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Integrated techno-economic and environmental assessments of sixty scenarios for co-firing biomass with coal and natural gas

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HIGHLIGHTS

- Developed techno-economic model for 60 scenarios for biomass co-firing with coal/NG.
- Partially paid-off plants (15 years) and fully paid-off plants (25 years) considered.
- CO_2 abatement costs range from $27.4 to $38.48/t$CO_2$ for fully paid-off coal scenarios.
- Sensitivity and uncertainty analysis were carried out for the cost analysis.
- Overall size of the power plant is the most sensitive parameter affecting LCOE.

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ABSTRACT

Displacement of fossil fuel-based power through biomass co-firing could reduce the greenhouse gas (GHG) emissions from fossil fuels. In this study, data-intensive techno-economic models were developed to evaluate different co-firing technologies as well as the configurations of these technologies. The models were developed to study 60 different scenarios involving various biomass feedstocks (wood chips, wheat straw, and forest residues) co-fired either with coal in a 500 MW subcritical pulverized coal (PC) plant or with natural gas in a 500 MW natural gas combined cycle (NGCC) plant to determine their technical potential and costs, as well as to determine environmental benefits. The results obtained reveal that the fully paid-off coal-fired power plant co-fired with forest residues is the most attractive option, having levelized costs of electricity (LCOE) of $53.12–$54.50/MW h and CO_2 abatement costs of $27.41–$31.15/tCO_2. When whole forest chips are co-fired with coal in a fully paid-off plant, the LCOE and CO_2 abatement costs range from $54.68 to $56.41/MW h and $35.60 to $41.78/t$CO_2$, respectively. The LCOE and CO_2 abatement costs for straw range from $54.62 to $57.35/MW h and $35.07 to $38.48/t$CO_2$, respectively.

1. Introduction

Increased energy use has resulted in heavy reliance on fossil fuels like coal, oil, and natural gas and led to a significant increase in greenhouse gas (GHG) emissions, which are considered to be the root cause of the rising global temperatures [1,2]. In 2010, the generation of electricity and heat, a major form of energy use, produced about 41% (close to 10,000 MtCO_2 per year) of global GHG emissions through the combustion of fossil fuels [1]. It is even more noteworthy that in Canada, where 16% of the electricity comes from coal power plants, coal power plants account for about 77% of the overall GHG emissions associated with the nation's entire electricity sector [3,4].

Several environmental policies exist around the world to encourage large industrial emitters, including utility companies, to reduce their overall GHG emissions. For example, in Canada the federal government mandated emissions-intensity levels of 0.42 tCO_2/MW h for new thermal power plants and 1.1 tCO_2/MW h for old plants [3,4], as well as a carbon levy in other jurisdictions [4–6]. The quest to reduce GHG emission levels has led to interest in biomass use. Biomass, a "nearly" carbon neutral-based energy, can be used effectively to mitigate GHG emissions [7–10]. Biomass can also be used in several ways to produce power and heat [11–15]. One of these is biomass co-firing.

Biomass co-firing, with either coal or natural gas (NG) in existing power plants, is considered an option to reduce the life cycle GHG emissions associated with the use of fossil fuel to produce electricity, as well as mitigate their impacts on the environment [16]. It also offers utility owners a reduced incremental investment

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Nomenclature

CO_2	carbon dioxide	CTG	combustion turbine generator
GHG	greenhouse gas	HRSG	heat recovery steam generator
LCV	low calorific value	LCOE	levelized cost of electricity
MW h	megawatt-hour	NG	natural gas
NOx	oxides of nitrogen	O&M	operation and maintenance
PC	pulverized coal	SOx	oxides of sulfur
STG	steam turbine generator	$/kW	dollars per kilowatt
$/tonne	dollars per metric ton	tCO_2	metric tons of carbon dioxide
VT	mean merchantable volume per hectare		

cost (i.e., the cost required to retrofit an existing plant) and fuel supply flexibility [6,9,10,17–19]. Biomass co-firing involves the simultaneous blending and combustion of biomass feedstock along with coal or natural gas (NG) to produce electricity mostly in existing power plants.

Coal/biomass co-firing occurs either in direct or parallel co-firing. In direct co-firing, the biomass feedstock is either fed directly into the boiler with the coal where it is milled and burned together with the coal or it is milled externally before being fed separately into the boiler to be burned with the coal [20,21]. Parallel co-firing is similar to direct co-firing except for the installation of a completely separate external biomass-fired boiler. Biomass feedstock is processed and fed separately into a dedicated boiler where it is burned to produce steam used to generate electricity in the power plant [9].

Biomass co-firing with natural gas, on the other hand, uses indirect co-firing technology. Here the biomass feedstock is first gasified to produce syngas, which is then co-fired with natural gas in a gas turbine. NG/biomass co-firing offers a higher co-firing rate than coal/biomass co-firing, enabling the substitution of up to 40% of the base fuel with biomass in the system [17,22,23]. Compared to coal/biomass co-firing, NG/biomass co-firing is rarely used, partly because it is still in a development form but also due to the much higher capital costs associated with the gasification process [17,24]. The most notable commercial operation of NG/biomass co-firing is found in Lahti, Finland, where several biomass fuels such as sawdust, straws, wood wastes, and other waste-derived fuels are gasified in fluidized bed gasifiers and then co-fired with natural gas in a turbine [24]. An overview of the different co-firing technologies is provided by Agbor et al. [23] and the technical challenges associated with co-firing are highlighted by Li et al. [25].

There are several studies published techno-economic assessments and feasibility studies of co-firing processes [7,21,26,27,19,28,29]. The economics of different coal/biomass co-firing options was studied by Basu et al. [21]. Their results show that the direct co-firing approach is the least expensive of all the co-firing options; however, their work does not include an environmental assessment of different co-firing options in terms of abatement costs. Al-Mansour and Zuwala [26] reviewed the best practices of biomass co-firing in Europe. They concluded that while direct co-firing is the most straightforward and least expensive option for co-firing biomass with coal, indirect co-firing can best handle higher biomass co-firing rates. A study by Malmgren and Riley [30] shows that while parallel co-firing has significantly higher biomass use rate, it is more expensive than direct co-firing due to higher plant modification costs. Rodrigues et al. [29] investigated the feasibility of mixing syngas from biomass with natural gas and also analyzed the cost and efficiency benefits associated with the process. Their results show that co-firing substantially increases the efficiency of electricity production from biomass and becomes more competitive than biomass firing only due to economies of scale, but their studies did not include an environmental assessment of the process [29].

Few techno-economic assessment and feasibility studies on co-firing include an environmental assessment along with the techno-economic analysis. At present, government and industry are interested in understanding the trade-offs of these two aspects of sustainability. Very little literature exists that could help them in their decision making, particularly in western Canada. In studies on biomass co-firing, comparative analyses of the coal/biomass and NG/biomass are scarcely discussed and this needs to be addressed due to the increase in natural gas-fired plants. Another important knowledge gap addressed in this study is the age of the power plant used for the co-firing plants. Existing literature on co-firing focusses mainly on old coal plants, while relatively new plants (plants less than 15 years old) have not been considered for co-firing. In studies by the Canadian Clean Power Coalition and Basu et al. [20,21], only paid-off plants were considered for biomass co-firing and currently, no study exists on new plants that are less than 15 years old. Studying the effect of co-firing biomass in relatively new coal or natural gas plants on electricity and GHG abatement costs will be of major interest, especially in jurisdictions where there are new plants that could be affected by an increase in carbon tax. This is key gap that this study addresses.

In light of the stated gaps in the literature, this study developed a data-intensive techno-economic model to comparatively evaluate the costs of co-firing three biomass feedstocks with coal and natural gas in both a fully paid-off modified plant and partially paid-off plant. This study also conducted an environmental assessment of co-firing biomass with coal and natural gas in western Canada, work that has not been done in detail until now.

The overall objective of this research is to perform an integrated techno-economic and environmental assessment for different biomass co-firing scenarios. The specific objectives are:

- To develop a techno-economic model to determine power generation costs ($/MW h) for the co-firing of biomass with coal for different power plant configurations.
- To develop a techno-economic model to determine power generation costs ($/MW h) for the co-firing of biomass with natural gas for different power plant configurations.
- To develop biomass harvesting and transportation models to estimate transportation and feedstock costs ($/tonnes) for three biomass feedstocks, namely whole forest (i.e., wood chips), agricultural resides (i.e., wheat straw), and forest residues.
- To develop GHG abatement costs ($/tonne of CO_2) for the co-firing of biomass with coal and natural gas in western Canada.
- To develop electricity generation and GHG abatement costs for the different co-firing scenarios.