Steam-Treated Wood Pellets: Environmental and Financial Implications relative to Fossil Fuels and Conventional Pellets for Electricity Generation

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Abstract
Steam-treated pellets can help to address technical barriers that limit the uptake of pellets as a fuel for electricity generation, but there is limited understanding of the cost and environmental impacts of their production and use. This study investigates life cycle environmental (greenhouse gas (GHG) and air pollutant emissions) and financial implications of electricity generation from steam-treated pellets, including fuel cycle activities (biomass supply, pellet production, and combustion) and retrofit infrastructure to enable 100% pellet firing at a generating station that previously used coal. Models are informed by operating experience of pellet manufacturers and generating stations utilising coal, steam-treated and conventional pellets. Results are compared with conventional pellets and fossil fuels in a case study of electricity generation in northwestern Ontario, Canada. Steam-treated pellet production has similar GHG impacts to conventional pellets as their higher biomass feedstock requirement is balanced by reduced process electricity consumption. GHG reductions of more than 90% relative to coal and ~85% relative to natural gas (excluding retrofit infrastructure) could be obtained with both pellet options. Pellets can also reduce fuel cycle air pollutant emissions relative to coal by 30% (NOx), 97% (SOx), and 75% (PM_{10}). Lesser retrofit requirements for steam-treated pellets more than compensate for marginally higher pellet production costs, resulting in lower electricity production cost compared to conventional pellets ($0.14/kWh vs. $0.16/kWh). Impacts of retrofit infrastructure become increasingly significant at lower generating station capacity factors, further favouring steam-treated pellets for both environmental and financial metrics.

Key words: Wood pellets; electricity generation; life cycle assessment; techno-economic analysis; Canada

1. Introduction
Use of biomass fuels for electricity generation can simultaneously contribute to a number of common policy objectives, including: increasing the use of renewable energy; reducing greenhouse gas (GHG) emissions; compliance with air pollutant (AP) emissions regulations; and encouraging economic development in communities dependent on agriculture and forestry sectors. Compared to raw biomass, wood pellets offer a more homogenous and energy-dense fuel with superior combustion characteristics (Zhang et al., 2010). Wood pellets are particularly well-suited for use in retrofit coal-fired generating stations, either as a supplemental fuel ("co-firing" with coal) or as the primary fuel, and have been identified as a potentially cost-effective option to reduce GHG emissions associated with electricity generation. As a result of these factors, wood pellet markets have rapidly grown, with 22 million tonnes of pellets produced globally in 2013 (FAO, 2014), a ten-fold increase over the past decade (Lamers et al., 2012).

Certain characteristics of conventional "white" wood pellets, however, negatively impact their viability as a fuel for electricity generation. Conventional pellets are hydrophilic and will absorb moisture from their environment during transport and storage, degrading the mechanical integrity of pellets (Graham et al., 2014) and negatively impacting combustion characteristics. Reducing water uptake requires storage of pellets in closed silos, which can significantly increase costs to retrofit coal generating stations. The friability of conventional pellets is also of concern, leading to dust formation and associated health risks due to airborne exposure and risk of explosion (Stelte, 2012). Further health risks may result from pellet degradation by fungal growth, resulting in exposure to airborne toxins and fungal spores (Graham et al., 2012; Stelte, 2012).

Thermally-treated pellets, including steam-treated pellets, have been evaluated for their ability to address limitations of conventional pellets. Thermally-treated pellets can be produced by torrefaction or steam treatment. Torrefaction involves heating solid biomass in a reduced oxygen environment, releasing a portion of the biomass volatiles and destroying the fibrous structure by breaking down the hemicellulose fraction (Ciolkosz et al., 2011; Koppejan et al., 2012). Steam treatment exposes biomass to steam at pressure, similarly releasing a portion of volatiles and degrading hemicellulose, followed by rapid depressurisation that further disrupts the fibrous structure. After thermal treatment, both torrefied and steam-treated pellets exhibit higher energy density, hydrophobicity, and greater durability in outdoor storage than conventional pellets (Obernberger and Thek, 2010; Koppejan et al., 2012; Graham et al., 2014). However, thermal treatment processes are generally more energy intensive and more costly than conventional pellet production methods. As such, it is necessary to better understand implications of thermal treatment, considering the potential for higher fuel costs and GHG impacts.

Realising potential environmental benefits by substituting wood pellets for fossil fuels depends on activities throughout the life cycle of fuel production and use. Prior life cycle studies have found that conventional wood pellets can significantly reduce GHG emissions relative to coal and natural gas-fired electricity generation, and contribute to reducing NOx and SOx emissions from coal combustion (e.g., Zhang et al., 2010). Similarly, comprehensive analyses must be developed to ensure that steam-treated pellets can deliver GHG emissions reductions compared to fossil fuels and to identify any trade-offs between pellet production technologies. Adams et al. (2015) compared torrefied and conventional wood pellets for UK consumption, finding GHG emissions to range from 17 to 40 $gCO_2eq./MJ_{pellet}$ for torrefied pellets and 27 to 40 $gCO_2eq./MJ_{pellet}$ for conventional pellets depending on the biomass drying requirement and fuel source, suggesting that torrefaction does not significantly impact GHG emissions relative to conventional pellets. Kabir and Kumar (2012) evaluated electricity generation from torrefied biomass, with GHG emissions ranging from 137 to 215 $gCO_2eq./kWh$ depending on the biomass source, which represents significant reductions relative to typical GHG emissions of coal-fired electricity production of approximately 1,000 to 1,200 $gCO_2eq./kWh$ (Zhang et al., 2010). Recent cost estimates to produce conventional, torrefied, and steam-treated wood pellets for electricity generation (Strauss, 2014) found both thermally-treated pellet types to be a lower cost alternative to conventional pellets: reduced dry storage costs more than compensated for higher pellet production costs. However, to our knowledge, no study has evaluated the life cycle environmental and financial impacts of steam-treated wood pellet production and use for electricity generation, nor compared with the performance of conventional pellets and fossil fuel generation alternatives.

While steam-treated wood pellets can address many technical barriers associated with conventional wood pellets, there is little understanding of the overall environmental and financial performance of steam-treated pellets for electricity generation. The objective of this study is to evaluate the production and use of steam-treated wood pellets for electricity generation. Life cycle GHG and selected air pollutant (AP) emissions are estimated and compared with conventional "white" wood pellets and reference fossil fuel generation pathways (coal, natural gas). Electricity generation costs for each pathway are assessed and the marginal cost of GHG emission abatement is quantified. We apply life cycle environmental and cost models to a case study of electricity generation in Ontario, Canada, which provides general insights of relevance to pellet production and use in other jurisdictions.

2. Methods

This study investigates, on a life cycle basis, environmental and financial implications associated with electricity generation by the following pathways:

1. Reference coal: Production of electricity from coal in the existing Thunder Bay Generating Station (GS) located in northwestern Ontario.
2. Reference natural gas: Production of electricity from a representative (hypothetical) natural gas combined cycle (NGCC) facility in the vicinity of Thunder Bay.
3. Reference biomass: Production of electricity from conventional “white” wood pellets as the primary (sole) fuel source at Thunder Bay GS.
4. Steam-treated pellets: Production of electricity from steam-treated “black” wood pellets as the primary (sole) fuel source at Thunder Bay GS.

Life cycle environmental and techno-economic models are developed to assess the energy use, GHG and AP emissions, and techno-economic implications of the electricity generation pathways. Coal and wood pellet pathways are based on operating experience of thermal electricity generation facilities in northwestern Ontario: Thunder Bay GS (150 MW) has been operating with steam-treated pellets as the primary fuel source since 2015, while the Atikokan GS (200 MW) has been operating with conventional pellets as its primary fuel since 2014 and is North America’s largest 100% biomass facility. Both facilities were previously operated with coal. The steam-treated pellet production model is based on information from demonstration-scale production by Arbaflame (www.arbaflame.no). All life cycle activities from resource extraction (e.g., forest management for biomass supply; coal mining) and fuel production (e.g., pellet manufacture) through to combustion at the GS for electricity generation are considered, inclusive of transportation stages. The production of energy and material inputs to these activities are modelled or obtained from databases, as detailed in Sections 2.1 and 2.2. Transmission and distribution of electricity are not included, as these are common to all pathways considered. Similarly, activities associated with electricity consumption by consumers are not included. Inputs and emissions from the construction of infrastructure and the manufacture of equipment generally have much smaller impacts than the operation of these systems and are therefore not considered in the present study, with one exception: retrofit infrastructure to enable wood pellet firing at the Thunder Bay GS is evaluated due to the substantial difference in infrastructure requirements for conventional and steam-treated wood pellet firing.

The functional unit selected for the electricity analysis is one kilowatt-hour (kWh) of electricity produced. Results for the biomass pathways are also presented on the basis of the energy content of the pellets (one MJ pellet) for all activities up to and including the delivery of pellets to the GS. The environmental metrics considered are primary energy demand, GHG emissions, and AP emissions (NO_x, SO_x, and PM_{10}). GHG emissions considered are CO_2, CH_4, and N_2O, which are aggregated to CO_2 equivalent (CO_2eq.) based on 100-year global warming potentials (IPCC, 2013). These values are 1 for CO_2, 34 for CH_4, and 298 for N_2O. The techno-economic analysis includes financial modelling of wood pellet production costs (conventional and steam-treated pathways) and calculation of the cost of electricity generation for all pathways.

2.1 Wood pellet pathways

2.1.1 Biomass supply

Biomass for pellet production is assumed to be supplied as roundwood from the boreal forest northwest of Thunder Bay. Harvest is assumed to occur in sustainably managed public forests within the region, creating a market for merchantable logs that are no longer marketable due to decline in the pulp and paper sector. Undertaking this harvest would therefore not compete with traditional forest products and can improve forest health and help avoid the propagation of species with limited commercial value. The biomass supply is comprised of hardwood species: 75% poplar, 23% white birch, and less than 1% each of red maple and black ash (Pembina, 2012).

Forest operations relevant to wood pellet production include: biomass harvesting; forest renewal; and forest road construction activities. Data for these activities are derived from an analysis undertaken by

FPInnovations for biomass harvest in northwestern Ontario and utilised in a life cycle study of wood pellet production for the Atikokan GS, located 180 km northwest of Thunder Bay (Pembina, 2012; Ter-Mikaelian et al., 2015). Bark associated with roundwood logs is assumed to be delivered intact and is therefore available as an energy source for conventional and steam-treated pellet manufacturing processes (0.21 oven dry tonnes (odt) of bark per odt of biomass based on supply species composition). Logs are transported 115 km by self-loading truck to a hypothetical pellet production facility, based on a biomass supply analysis from Pembina (2012). Biomass sources in addition to roundwood (e.g., mill residues including sawdust; harvest residues) could be utilised in the production of conventional and steam-treated wood pellets; implications of alternative biomass sources on environmental and financial performance are discussed in Section 4.

An assumption in this study is that the emissions of CO_2 resulting from the combustion of biomass pellets are entirely balanced by the carbon sequestered by the trees during growth. This assumption is commonly used in such studies (e.g., Zhang et al., 2010), but the assumption may not always be correct. A number of studies have attempted to quantify the impact of forest carbon dynamics (the "cycling" of carbon between forest, products, atmosphere, and tree regrowth) (Manomet 2010; McKechnie et al., 2011). However, there is no scientific or political consensus as to how carbon cycling should be included in bioenergy studies or related policies. In the current study, we do not consider GHG emissions implications associated with forest carbon dynamics. However, we discuss the potential implications of this assumption in Section 4.

2.1.2 Wood pellet production
The conventional pelletization process is presented in Figure 1a. At the pellet production facility, the logs first pass through an initial debarking stage. Bark is diverted from the pellet stream for use as process energy to dry the remaining biomass. The biomass destined for pelletization passes through an initial grinding stage, is then further ground in a hammermill, and then dried to about 10% moisture content. The biomass is subsequently compressed in a pellet mill to form pellets and these are then cooled. Data on electricity and biomass consumption during pelletization were provided by a pellet producer in the northeastern United States and reflect requirements for a modern facility with a capacity of 12 odt of pellets per hour (Zhang et al., 2010). Table 1 presents details of the energy and mass balances of the conventional pellet production process. The total electricity use for production of the conventional pellets is 144 kWh per odt of pellet. Electricity required for the facility is assumed to be provided by the average Ontario generation mix (IESO, 2013). Pellets are assumed to be transported by rail to Thunder Bay GS (275 km).

The steam-treated pellet production process is similar to that for conventional pellets (Figure 1b). Biomass supply, pellet plant location, and preparation of input biomass (debarking, initial grinding) are assumed to be similar to those for the conventional pellet production. Steam-treated pellets undergo a steam treatment reaction, during which biomass is heated to 200-300°C and held for 1-15 minutes and then rapidly decompressed. The steam treatment process contributes to size reduction of the biomass, thereby reducing milling requirements and associated electricity inputs. At least two reactors are employed in the process to minimize energy consumption of the process by using the vapour discharged from the first reactor as a preheating medium for the material supply to the second reactor. Downstream processes (drying, pelletization, cooling) are similar to the conventional pellet production process.

Key pellet production process data are shown in Table 1. Data regarding the mass and energy balances of the steam-treated pellet process are provided by Arbaflame AB, extrapolating data from operation of a demonstration facility (capacity 40,000 t/yr) to larger-scale production (100,000 to 200,000 odt/yr). These data were verified by simulation of the production process with Aspen Plus® process modeling software (www.aspentech.com), which has been commonly employed in the simulation and modeling of biofuels and bioproducts (e.g., Humbird et al., 2011) and has an intensive databank of lignocellulosic feedstocks (including wood) and thermodynamic models to handle solid biomass processes. Industrial data are modified and supplemented to reflect the specifics of the pathways modelled in this study, including roundwood biomass preparation and milling activities; steam generation from bark; and incorporation of wastewater treatment processes. Results of the process modeling are compared with publically available information, including patents (Zilkha, 2010; ArbaFlame, 2005) and relevant literature (Lam, 2011; Biswas et al., 2011; Tooyserkani et al., 2013) to ensure representativeness of the data used in the current study. Total electricity required for the steam-treated pellet production process is 120 kWh/odt pellet, while bark is sufficient to provide all thermal energy requirements. Pellet characteristics are based on generator specifications for conventional and steam-treated pellets; higher energy content (5%) could be achievable when using exclusively hardwood feedstock. Assumptions for pellet transport from the mill to GS are the same as for conventional pellets.

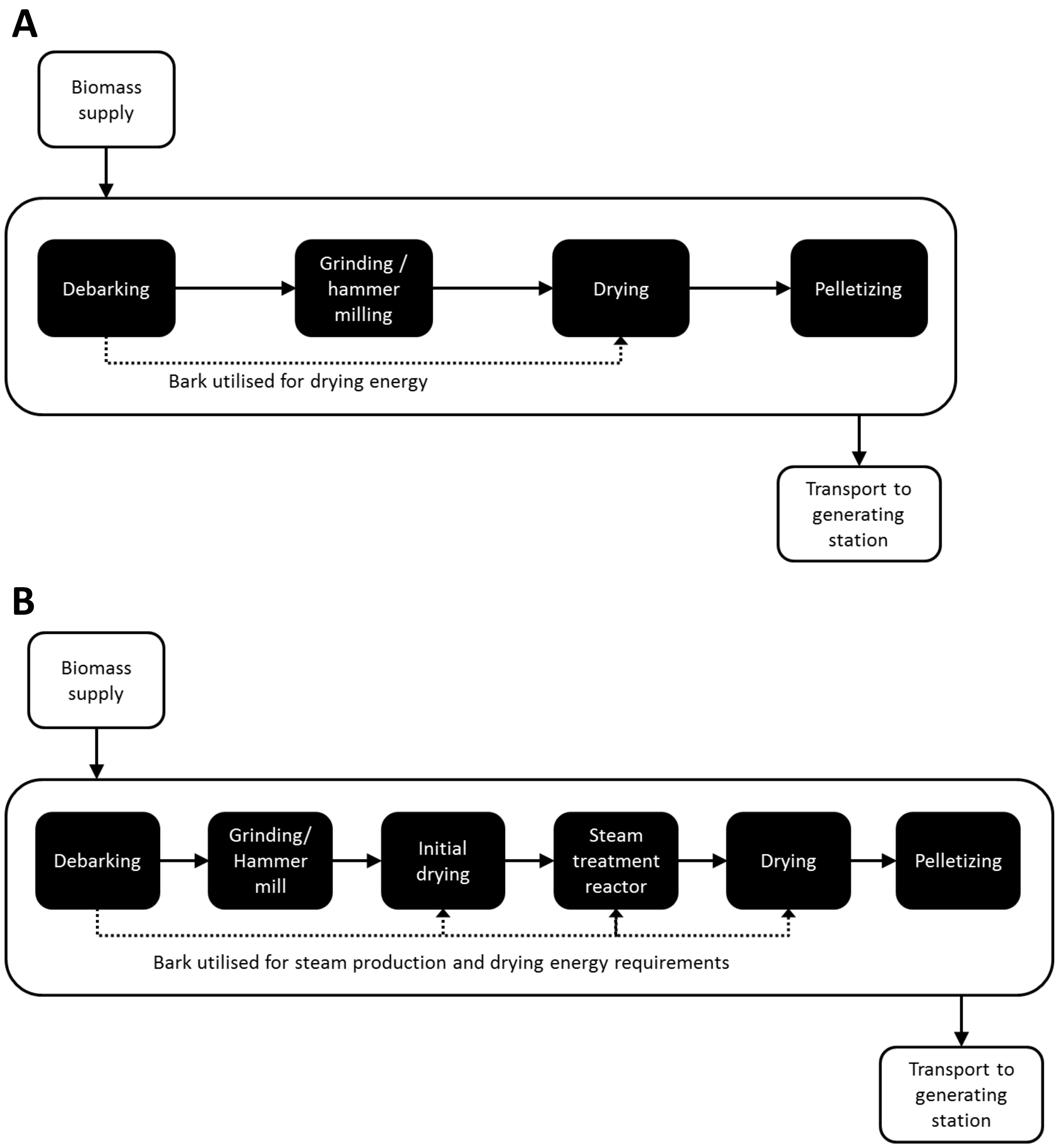

Figure 1. Block flow diagram of the conventional pellet production process (A) and the steam-treated pellet production process (B).

Table 1. Parameters and assumptions for the conventional and steam-treated pellet production processes

	Conventional Pellets	**Steam-treated Pellets**
Debarking, initial grinding electricity use ($kWh/odt_{biomass}$)	3.75	3.75
Pellet production		
Electricity (kWh/odt_{pellet})	144	120
Thermal energy (GJ/odt_{pellet})	3.0	3.8
Mass loss (%)	negligible	14%
Pellet characteristics		
Moisture content (%)	5%	5%
Energy content (GJ/odt_{pellet})	19 [1]	21 [1]
Transportation to GS		
Mode	Rail	Rail
Distance (km)	275	275

Notes: 1. Based on specifications for conventional and steam-treated pellets (Mager, 2015a).

2.1.3 Wood pellet firing infrastructure

Retrofit requirements differ between the two pellet types considered in this study. For conventional pellets, covered storage silos are needed to prevent water absorption and mechanical degradation of the pellets. In contrast, steam-treated pellets are compatible with open storage due to their hydrophobic nature. Further, steam-treated pellets are friable and fracture during milling, which makes use with existing coal pulverizers and burners possible. Conventional pellets do not fracture but instead break down to their constituent dust during milling. As a result, coal GS conversion for conventional pellet utilisation can require burner modifications or replacement to deliver fuel to the boiler at the proper velocity. For both conventional and advanced pellets, conveying and dust suppression equipment is needed to handle pellets on site, although steam-treated pellets typically generate less dust due to their lower susceptibility to disintegration during storage and handling compared to conventional pellets.

Generating station retrofit infrastructure models are developed based on actual conversions of coal-fired GSs (Atikokan, Thunder Bay) to utilise conventional and steam-treated pellets, respectively. The Atikokan GS began operation in 2014 utilising conventional pellets as its primary fuel. The conversion of Atikokan GS from coal to pellet fuelling included addition of two pellet storage silos (10,000 t_{pellet} capacity), new fuel handling and storage systems, and modifications to furnace and controls systems. The Thunder Bay GS began operation in 2015 using steam-treated pellets as its primary fuel. Due to greater compatibility with existing systems, the conversion of Thunder Bay GS required far less infrastructure investment, limited to material handling and dust suppression systems. In the present study, we assume that the Atikokan and Thunder Bay retrofits are reasonably typical of coal GS conversion to conventional and advanced wood pellets, respectively, and that modifications similar to those that occurred at Atikokan GS would be necessary at Thunder Bay GS to enable conventional pellet firing.

There are limited data available regarding the material and energy inputs for the Atikokan and Thunder Bay GS retrofit infrastructure as these projects have already been completed and such data were not collected during the retrofit activities. This data limitation precludes the possibility of conducting a "process-based" life cycle assessment (Hendrickson, 1997) based on an inventory of inputs and emissions for the retrofit activities. Therefore, to estimate environmental impacts associated with GS retrofit infrastructure, we employ an Economic Input-Output Life Cycle Assessment (EIO-LCA) approach wherein monetary flows between industry sectors are correlated with environmental impacts (Hendrickson et al., 2006). The most recent Canada EIO-LCA model (Norman et al., 2007; CMU, 2016) is updated for use in the current study. Retrofit costs are converted to equivalent producer prices (required for use in the EIO-LCA model) by accounting for sales tax (13%), sector-specific profit margins (Damodaran, 2015; Yardeni, 2015), and assumed transport costs (10%). Environmental impacts associated with sector-specific economic activity are updated based on national trends in Canadian GDP (Statistics Canada, 2015a), GHG emissions

(Environment Canada, 2015a), energy consumption (Menard, 2005; Nyboer et al., 2014; Statistics Canada, 2015b), and AP emissions (Environment Canada, 2015b) to approximate recent EIO-LCA emissions factors. While this approach to updating the EIO-LCA model does not take into account recent changes in the relative contribution of sectors to total GDP or sector-specific initiatives that may affect energy use and environmental impacts, overall there is significant inertia in an economy and for the purposes of the current study, the model is expected to provide relevant insights. Cost data related to the Atikokan and Thunder Bay GS retrofits (Table 3) are input to the model: $773/kW (retrofit for conventional pellets) and $31/kW (retrofit for steam-treated pellets). Total project cost divided across the relevant industrial sectors is based on input and advice from Ontario Power Generation (Mager, 2015b). Conventional pellet retrofit costs are allocated between the "Non-Residential Building and Engineering Construction" (65%) and "Machinery Manufacturing" (35%) sectors, whereas all retrofit costs for steam-treated pellets are allocated to the "Machinery Manufacturing" sector.

2.1.4 Electricity generation

The biomass pathways assume the retrofit of the Thunder Bay GS to use pellets as sole fuel. Use of pellets results in heat rate degradation due to several technical issues related to the firing and milling of wood pellets in facilities initially designed for coal use (see Zhang et al. 2010). Data for heat rates and AP emissions (NO_x, SO_x, PM_{10}) are provided by Ontario Power Generation from test firings of steam-treated pellets at Thunder Bay GS and operation of the nearby Atikokan GS with conventional pellets as the primary fuel source (Marshall, 2014). Heat rates are dependent on GS operation: heat rate degradation (decreasing generation efficiency) typically occurs when a GS is operated below its rated capacity. Data from Ontario Power Generation operations allow us to estimate GHG emissions as a function of electrical output over a range from approximately 30% to 100% of rated capacity. As a base case, we assume the GS would be operated at full capacity to maximise efficiency. Non-CO_2 GHG emissions data from pellet combustion are not available and are estimated based on database values for biomass combustion (NRCan, 2014) and assumed to vary in proportion to the fuel consumed. As discussed in Section 2.1, the current study assumes that the emissions of CO_2 resulting from biomass pellet combustion are entirely balanced by the carbon sequestered by the plants during growth. As such, biomass combustion-related CO_2 emissions are not included in the quantification of life cycle GHG emissions.

The capacity factor of GS operation – the ratio of actual electricity output relative to operation at 100% of capacity – is an important factor in assessing environmental and financial impacts of the electricity generation pathways. Fixed costs (capital costs, fixed operation and maintenance costs) and environmental impacts (e.g., associated with retrofit infrastructure) become increasingly significant at lower capacity factors, as they are divided over a smaller quantity of generated electricity. As a base case, we assume GS operation at a capacity factor of 55%, which is within the range of historic operation of the Thunder Bay GS, and evaluate the sensitivity of results to capacity factors ranging from 5% to 100%. We do not assess the implications of transient operation of the GS in the present study (e.g., start-up auxiliary fuel use, power output ramping).

2.2 Reference fossil fuel pathways

The coal reference pathway is modelled based on historic operation of the Thunder Bay GS utilising coal as its primary fuel. Upstream emissions (coal mining, processing and transport to the GS) and combustion at the Thunder Bay GS are included in our analysis. Thunder Bay GS's two operating coal-fuelled generators produced up to 306 MW of electricity, using low-sulfur Powder River Basin subbituminous coal. In the current study, we examine the generation of electricity in one unit, which has a net generating capacity of 150 MW. Key data and assumptions for the coal pathway are shown in Table 2. We assess environmental and financial performance over a range of capacity factors similar to the wood pellet pathways (see Section 2.1.4). We also assess the impact of electricity output rate on life cycle GHG emissions based on heat rate (generation efficiency) data provided by Ontario Power Generation for operation from approximately 25% to 100% of rated capacity (Marshall, 2014).

Table 2. Parameters and assumptions for the coal reference pathway

Life Cycle Activity	Value and Details
Coal type and origin	100% Sub-bituminous Northern Powder River Basin from Montana [1]
Mining and processing	100% surface mined [2]
Transportation mode and distance	Rail: 1,660 km (Montana to Superior, Wyoming) Vessel: 2 days (Superior to Thunder Bay) [1]
Coal Higher Heating Value (GJ/t)	18.7 (as received) [1] 27.2 (dry)
Coal moisture content as received (%)	31 [1]
Sulfur content (% by wt.)	0.41 [1]

Notes: 1. Personal communication (Marshall, 2014). 2. US EIA (2009)

The natural gas reference pathway is based on a hypothetical natural gas combined cycle (NGCC) GS located in the vicinity of the Thunder Bay GS and which would receive gas from Alberta. Implications on results of a single cycle gas turbine system are also discussed (Section 3.2). Upstream emissions (extraction of the natural gas in Alberta, processing and transport to the GS) and combustion at the GS are included in the analysis. We adapt models developed in prior studies (Zhang et al., 2010; Sanscartier et al., 2013) for this analysis. We do not consider retrofitting of the coal GS to natural gas boiler or NGCC systems in the present study. Similar to the wood pellet and coal pathways, we consider operation of the NGCC GS over a range of capacity factors from 5% to 100%. We also estimate the impacts of electricity output rate on life cycle GHG emissions to account for heat rate degradation at low outputs. Reported efficiency data for a typical NGCC system designed for variable load operation is utilised to assess emissions for outputs ranging from approximately 20% to 100% of rated capacity (IEAGHG, 2012). Emissions of CH_4 and N_2O are estimated based on data from NRCan (2014) and assumed to vary proportionally to the quantity of natural gas combusted.

2.3 Financial analysis

Life cycle cost models are developed to estimate the cost of producing steam-treated and conventional wood pellets, and the cost of producing electricity from the coal, natural gas, and biomass pathways. Capital (including financing), fixed operating and maintenance (O&M), non-fuel variable O&M, and fuel costs are considered. Taxes, subsidies, and profit margins are not included in the analysis.

For all pathways, the cost of electricity is calculated as the ratio of the annualised cost of the GS to the electricity output during the year:

$$COE = \frac{AC}{AE_{output}} \quad (1)$$

where COE = cost of electricity (\$/kWh); AC = annual cost (\$/yr), calculated using Eq. 2; AE_{output} = annual net electricity generation (kWh/yr), taking into account the net capacity of the system and the GS capacity factor. Annual costs are calculated as:

$$AC = ACC + AFOM + AVOM + FC \quad (2)$$

where ACC = annualised capital cost ($/yr); AFOM = annual fixed O&M cost ($/yr); AVOM = annual variable O&M cost ($/yr), estimated based on annual electricity output; and AFC = annual fuel cost ($/yr), estimated based on annual electricity output, heat rate of a given generation pathway, and delivered fuel cost.

The marginal cost of GHG emission abatement associated with the wood pellet pathways is calculated by comparing GHG emissions and electricity generation costs with those of the reference fossil fuel pathways:

$$Cost_{GHG} = \frac{COE_{pellet} - COE_{reference}}{GHG_{reference} - GHG_{pellet}} \quad (3)$$

Where $Cost_{GHG}$ is the marginal cost of GHG emission abatement ($/t$CO_2$eq); COE is the cost of electricity ($/kWh) produced by pellets and by reference fossil fuel pathway; and GHG is the life cycle GHG emissions (tCO_2eq./kWh) associated with the pellet and reference fossil fuel pathway.

2.3.1 Wood pellet production

Key financial parameters and assumptions related to the wood pellet production cost models can be found in Table 3. Biomass feedstock cost, including forestry operations and delivery to the pellet mill, is estimated based on previous financial analyses of wood pellet production in Ontario (Deloitte, 2008; KPMG, 2008) at $100/$odt_{biomass}$. This estimate is in line with other estimates of biomass procurement costs from roundwood in the northwest boreal forest region of Ontario (e.g., IEA Bioenergy, 2014). As feedstock costs can represent upwards of 50% of pellet production costs, we consider the sensitivity of results to this parameter by considering feedstock costs indicative of other forestry biomass sources, including mill residues ($40/odt) and harvest residues $70/odt) (IEA Bioenergy, 2014; Ralevic et al., 2010). Implications of these alternative feedstocks on forest operations and pellet production processes, including their associated environmental impacts, are outside of the scope of the current study.

Wood pellet production activities include: size reduction, drying, pelletization, cooling, and storage. In the case of advanced, steam-treated wood pellets, size reduction is followed by a high pressure/temperature steam treatment and, after depressurization, a drying stage. Key financial analysis parameters for pellet production are shown in Table 3. Prior models of conventional wood pellet production in Ontario (Deloitte, 2008; KPMG, 2008) are updated and supplemented with recent cost data to model wood pellet production pathways for this study. Capital costs are scaled to a year 2015 basis using the Chemical Engineering Plant Cost Index (CEPCI, 2015) and representative Canadian and US dollar exchange rates in 2008 and 2015. Labour costs reported in Deloitte (2008) are scaled by a factor of 1.07 to reflect the most recent wage data for Canada's manufacturing sector (Statistics Canada, 2015c). Equipment-specific maintenance costs are assessed as equipment-specific capital cost based on Thek and Obernberger (2004).

The conventional wood pellet production cost model is adapted to estimate costs of steam-treated pellet production. Additional capital expenses associated with equipment for biomass steam treatment (pre-drying, steam generation, steam treatment reactor) are partially offset by reduced milling requirements. Capital expenses for steam-treated pellet production are estimated by the authors based on information supplied by Arbaflame (Brusletto, 2015). Cost data for steam-treated pellet production should not be interpreted as an estimate of costs of specific current or future Arbaflame pellet production systems.

Table 3. Wood pellet production parameters and assumptions for financial analysis.

	Conventional pellets	**Steam-treated pellets**
Pellet mill characteristics		
Capacity (odt_{pellet}/yr)	150,000	
Feedstock	Roundwood	
Thermal energy	Bark (included in roundwood)	
Capital costs ($/t-yr)	180 [1]	225 [1, 2]
Financing assumptions		

Economic life (yrs) Debt (%)/equity (%) Return on equity (%) Debt rate (%)	20 50/50 20 8	20 50/50 20 8
Operating and maintenance costs ($/t-yr) Labour Electricity Maintenance	 11 [1] 14 [3] 9 [1]	 11 [1] 16 [3] 11 [1]
Delivery to generating station ($/odt$_{pellet}$)	10	10

Notes: 1. Deloitte (2008) and KPMG (2008). 2. Brusletto (2015). 3. AMPCO (2015).

2.3.2 Electricity generation and reference pathways

Key financial data for electricity generation from wood pellets and reference fossil fuel pathways are shown in Table 4. Generating station retrofit requirements to enable wood pellet firing at existing coal GS differ significantly between conventional and steam-treated wood pellets, as explained in Section 2.1.3. Generating station retrofit costs are modelled assuming project costs for the conversion of Ontario Power Generation's Atikokan GS and Thunder Bay GS are representative of typical GS conversions to conventional and advanced pellets, respectively (Wong, 2015). A 10 year lifespan is assumed for the pellet retrofits based on expected lifetime of the retrofit plants, while the hypothetical new-build NGCC is assumed to have a 20 year economic life. For the coal pathway, capital costs are treated as sunk costs and so do not contribute to the assessed cost of electricity generated from coal. Capital costs for the NGCC pathway are from US EIA (2013). Fixed O&M and non-fuel O&M costs for all wood pellet and reference fossil fuel generation facilities are modelled based on US EIA (2013).

Coal fuel costs are assessed for Powder River Basin coal, which was historically utilised at the Thunder Bay GS, based on recent spot price (US EIA, 2015a) and transport cost data (US DOE, 2007). Baseline natural gas fuel costs are estimated based on 2014 reported average US electricity generator costs (U.S. EIA, 2015b). Natural gas costs could be higher for facilities located in regions with restricted natural gas supply such as northwestern Ontario. In such cases, guaranteeing fuel availability would require procurement of firm natural gas supply or provision of on-site storage, both of which would entail additional costs (IESO, 2015). We consider a hypothetical higher natural gas cost scenario ($10/GJ) to account for these additional costs.

The impacts of GS capital and fixed O&M costs on electricity generation price are highly dependent on the GS capacity factor. Comparing high and low capacity factors, fixed costs are spread over relatively greater (or smaller), electricity outputs, respectively. As a base case, the financial analysis assumes a capacity factor of 55%, which is within the range of historic operation of the Thunder Bay GS. In addition, we evaluate the sensitivity of results to GS capacity factors ranging from 5% to 100%.

Table 4. Electricity generation parameters and assumptions for financial analysis.

	Coal	NGCC	Conventional pellets	Steam-treated pellets
Capital costs ($/kW)	N/A	1,190 [1]	773	31
Financing assumptions				
Economic life (yrs)		20	10	10
Debt (%)/equity (%)		50/50	50/50	50/50
Return on equity (%)		15	15	15
Debt rate (%)		8	8	8
Operating and maintenance costs				
Fixed O&M ($/kW)	49 [1]	17 [1]	132 [1]	132 [1]
Non-fuel variable O&M ($/MWh)	5.8 [1]	4.7 [1]	6.6 [1]	6.6 [1]
Fuel cost ($/GJ)	2.8 [2]	6.1 [3] (10 [4])	calculated	calculated

Notes: 1. US EIA (2013). 2. Powder River Basin spot price (US EIA, 2015a); transport cost US DOE (2007). 3. 2014 average US natural gas cost reported by electricity generators (US EIA, 2015b). 4. Higher natural gas cost scenario $10/GJ to account for potential additional costs of firm natural gas supply in regions with restricted natural gas supply.

3. Results

3.1. Wood pellet production

Inputs to the pellet production processes differ due to mass loss during the steam treatment process (requiring greater biomass input than conventional pellets) and the lower electricity requirement associated with steam-treated pellet production. These factors contribute to a marginal decrease in GHG emissions for steam-treated pellet production relative to conventional pellets when considered on a pellet energy content basis (5.3 $kgCO_2eq./GJ$ and 5.5 $kgCO_2eq./GJ$ respectively) as shown in Figure 2. In contrast, evaluating GHG emissions on a pellet mass basis results in slightly higher GHG emissions (6%) for steam-treated pellets due to differences in energy density. For both pellet types, forest operations (for biomass supply), transportation (to mill and GS) and pelletization each account for approximately 1/3 of total GHG emissions. Impacts of forest operations are specific to northwestern Ontario and could vary regionally depending on local climate (e.g., growth rate) and management practices. Pelletization impacts are dominated by electricity generation and are therefore dependent on characteristics of the local grid. Due to ongoing efforts to reduce the GHG intensity of Ontario's electricity sector (including the phasing out of coal-fired generation), impacts of conventional pellet production have declined by more than 30% compared to our previous study (Zhang et al., 2010). Ongoing efforts to decarbonise transport fuels (e.g., utilisation of natural gas or renewable fuels in place of diesel) could similarly reduce GHG emissions associated with biomass supply. AP emissions associated with steam-treated pellet production show similar trends relative to conventional pellets: NOx, SOx, and PM_{10} emissions are 12% to 14% higher when evaluated on a mass basis (per odt_{pellet}), but are only marginally higher (2% to 3%) when considered on an energy content basis.

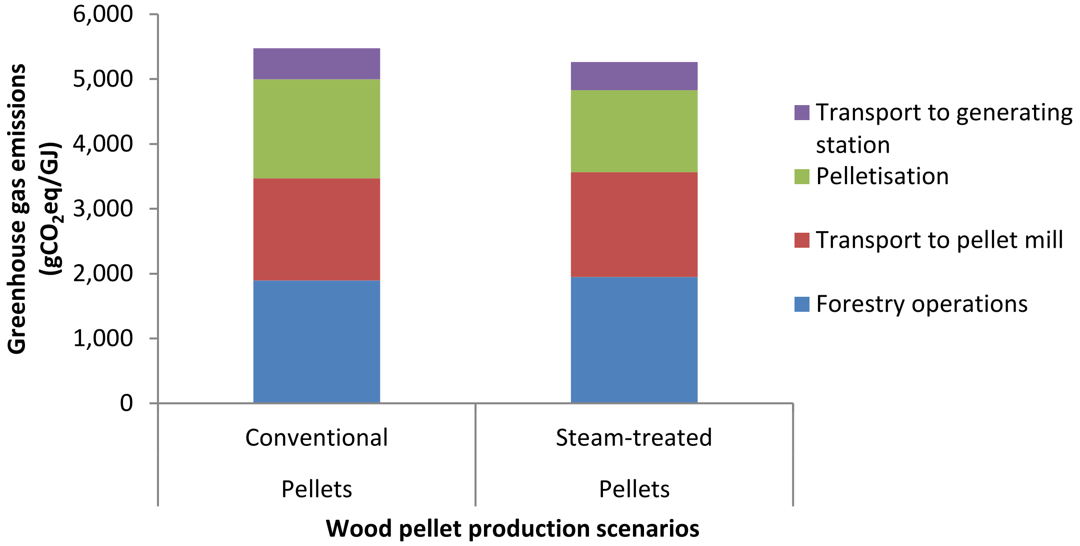

Figure 2. Life cycle GHG emissions associated with the production of conventional and steam-treated wood pellets.

3.2. Electricity generation: Fuel cycle

Both conventional and steam-treated wood pellet pathways can reduce GHG and AP emissions relative to the fossil fuel reference pathways. GHG and AP emissions over the fuel cycle (all life cycle activities excluding retrofit infrastructure for wood pellet firing) for all electricity generation pathways are shown in Figure 3. GHG emissions associated with generation of electricity from conventional and steam-treated wood pellets are comparable (81 $gCO_2eq./kWh$ and 78 $gCO_2eq./kWh$, respectively) and represent the lowest emissions of the pathways considered. Forest operations, pellet production, and transport activities dominate GHG emissions for the pellet pathways, due in part to the assumption that biogenic CO_2 emissions from biomass combustion are balanced by carbon uptake in forests and therefore do not contribute to atmospheric GHGs. As such, only non-CO_2 GHGs (CH_4, N_2O) are considered during the combustion stage, which make a minor contribution to total GHG emissions. In contrast, the predominant source of GHG emissions for the fossil fuel pathways is the combustion of coal or natural gas at the GS. Emissions associated with fuel production and transportation represent only 4% and 15% of total life cycle emissions for coal and natural gas pathways, respectively. By displacing these fuels, wood pellets can achieve substantial GHG reductions: relative to coal and NGCC, pellets can reduce GHG emissions by 92% and 83%, respectively.

Results for fuel cycle AP emissions indicate that conventional and steam-treated wood pellet pathways have similar emissions and can reduce key emissions relative to coal. Compared to the reference coal pathway, pellet-fired generation can reduce emissions by 30% (NOx); 97% (SOx); and 75% (PM_{10}). AP emissions associated with the coal pathway arise primarily from fuel combustion at the GS and, in the case of NOx emissions, from transportation activities. It is important to note that technical solutions to AP emissions from stationary sources exist and could be applied to coal-fired GSs to minimise these emissions (e.g., selective catalytic reduction (NOx); flue gas desulphurisation (SOx); bag house/particulate filters (PM_{10})). Similarly, NOx emissions during combustion of wood pellets are significant for the pellet pathways, but could be mitigated by flue gas treatment. As such, AP emissions reported here are relevant only to this particular case study, and do not represent outcomes if additional AP mitigation equipment is employed.

Transport emissions are significant for the coal pathway and would also be important for long-distance wood pellet supply chains, including scenarios where pellets are exported to supply European pellet markets. Due to their higher energy density, long distance transport impacts of steam-treated pellets would be less than for conventional pellets. Vessel shipment is a significant source of global NOx emissions at present; however, engine modifications and introduction of emissions mitigation measures such as selective catalytic reduction could reduce these emissions by 90% (Chalmers, 2008). Increasingly stringent

AP emissions requirements for marine engines, regulated under the International Convention for the Prevention of Pollution from Ships (MARPOL), will contribute to reducing transport impacts over the longer term (IMO, 2015) although this will depend in large part on the rate at which existing vessels are retrofitted or replaced.

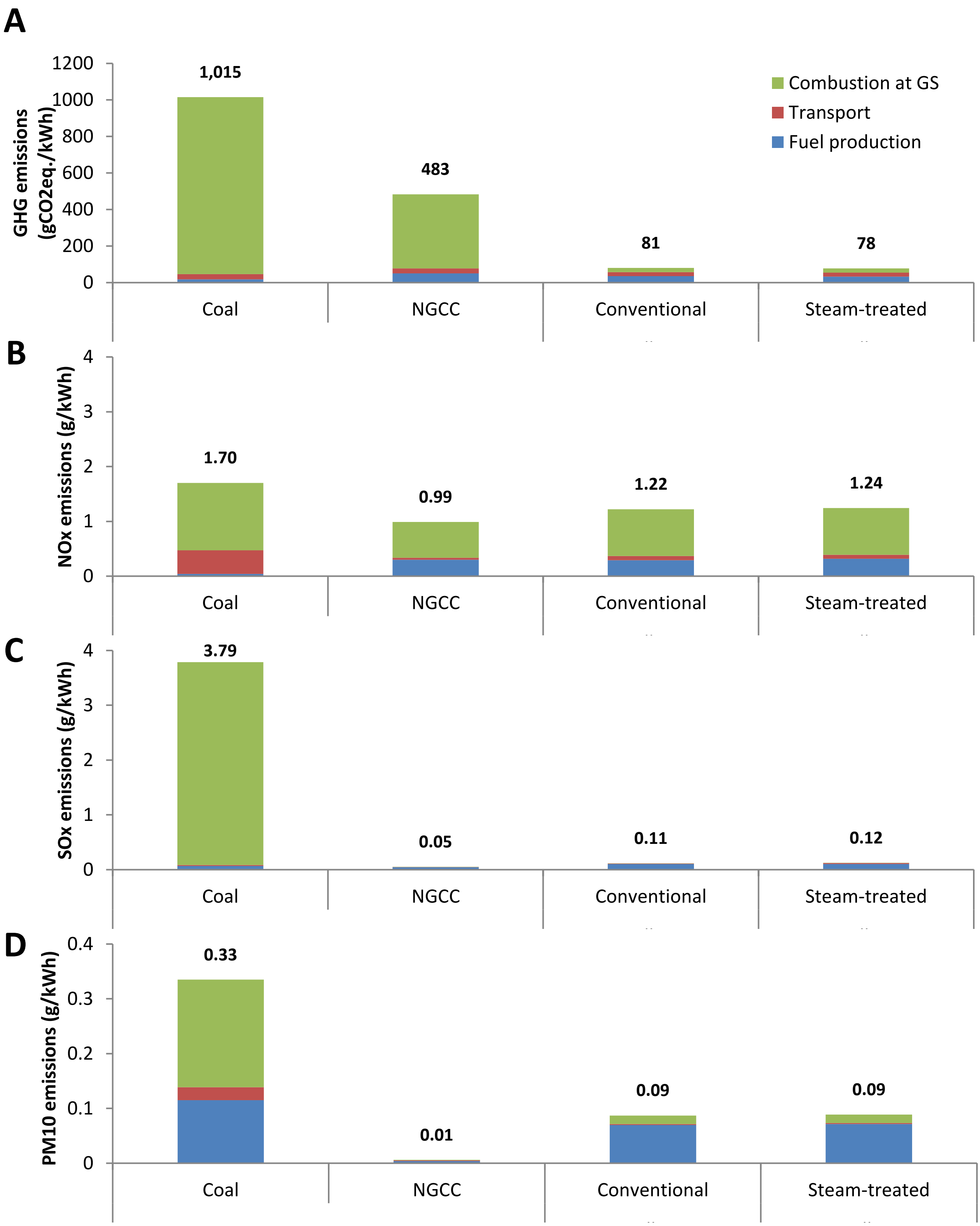

Figure 3. Fuel cycle greenhouse gas and air pollutant emissions for electricity generation by reference fossil fuel and wood pellet pathways. A: GHG emissions; B: NOx emissions; C: SOx emissions; D: PM_{10} emissions. Results exclude infrastructure impacts of all pathways.

SOx and PM10 emissions are very low for the NGCC and wood pellet pathways when compared to coal due to the comparatively low sulphur and ash contents of these fuels. For the pellet pathways, fuel production activities are the dominant source of these emissions. Emissions are therefore particularly sensitive to the sources of electricity input to pellet production. Reliance on more AP emission-intensive electricity sources in other jurisdictions, such as typical coal-fired generation facilities, could therefore significantly increase emissions associated with these pathways.

At electricity outputs less than the rated capacity, all investigated pathways demonstrate an increasing heat rate, and therefore, more fuel is required per unit of electricity produced. As a consequence, life cycle emissions proportionally increase (Figure 4). Results for the conventional and steam-treated pellets are similar, and so only a single set of wood pellet results is shown in Figure 4 for clarity. GHG emissions associated with the coal-fired generation pathway increase by nearly 50% (to 1,440 $gCO_2eq./kWh$) if operated at 30% of rated capacity, while GHG emissions associated with wood pellets also increase by 40% if operated at this lower output. Heat rate degradation trends are similar for the wood pellet and coal pathways; as such, relative GHG reductions from using wood pellets in place of coal are largely independent of the rate of electricity output (92% reduction at all outputs considered), but the absolute difference changes, favouring the lower carbon intensity wood pellets at lower capacity ratings. The NGCC pathway is modelled based on contemporary facilities designed for operation at both base load and partial load, where minimising heat rate degradation at partial loads is a design priority (IEAGHG, 2012). As a result, heat rate degradation is less severe for this pathway and GHG emissions increase only modestly (20%) when output is decreased from 100% to 30% of rated capacity. At very low capacity factors typical of a peak load facility, a single cycle gas turbine system would be a more appropriate comparator than the NGCC pathway considered in the current study. Such a facility would exhibit lower generation efficiency and correspondingly greater GHG emissions than the NGCC pathway considered here, but would provide greater operational flexibility (higher power output ramp rate; rapid start up). While technical performance parameters related to the dynamic functioning of electricity generators are essential to system design and planning, they are difficult to capture within a life cycle study. The results for all pathways are based on steady operation of the GS at various electricity outputs; transient operation (e.g., ramping up/down output) is not considered, and could further impact generation efficiency.

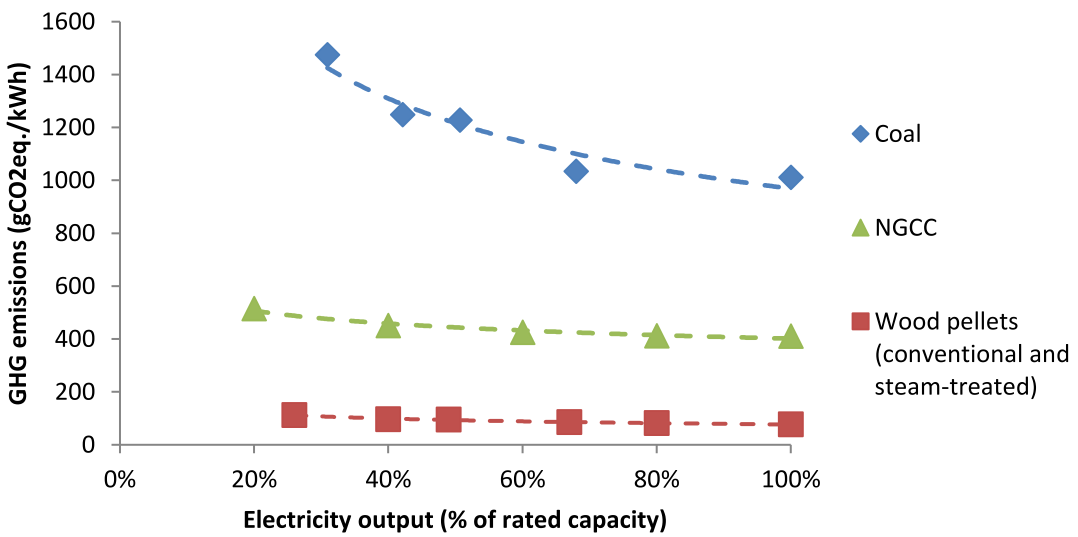

Figure 4. Fuel cycle GHG emissions as a function of electricity production rate relative to GS rated capacity. Combustion emissions at the GS are included in the results. Infrastructure impacts are excluded.

3.3. Electricity generation: Wood pellet firing infrastructure at GS

The environmental impacts of GS retrofit infrastructure for conventional pellets are generally two orders of magnitude greater than for steam-treated pellets. For conventional and steam-treated pellet infrastructure, respectively, we estimate GHG emissions to be 110 ktCO_2eq. and 1.4 ktCO_2eq.; NOx emissions to be 140 t and 2 t; SOx emissions to be 390 t and 11 t; and PM_{10} emissions to be 23 t and < 1 t. These results correspond to the more extensive retrofit and greater capital investment required for conventional pellet firing compared to steam-treated pellets. As discussed in Section 2.1.3, there is large uncertainty associated with results from the EIO-LCA methodology and the approach used to update this model to better reflect current environmental impacts of the Canadian economy. However, these results can be interpreted as reasonably indicating that GS conversion to use steam-treated pellets would result in much smaller environmental impacts than conversion to fire conventional pellets.

For conventional pellets, retrofit infrastructure can be a significant contributor to life cycle GHG and SOx emissions. Figure 5 shows the total life cycle environmental impacts, inclusive of fuel cycle and retrofit infrastructure activities, for conventional and steam-treated pellets. In our base case assumption of a 55% capacity factor, retrofit infrastructure for conventional pellets represents 14% of total life cycle GHG emissions (13 gCO_2eq./kWh), and 30% of SOx emissions (0.05 g/kWh). These results are largely driven by the average impacts of Canada's non-residential and engineering construction sector, which is comparatively GHG- and SOx-intensive compared to the average Canadian economy. Infrastructure for conventional pellets has a comparatively small impact on NOx emissions (1%) and PM10 emissions (3%). For steam-treated pellets, retrofit infrastructure is estimated to contribute less than 1% of total impacts in all categories considered in this study.

Infrastructure impacts are fixed and therefore independent of GS operation; therefore, at lower capacity factors, the contribution of retrofit infrastructure to life cycle impacts of electricity generation is more significant. At a 10% capacity factor, infrastructure contributes 50% of total life cycle GHG emissions for conventional pellets, resulting in total GHG emissions of 150 gCO_2eq./kWh. While infrastructure is significant relative to other key activities in this pathway (biomass supply; pellet production; transport), total emissions are still far less than those for the reference coal (1,015 gCO_2eq./kWh) and NGCC (483 gCO_2eq./kWh) reference pathways, and so, retrofit infrastructure does not impact the conclusion that the wood pellet pathways significantly reduce GHG emissions relative to the fossil fuel pathways. Similarly, conventional pellets can reduce NOx, SOx, and PM_{10} emissions relative to coal even when operated at low capacity factors. For steam-treated pellets operating at 10% capacity factor, retrofit infrastructure remains an insignificant contributor to total GHG emissions (approximately 1% of total emissions) and similarly, does not significantly impact AP emissions for this pathway.

This analysis assumes that retrofits undertaken at the Atikokan GS (conventional pellets) and Thunder Bay GS (steam-treated pellets) are adequate for GS operation across a full range of capacity factors. However, both GSs are currently operated at low capacity factor and additional retrofits may be required to achieve the higher capacity factors considered in the present study. For example, conventional pellet storage at Atikokan GS is equivalent to only 10 days operation at full load. As such, the steep reductions in infrastructure impacts when capacity factor increases (as indicated in Figure 5) may not be achievable, with particular impact on the results for conventional pellets at moderate to high capacity factors.

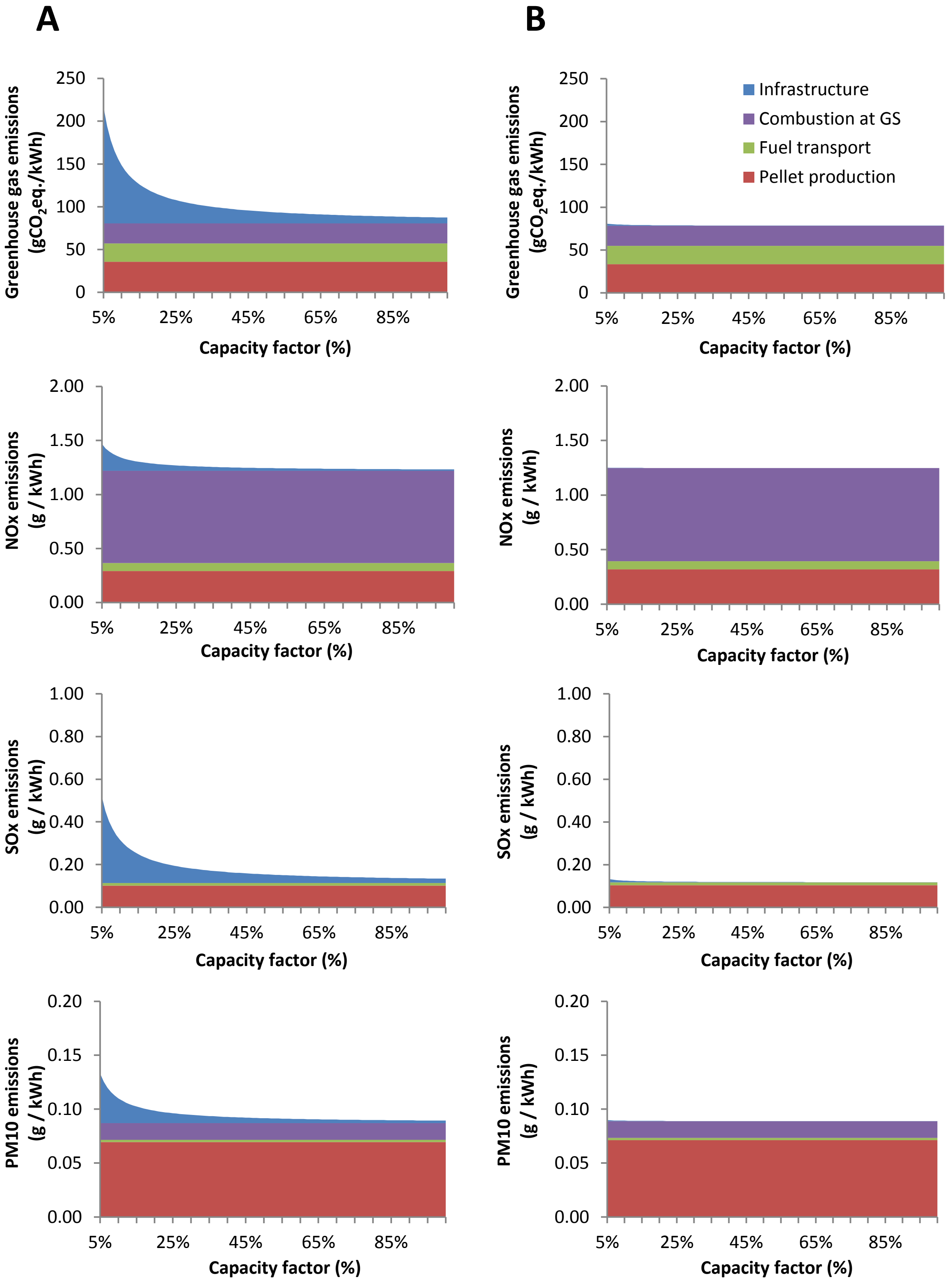

Figure 5. Life cycle GHG and AP emissions for electricity generation by (A) conventional wood pellets and (B) steam-treated wood pellets, inclusive of fuel cycle and retrofit infrastructure impacts.

3.4. Financial analysis

3.4.1. Wood pellet production

Costs associated with wood pellet production vary between conventional and steam-treated pellets, in line with trends seen for GHG emissions results (Section 3.1). On an energy basis, steam-treated pellets have a slightly higher production cost than conventional pellets ($10.2/GJ and $9.9/GJ, respectively) as shown in

Figure 6. Compared on a mass basis, steam-treated pellets have a 20% higher production cost ($215/odt$_{pellet}$ vs. $190/odt$_{pellet}$), although such a comparison is less appropriate as it ignores the higher energy density of steam-treated pellets. Larger biomass requirements for the steam-treated pellets are negated by the increased energy content of this fuel relative to conventional pellets. The higher cost for steam-treated pellets arises primarily due to greater capital requirements associated with the steam treatment reactor and ancillary equipment, which increases capital financing costs by approximately 50%. However, pellet production costs are relatively insensitive to capital: doubling capital costs would increase the cost of steam-treated pellet production by only 7%. Transportation costs from the pellet mill to GS are small; while we do not account for potential cost savings for steam-treated pellets due to their higher energy density, this does not appreciably impact results presented here due to the short transport distances assumed.

For both pellet production processes, feedstock cost is the most significant contributor to pellet cost (53% and 54% of the total, for conventional and advanced pellets, respectively). Utilisation of lower cost forest biomass sources could reduce the cost of pellet production. Pellet production from mill residues would result in pellet costs of $130 and $145/odt (conventional and advanced pellets, respectively). Harvest residues would result in pellet costs of $160/odt (conventional pellets) and $180/odt (advanced pellets). While utilisation of mill and harvest residues would therefore be expected to result in lower pellet costs, supply of these materials is less secure as they are reliant on forest product manufacture and forest harvesting operations.

Calculated pellet production costs are similar to values reported elsewhere. North American conventional pellet production costs have been estimated to range from $180 to $210/tonne (Pirraglia, 2010; Strauss, 2013). Our results are near the low end of this range; as we consider a relatively high cost feedstock, this indicates that the non-feedstock costs of pellet production reported here may slightly underestimate actual production costs. Strauss (2014) assessed the cost differential between conventional and steam-treated pellets in the US to be approximately $0.8/GJ (CAD); the current analysis finds a smaller cost difference between pellet types ($0.3/GJ) as higher feedstock and capital costs for steam-treated pellets are partially offset by lower operating costs.

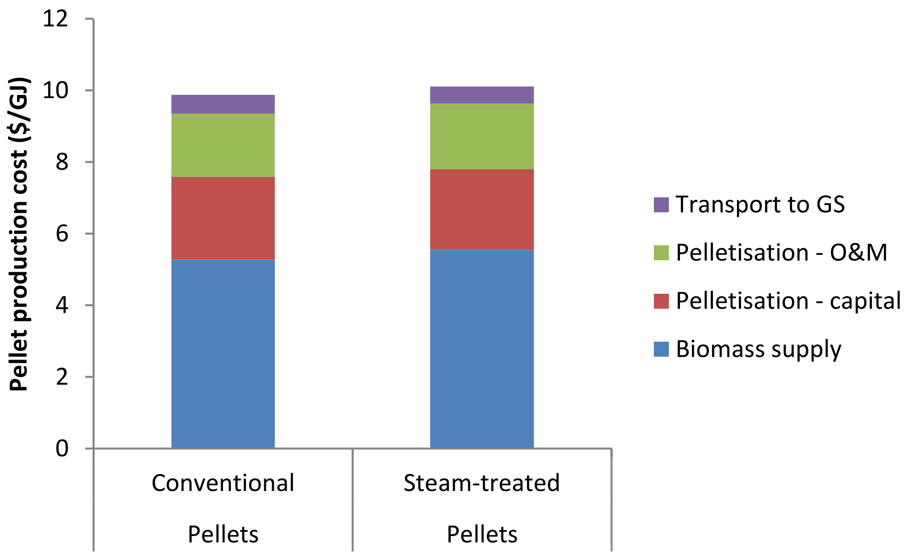

Figure 6. Costs associated with the production of conventional and steam-treated wood pellets.

3.4.2 Electricity generation costs

Steam-treated wood pellets can offer a cost advantage over conventional pellets. Although production costs of steam-treated pellets are higher than conventional pellets, as discussed above, this can be more than compensated for by lower capital costs associated with retrofitting the GS (Figure 7). The relative contribution of fixed costs, including retrofit infrastructure as well as fixed operating and maintenance costs, is highly dependent upon the capacity factor at which the GS operates. At a GS capacity factor of 55%, electricity generation from steam-treated pellets is approximately 10% less costly than from conventional pellets ($0.14/kWh and $0.16/kWh, respectively) due to minor difference in retrofit infrastructure costs in the case of steam-treated pellets ($0.001/kWh vs. $0.025/kWh for conventional pellets). At lower capacity factors, fixed costs represent a larger share of total costs. The potential cost advantage of steam-treated pellets is therefore more significant if the GS is operated for lower output (e.g., to provide peak power). For example, at a 10% capacity factor, generation costs from steam-treated pellets are estimated to be approximately 30% less than for conventional pellets ($0.27/kWh and $0.39/kWh, respectively). In contrast, at higher capacity factors, the total cost of electricity generation from the two pellet types converge, reaching $0.13/kWh at capacity factors of 90% and more.

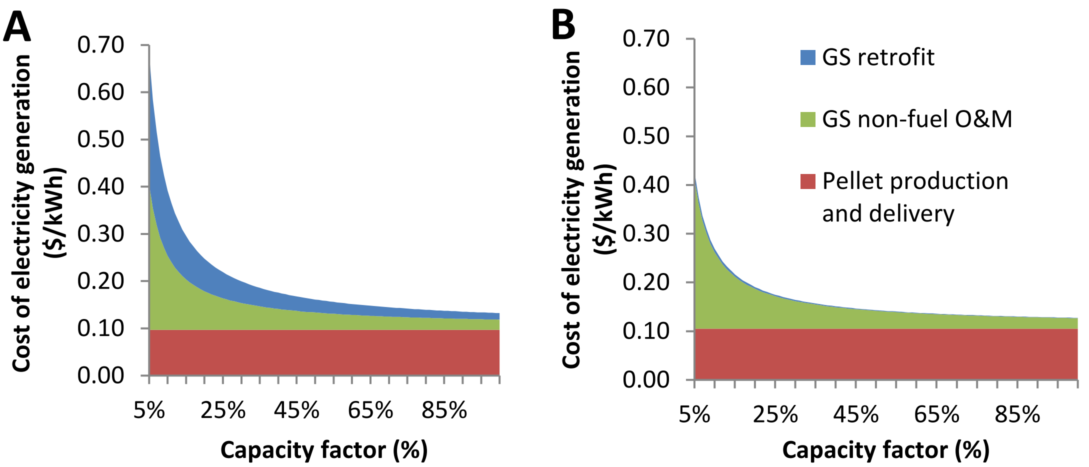

Figure 7. Cost of electricity generation from A: conventional pellets and B: steam-treated pellets as a function of GS capacity factor.

Wood pellet electricity generation costs exceed those of the fossil fuel reference pathways; however, costs are generally in line with those of other renewable electricity pathways and GHG emissions mitigation measures. Figure 8 compares electricity generation costs for all pathways, assuming a GS capacity factor of 55%. Coal-fired generation is found to be the lowest cost electricity generation pathway of those considered ($0.045/kWh), largely due to the treatment of existing coal generation capital as sunk costs. Electricity generation costs associated with the NGCC pathway are higher due to capital requirements and fuel costs. At recent US utility natural gas prices ($6/GJ), the NGCC cost is approximately double that of coal ($0.094/kWh); this increases to $0.12/kWh at a higher natural gas price of $10/GJ to reflect the potentially higher cost of supplying natural gas in northwestern Ontario. Wood pellet electricity generation represents the highest cost pathways, with costs driven by three main factors: the higher cost of pellets compared to coal and natural gas; significant non-fuel operating and maintenance costs for biomass-fired facilities; and, in the case of conventional pellets only, the cost of retrofitting coal facilities to enable wood pellet firing. However, total generation costs from pellets are competitive with existing rates paid for biomass-based renewable electricity in Ontario ($0.175/kWh under the Province's Feed-in Tariff Programme (IESO, 2016)) and other generation sources such as photovoltaics.

We compare the electricity generation costs and GHG emissions impacts of the wood pellet pathways with the reference fossil fuel pathways to estimate the marginal cost of GHG emission abatement. Displacing coal-fired generation with wood pellet-based generation achieves GHG emissions reductions at a cost of $125/t CO_2eq. for conventional pellets and $100/tCO_2$eq. for advanced pellets (assuming 55% capacity factor for coal and pellet pathways). The displacement of NGCC generation with pellets is less favourable at the lower assumed natural gas price ($6/GJ), with a GHG emissions abatement cost of $170/tCO_2$eq. and $115/tCO_2$eq. for conventional and advanced pellets, respectively. However, if a higher natural gas cost of $10/GJ is considered, the pellet pathways become considerably more cost-effective at reducing GHG emissions. In this higher gas cost scenario, steam-treated pellets can mitigate GHG emissions at a cost of $50/tCO_2$eq., which is less than the US Environmental Protection Agency's central estimate of the economic damage of GHG emissions in 2020 (approximately $65/tCO_2$, converted to current Canadian dollar equivalent; US EPA, 2015).

Electricity production costs, and correspondingly, the cost of GHG abatement, could be reduced by utilising lower cost biomass feedstocks than roundwood ($100/odt). Using other forestry biomass sources such as harvest residues (~$70/odt) and mill residues (~$40/odt) (IEA Bioenergy, 2014; Ralevic et al., 2010) for steam-treated pellet production could reduce electricity generation costs to $0.123/kWh and $0.106/kWh, respectively. As a result, marginal GHG abatement costs as low as $65/tCO_2eq. (displacing coal) and $30/tCO_2eq. (displacing natural gas at $6/GJ) could be achieved, while pellet pathways could be directly cost-competitive with NGCC at natural gas costs of $10/GJ. While there are potential financial advantages to utilising these alternative forestry feedstocks, the reliance on waste materials from conventional forestry operations would introduce additional supply risk relative to purpose-harvested biomass. Assessing the viability of alternative biomass supply chains is outside of the scope of the present study.

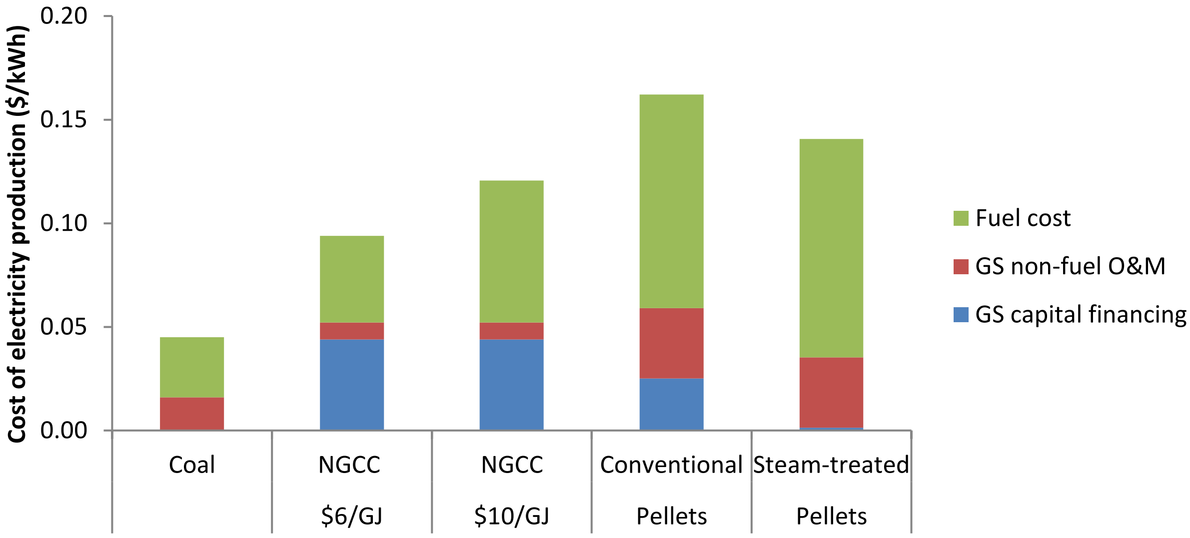

Figure 8. Cost of electricity generation for reference fossil fuel and wood pellet pathways. All values assume generating station is operated at a capacity factor of 55%.

4. Discussion

Steam-treated wood pellet production for electricity generation can significantly reduce GHG emissions relative to fossil fuel alternatives, while also reducing AP emissions relative to coal combustion. While the steam-treated pellet production process requires greater feedstock inputs and capital expenditure, environmental performance is similar to conventional pellets over the fuel cycle and marginally higher pellet production costs are more than compensated for by reduced retrofit requirements for coal GS conversion. Further technical advantages for steam-treated pellets are of importance for GS operators but are not readily apparent from life cycle assessment, including: low cost uncovered storage enables greater flexibility in GS output, for example to provide seasonal peaking requirements; hydrophobicity allows use of wetting agents to control dust at its source and thereby effectively mitigates explosion risk; and friability provides superior milling and combustion performance, enabling GS operation at lower loads and providing greater operational flexibility (e.g., ramp rate).

We find that retrofit infrastructure can represent a significant share of life cycle environmental impacts of wood pellet production and use. This stands in contrast to an assumption common to life cycle studies of energy systems: that infrastructure can be excluded as the throughput of energy and materials will be of far greater significance. While this assumption is reasonable in many cases – including results for the steam-treated pellet pathway in this study – it is less likely to be valid in scenarios that are infrastructure-intensive or where facilities are operated at a low capacity factor. The estimate of infrastructure impacts in the present study is highly uncertain due to the method employed (EIO-LCA) and approach to updating emissions factors to more closely represent the current state of the Canadian economy. However, the magnitude of results indicates that energy system infrastructure can in some cases be of importance, a conclusion that is supported by prior studies of renewable energy system infrastructure (e.g., Daly et al., 2015).

A key assumption in the present study is that biomass-based CO_2 emissions do not contribute to atmospheric GHGs. Through sustainable forest management practices, roundwood harvest for bioenergy or conventional forest products can be undertaken without degrading the productive forest base, ensuring that carbon removals are ultimately balanced by forest regrowth. However, there is a question of when this balance is achieved, due to the slow nature of forest regrowth (e.g., McKechnie et al. 2011). There is currently a great deal of uncertainty as to how forest carbon dynamics should be quantified in life cycle studies. While we do not consider forest carbon impacts in the present study, we recognise that this could delay the achievement of GHG emissions reductions identified here. Utilisation of non-roundwood biomass sources could help to address this issue and, as identified earlier, improve the financial performance of electricity generation from wood pellets. Further evaluation of alternative forest biomass resources (mill and harvest residues), their current uses, and other potential applications would enable better understanding of potential supply risks associated with utilising residual materials and support their valorisation.

While not directly evaluated in this study, our results indicate that electricity generation from biomass has the potential to play a strategic role as a very low GHG emissions and dispatchable generation pathway that can help to balance the variability of intermittent renewable energy sources (wind, solar). Steam-treated pellets offer environmental advantages relative to ongoing reliance on coal and natural gas fuels and are found to be cost-competitive when externalities are taken into account (e.g., social cost of CO_2 emissions). Superior technical characteristics of steam-treated pellets relative to conventional pellets result in lower overall costs; however, other advantages (e.g., greater operational flexibility) are more difficult to quantify in a life cycle modelling context. Evaluation of biomass-fired generation pathways from the overall perspective of the electricity sector could account for such technical performance characteristics, and thereby provide an increased understanding of the role to be played by steam-treated pellets in domestic and international energy markets.

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