 kW_e CHP gasification facility installed at the HFWR sawmill using wood chips as fuel (System 1); or (2) an existing 211 MW_e coal-fired generating station in Atikokan, Ontario retrofitted to combust wood pellets, generating electricity only (System 2).

Each system is evaluated under two scenarios that are differentiated on the basis of key parameters related to operational and regulatory conditions. One scenario represents favorable conditions (S1a and S2a) from a bioenergy project cost perspective, and the other represents current conditions in Ontario (S1b and S2b). Differences between S1a and S1b relate to operation and maintenance (O&M) costs, whereas capacity factor, which is itself a function of the total annual biomass supply (further described in Section 3), differs between S2a and S2b. To account for the possibility that FIT escalation rates are adjusted, the scenarios modeled under favorable conditions (S1a and S2a) include an escalation rate that is equivalent to the CPI (Consumer Price Index) inflation rate (3%/year as in Moore et al., [4]), whereas the scenarios modeled under current conditions (S1b and S2b) include an escalation rate that is equivalent to half of the CPI inflation rate (1.5%/year). Thus, the favorable operational and regulatory conditions, relative to existing conditions, incorporate the following assumptions: (1) the removal of the requirement that an operating engineer must be present at all times while the bioenergy facility is in operation (see Section 2.3.5); (2) an increase in the capacity factor of the large-scale