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# Renewable energy and carbon capture and sequestration for a reduced carbon energy plan: An optimization model

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ABSTRACT

Built on a framework that combines geographic analysis and a multi-objective optimization model used to analyze costs and benefits of renewable energy sources (wind farms, solar farms, biomass co-fire, rooftop solar), this research introduces the potential for carbon capture and sequestration (CCS) in the model as a tool for carbon emissions reduction. The carbon capture process is available for retrofit at existing coal plants and the sequestration of carbon is allowed in underground saline aquifers. The aim of this research is to provide a model that can compare renewable energy and CCS to determine the optimal combination of these resources. Over the course of 47 model iterations, CCS is implemented five times, with a maximum of 1.71% of a required 30% decrease in carbon emissions. Renewable energy options were more cost-effective means of achieving environmental goals. With respect to public policy and planning, expanding the potential role of rooftop solar generation is more cost-effective than implementing CCS. Finally, the introduction of a $30/ton carbon tax was not always sufficient to encourage investment in CCS, and through the use of tax incentives for renewable energy combined with a carbon tax, the greatest reduction in emissions were found.

## 1. Introduction

In the past five years, while the proportion of electricity generation from renewable sources has increased worldwide [1], carbon dioxide ($CO_2$) emissions have continued to rise worldwide due to increasing demand for energy, and in 2013 the amount of $CO_2$ in the atmosphere passed 400 parts-per-million for the first time [2]. In the United States, $CO_2$ emissions were on the decline in recent years, but increased in 2014 [3]. The Intergovernmental Panel on Climate Change (IPCC) released their Fifth Assessment Report in 2014 and declared that "continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems. Limiting climate change would require substantial and sustained reductions in greenhouse gas emissions which, together with adaptation, can limit climate change risks" [4]. In order to effectively mitigate risks from climate change, the IPCC not only focused on increased use of renewable sources, such as solar and wind, but stated that "many models could not limit likely warming to below 2° if bioenergy, CCS [carbon capture and sequestration] and their combination (BECCS) are limited" [4]. The United States Environmental Protection Agency released the Clean Power Plan in August 2015, calling for a 30% reduction in carbon emissions from power generation compared to 2005 levels to be achieved by 2030 [5]. Meeting these requirements will require investment in new electricity generation from lower carbon-emitting sources, such as natural gas or renewable energy, or the implementation of technologies to reduce carbon emissions from existing fossil fuel generating facilities. This paper builds on a previously published research framework devoted to renewable energy development and public policy analysis in a geographically-based mathematical optimization model focused on the greater southern Appalachian mountain region [6–9] and incorporates the possibility of CCS into this framework to determine the most effective investments for a reduced carbon future. It is worth noting that the combination of geologic characteristics that allow for carbon storage, the potential for wind and solar, and the high concentration of coal power plants in the region, necessitates that the results presented in this work are unique to these circumstances, but the modeling framework can be utilized in other regions or countries.

## 2. CCS overview

CCS generally refers to the family of technologies that are utilized to capture carbon emissions from facilities using fossil fuels for electric generation, then transport these emissions via pipeline to the appropriate locations for underground storage. CCS is a relatively young technology, with research and development still being quite crucial to the future commercialization of this process. In the United States,

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money is being devoted to pilot projects and research, particularly in states such as West Virginia [10] and Wyoming [11] where large coal reserves remain and future economic activity in these states is tied to the ability to utilize this resource. Even at the national level, the United States is funding numerous projects devoted to CCS technology research and development [12,13].

While CCS can be built-in for new fossil fuel generation facilities, existing plants can be retrofitted to utilize CCS, but this is expected to come at a greater cost per ton of carbon captured than installing this technology at new facilities [14]. In the United States, coal trails natural gas with respect to new capacity being constructed for electricity generation [15], and given the lower levels of $CO_2$ emissions from natural gas, the use of CCS as these facilities has not been widely explored. In April 2015, natural gas surpassed coal as the top source of energy generation in the United States [16]. Though coal remains a prominent source of electricity generation, accounting for 39% of generation in 2014 [17], it is also contributes a substantially-higher level of $CO_2$ emissions, 77% of total in 2014 [18]. Given the current decommissioning rate for coal plants, which is expected to continue [19], and the Clean Power Plant being introduced, the use of coal in the United States is expected to continue to decline unless economic and environmental conditions improve for this energy source.

The majority of the research on CCS tends towards the engineering or technical aspects [20] of these projects and there some good overviews available [21,22]. This work will synthesize and utilize the most relevant information from this technical research in an optimization model for energy planning. CCS is a three-stage process dependent on capturing, transporting, and storing the carbon emissions [23]. There have been three primary methods developed for capture of carbon: oxy-fuel combustion, pre-combustion capture, and post-combustion capture. While the implementation methods vary, the goal of each process is to isolate and separate the carbon emissions for transport and sequestration. These three methods each have different benefits, considerations, and costs. However, post-combustion capture, generally through the use of a solvent, is considered the most appropriate for retrofit of existing coal facilities [21]. Since the initial goal of this research framework was to explore the potential role of renewable energy, the model, discussed in further detail in Section 3, does not allow for the creation of any new fossil fuel generation facilities. Therefore the operation of CCS in this model concerns the retrofitting of existing coal plants, which has shown to be a more cost-effective and potentially suitable as a means of carbon emissions reduction in recent years [24]. Even with these improvements, these retrofits are still considered unproven and financially risky without enhanced oil recovery (EOR) opportunities [25]. EOR is the process wherein captured $CO_2$ emissions can be utilized in oil drilling operations to increase or improve extraction activities [26], or these captured emissions can be used to help mine coal from otherwise uneconomic seams and beds [27]. An additional consideration for implementation of retrofit post-combustion technology is that this process reduces the electricity generated by the facility due to the energy needs of this capture process [28].

The first existing facility to be retrofit for post-combustion carbon capture on a commercial scale opened in Saskatchewan, Canada in October 2014 [29]. The Boundary Dam facility's Unit #3 was rebuilt at a cost of $1.47 billion CAD, including $240 million CAD of government funding, with the capability to capture 90% of CO2 emissions from the plant, currently estimated to be 1 million tons annually. The retrofit resulted in a reduction of nameplate capacity from 139 MW to 110 MW, a 20.86% loss of generation capability. The use of anime scrubbing as a solvent, one of the most effective means of retrofit [30], was the method utilized for carbon capture at the Boundary Dam plant. It should be noted that part of the economic incentive for this project is that approximately 50% of the captured carbon emissions will be utilized in EOR [31]. Though the sale of these carbon emissions for use in EOR might make the financial prospects of CCS projects more attractive, from an environmental perspective utilizing carbon emissions to improve fossil fuel extraction is counter-intuitive to the goals of reducing the levels of $CO_2$ in the atmosphere. As of March 2016, the facility has been plagued with multiple shutdowns and tens of millions of dollars in repairs and additional equipment, resulting in failure to reach emissions reduction targets [32]. The data utilized in this research is derived in part from the Boundary Dam project and thus these estimates might not reflect the final total costs or operating efficiencies given the problems encountered with this project but remain the most plausible estimates at this time.

Beyond the retrofit requirements at coal plants, the carbon must ultimately be sequestered in geologic formations suitable for this task. Estimation of geologic storage is a difficult task, with various methodologies being utilized [33]. One potential storage opportunity utilizes saline aquifers, such as those found in sandstone formations [34]. Within the greater southern Appalachian mountain region used for this study, there exist large sandstone deposits in the Oriskany formation that are suitable for carbon storage [35,36] and these formations have been explored as part of the United States Department of Energy National Carbon Sequestration Database program [37].

Even with sufficient capacity for geologic storage, the transportation of carbon from source to injection well and the placements of injection wells must also be considered. Pipelines are the most appropriate method of carbon transportation, the economics and benefits of which were analyzed in [38]. Finally, the selection of locations for injection wells must be considered carefully. Injection wells for geologic sequestration are governed by the EPA's Class VI Well Regulations. One aspect of the regulations for these injection wells is the need to perform an analysis for issues relating to faults in the area, however there is no explicit regulation for minimum distances necessary. In the United States, the increased prominence of drilling for fracking operations and other energy extraction projects wherein fluids are injected into the earth has been linked with increased earthquake activity [39], and proper consideration of faults needs to be acknowledged when modeling carbon sequestration injection wells. In addition to the location of an injection well relative to faults, the location of the injection well relative to other injection wells must be considered. Once sequestered, the carbon gases flow and plume within the storage area, and the placement of wells too close to each other can reduce the storage available at each well location, or have potential environmental and geologic impacts [40]. Thus, adequate distance between injection wells is necessary to provide safe and economic sequestration.

Beyond the technical details involved in CCS implementation, there are additional considerations regarding economic feasibility of, and need for public policy to support, such projects. However, such research has been less abundant, but there are several prominent examples [41,42]. The model in this research differs in numerous ways. First, [42] does not allow for the retrofit of existing coal plants for CCS implementation. While [41] does allow for retrofit, it also provides the capability to construct new fossil fuel facilities, while this research does not; the need for new electricity demand must be met via new renewable generation. In addition, this model contains technological and economic updates, reflecting the changes in the past decade to renewable energy and CCS development when compared to [41]. This research explores tax incentives for renewable sources and a tax placed on carbon emissions which were not seen in [41,42]. The optimization model presented in this research also allows for the exploration of multiple objectives, as well as the inclusion of a capital investment constraint. Finally, some of the geographic information systems (GIS)-based work presented in Section 3.3 differs from the work presented in [41,42], especially with respect to greater explanation of carbon storage capability in this paper.