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An evaluation of greenhouse gas mitigation options for coal-fired power plants in the US Great Lakes States

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ARTICLE INFO

Article history:
Received 8 December 2008
Received in revised form
18 October 2009
Accepted 24 October 2009
Available online 20 November 2009

Keywords:
Biomass
Co-firing
Coal
Energy crops
Great Lakes States
Greenhouse gas mitigation
Life Cycle Assessment
Sequestration

ABSTRACT

We assessed options for mitigating greenhouse gas emissions from electricity generation in the US Great Lakes States, a region heavily dependent on coal-fired power plants. A proposed 600 MW power plant in northern Lower Michigan, USA provided context for our evaluation. Options to offset fossil CO_2 emissions by 20% included biomass fuel substitution from (1) forest residuals, (2) short-rotation woody crops, or (3) switchgrass; (4) biologic sequestration in forest plantations; and (5) geologic sequestration using CO_2 capture. Review of timber product output data, land cover data, and expected energy crop productivity on idle agriculture land within 120 km of the plant revealed that biomass from forestry residuals has the potential to offset 6% and from energy crops 27% of the annual fossil fuel requirement. Furthermore, annual forest harvest in the region is only 26% of growth and the surplus represents a large opportunity for forest products and bioenergy applications. We used Life Cycle Assessment (LCA) to compare mitigation options, using fossil energy demand and greenhouse gas emissions per unit electricity generation as criteria. LCA results revealed that co-firing with forestry residuals is the most attractive option and geologic sequestration is the least attractive option, based on the two criteria. Biologic sequestration is intermediate but likely infeasible because of very large land area requirements. Our study revealed that biomass feedstock potentials from land and forest resources are not limiting mitigation activities, but the most practical approach is likely a combination of options that optimize additional social, environmental and economic criteria.

1. Introduction

In the United States, pressure to meet increasing energy demands from renewable resources that reduce overall CO_2 emissions is mounting. Nationally, nearly three-quarters of all electricity generation relies on fossil fuels, mostly coal [1]. In the Great Lakes States, reliance on coal is even greater; Minnesota, Wisconsin and Michigan depend on coal to supply between two-thirds and four-fifths of electricity generation [2]. With the enactment in 2008 of new legislation in Michigan, all three states now have renewable portfolio standards in place that mandate increasing reliance on renewable energy in the electric power generation sector. In parallel, all three state governments and many private electricity generation

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0961-9534/$ – see front matter
doi:10.1016/j.biombioe.2009.10.013

companies in the region are members of The Climate Registry, a nonprofit organization focused on reporting systems for greenhouse gas emissions in anticipation of emissions trading.

While a number of options are available for meeting renewable targets and reducing greenhouse gas emissions (e.g., wind, solar), the heavy reliance on coal and the abundance of forest and agriculture resources in the region suggests displacement of coal with biomass is a promising option. Biomass combustion mitigates some of the environmental impact of electricity generation by displacing fossil fuels that would have otherwise been combusted, and thus reducing the net emission of fossil carbon to the atmosphere. A different, and often complementary, approach to mitigation is to undertake activities that sequester atmospheric carbon. This can take the form of biological sequestration, where management activities cause increases in biomass stocks, or geological sequestration, such as CO_2 compression and injection into belowground geologic formations [3].

In this study, we assessed the potential for biomass feedstock production and biological carbon sequestration in the northern Great Lakes States region, and then compared mitigation strategies using Life Cycle Assessment (LCA). In our LCA approach we consider environmental impacts, energy consumption, resource depletion, and other impact categories for an entire product system. LCA provides a rigorous methodology for comparing product systems, with recognized standards through the International Organization for Standardization, ISO 14040–14049. Our LCA included a base case of coal-fired power generation and five product system options: (1) fossil fuel substitution with forest residuals; (2) substitution with short-rotation woody crops; (3) substitution with switchgrass; (4) biologic sequestration in forest plantations; and (5) geologic sequestration using CO_2 capture and compression.

To provide a realistic context, we framed the assessment around a proposed 600 MW base load power plant near Rogers City (45°25′16″N, 83°49′01″W), located in the northern Lower Peninsula of Michigan. This facility, using circulating fluidized bed technology and burning Powder River Basin coal from Wyoming, will consume about 2.5 $Tg\,y^{-1}$ of fuel, and release about 5.1 $Tg\,y^{-1}$ of CO_2 into the atmosphere (Table 1). We evaluated biomass fuel substitution at a rate of 20%, because we understood this to be the maximum possible co-firing rate in a plant of this type. For comparison, we evaluated both biologic and geologic sequestration at a rate equivalent to the amount of CO_2 offset through 20% substitution with biomass fuels. But first, we reviewed the potential production of various biomass feedstock sources and biological sequestration possibilities in the study area.

Table 1 – Assumptions and key specifications used in this study.

Plant specifications	
Plant size	600 MW
Heat input	6.2 $TJ\,h^{-1}$
Operating hours	8,300 h (~95% capacity)
Critical assumptions	
PRB coal	19.2 $MJ\,kg^{-1}$
Biomass	18.3 $MJ\,kg^{-1}$
CO_2 at 100% PRB coal	5.1 $Tg\,y^{-1}$
Feedstock and offset requirements	
PRB coal	2.5 $Tg\,y^{-1}$
Biomass at 20% offset	590 dry $Gg\,y^{-1}$
CO_2 sequestration at 20% offset	1.0 $Tg\,y^{-1}$

Note: PRB Coal = Powder River Basin (Wyoming) coal.

1.1. *Biomass feedstock opportunities*

Typically, both national-scale biomass resource assessments (e.g., [4]) and regional studies in the Great Lakes States (e.g., [5–7]) divide biomass into three classes that depend upon source: forestry, agriculture, and waste. We prefer to classify feedstocks based on the intensity of the production system, where intensity is defined in terms of inputs of energy and nutrients and the degree to which management alters an ecosystem from a native successional trajectory.

We choose this approach because our goal is to appraise the potential for biomass to mitigate greenhouse gas emissions, and high-intensity biomass production systems tend to have a lower benefit [8]. Also, the opportunity in the Great Lakes States relates to existing forests and idle agriculture land in the Northern Lakes and Forests Ecoregion (Fig. 1). This ecoregion is distinguished from ecoregions to the south by extensive cover of forests, nutrient poor glacial soils, relatively low agricultural productivity and long distances to potential urban markets [9]. Therefore, we emphasize woody energy crops (e.g., switchgrass, hybrid poplar) as the highest intensity option, followed by managed forests and low intensity, high diversity forest or mixed perennial grassland systems. Ultimately, the optimum choice for any given location will be the one that minimizes greenhouse gas emissions over the entire life cycle, considering tradeoffs between production intensity, productivity and logistics costs such as processing, handling and transportation. But for the purposes of discussing an array of feedstock options, intensity is a reasonable distinguishing concept.

Dedicated energy crops are fast-growing plants cultivated in an agricultural setting, usually as monocultures, and managed to maximize biomass production. The most promising crops in the US include the perennial grasses switchgrass (*Panicum virgatum* L.) and *Miscanthus* (*Miscanthus* spp.) and woody species of willow (*Salix* spp.) and poplar (*Populus* spp.). All but *Miscanthus* are native to the US, though many of the most promising poplar hybrids involve crosses with non-native parents. Energy crops achieve the greatest yield when established using an intensive, agricultural model, including tillage, herbicide application and irrigation; cultivated under optimum conditions, yields for all four crops can exceed 20 dry $Mg\,ha^{-1}\,y^{-1}$ [10–13]. However, operational trials suggest typical yields in the upper Midwest should be closer to 4–9 dry $Mg\,ha^{-1}\,y^{-1}$ [10,14,15].

We consider switchgrass and hybrid poplar as the most promising energy crop options, because they achieve similar yields to other alternatives but with lower inputs [16]. For example, while willow yields can be very high, establishment usually involves repeated plowing, disking and herbicide applications to prepare very uniform planting conditions prior to establishing dense stands of cuttings, typically