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Optimal scale of carbon-negative energy facilities

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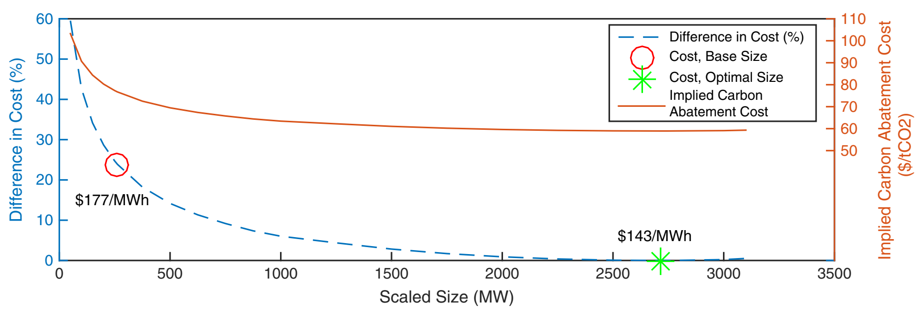
HIGHLIGHTS

- Develops a spatially-explicit framework for optimal scaling of BECCS facilities.
- Applies this framework to large spatial datasets in Illinois.
- Finds deviations from optimal scaled size have little effect on system costs.
- Finds that economies of scale support a centralized BECCS infrastructure.

GRAPHICAL ABSTRACT



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ABSTRACT

Bioenergy with Carbon Capture and Storage (BECCS) may be one of the few cost-effective carbon-negative electricity technologies, but little work has focused on design of such systems. BECCS, like other bioenergy facilities, will likely exhibit economies of scale in capital costs, but diseconomies of scale in biomass transportation and supply costs. In this paper we develop a spatially explicit optimization framework to characterize the drivers of optimal sizing for potential BECCS facilities in Illinois. The approach leverages county-level biomass supply data, detailed road transportation networks, existing technology cost estimates, and previous geologic characterizations of long-term CO_2 storage. Optimal scales are an order of magnitude larger than proposed scales found in existing literature. Biomass supply, scaling exponents, and technology costs are large drivers of optimal scale, while facility location, pretreatment options, and transportation costs are less important. When choosing between multiple facility locations, economies of scale support a centralized BECCS infrastructure. Deviations from optimal scaled size have little effect on overall systems costs – suggesting that other factors, including regulatory, political, or logistical considerations, may ultimately have a greater influence on plant size than the techno-economic factors we consider here.

1. Introduction

The urgency of climate change has led to societal pressure not only for technologies that reduce CO_2 emissions, but also those that can reduce the net amount of CO_2 in the atmosphere [1–4]. These technologies, collectively referred to as Carbon Dioxide Removal (CDR) options, include direct air capture of CO_2, biochar, afforestation, soil carbon sequestration, ocean fertilization, and bioenergy with carbon capture and sequestration (BECCS) [5,6]. Deploying BECCS results in a net reduction in atmospheric carbon, and may be an important technology for dealing with abrupt climate change [7]. Currently, BECCS is being deployed at commercial scale in ethanol production and waste incineration facilities [8,9]. Previous work, primarily using Integrated Assessment Models (IAMs), has identified the critical role of BECCS in long-term climate change mitigation, particularly should carbon-negative tech-

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nologies be required [3,4,10,11]. Additionally, recent work exploring BECCS deployment in low-carbon power systems indicates that BECCS could be a key technology for aggressive decarbonization in pre-2050 timeframes [12,13]. This work, however, has not focused on practical design issues for BECCS facilities, including systems scale.

Bioenergy facilities, including BECCS facilities, likely exhibit economies of scale in capital costs, but diseconomies of scale in biomass transportation and supply costs [14]. The intuition behind capital cost economies of scale is that the capacity of different plant components (e.g., boilers) is a function of volume, while the cost of these components is a function of the material involved, which will scale at a rate closer to the component surface area. For a perfect sphere, volume grows as a cubic function of radius while surface area grows quadratically, so facility capital costs exhibit economies of scale. In contrast, transport costs exhibit diseconomies of scale because as plant capacity increases, feedstock must be hauled from longer distances. Profit-maximizing or cost-minimizing producers must also buy more expensive sources of biomass to satisfy plant demand. Probing these tradeoffs results in an optimal scale for BECCS facilities, which minimize average costs for a single facility, or total costs for a portfolio of facilities. Previous high-resolution modeling of BECCS deployment has treated BECCS capital costs as linear, despite the likelihood of non-linear costs [12].

Two key factors affecting optimal scale are biomass availability and cost. Estimates of lignocellulosic feedstock supply for bioenergy production are influenced by assumptions about available land, diet, population, and yield increases [15]. Additional constraints include water availability and competing demands for land [16,17]. The spatial distribution and cost of bioenergy resources have been estimated via a variety of methods, resulting in detailed inventories in the continental United States [18]. These publicly available biomass inventories can promote transparency and consistency in biomass and bioenergy analysis.

Biomass is less energy-dense and more spatially distributed than fossil fuels or other forms of renewable energy such as solar and wind, increasing the importance of management and logistics in cost-effective bioenergy supply. Optimization via linear programming, non-linear programming, and mixed-integer linear programing can help design bioenergy supply chains subject to constraints on supply and sustainability [19]. In this paper we use large spatial datasets to characterize the drivers of optimal sizing, both for a single facility and multiple facilities. This framework can be applied to a broad range of bioenergy technologies, including BECCS, and to diverse geographic areas.

We then apply this framework to optimally size BECCS facilities in Illinois, leveraging county-level biomass supply data, detailed road transportation networks, existing technology cost estimates, and previous geologic characterizations for long-term CO_2 storage. Illinois contains relatively plentiful low-carbon biomass resources from corn stover and other crop residues, as well as excellent geologic sequestration potential for CO_2 in the Illinois Basin [20]. For example, the Illinois Industrial Carbon Capture and Storage Project in Decatur, IL is one of the first commercial applications of BECCS in the world [21]. Several other commercial-scale CCS projects, such as the FutureGen Coal CCS facility in Meredosia, IL, have been proposed around the state [22]. As of 2010, Illinois contained six paper mills, presenting further options for bioenergy integration [23].

Our study is novel in several respects. First, we focus on BECCS, an emerging bioenergy technology for climate change mitigation, which has not been subject to detailed examination of practical design issues. Second, we develop a spatially-explicit model for optimal scale, which leverages publicly available biomass supply and transportation databases. Relatively few studies have studied economies-of-scale in a spatially-explicit context. Those that have rely on self-generated, rather than publicly available, biomass availability and cost estimates, and have studied conventional, rather than emerging, biomass facilities [24,25].

We focus on BECCS systems for electricity production. Biomass can be converted to electricity via two methods: (1) direct combustion, and (2) gasification [26]. Different conversion methods have varying degrees of permanence, CO_2 fixation efficiency, and technical potential, with important implications for climate change mitigation [27]. BECCS for electricity can proceed via post-combustion capture, pre-combustion capture, or oxycombustion processes [28]. BECCS can also proceed via ethanol, gasoline, diesel, or biogas production [17,29–31]. BECCS for fuel or chemicals production can occur on biochemical or thermochemical conversion processes [32].

Using Illinois as a case study, we find optimal scale for several BECCS technologies, biomass availability scenarios, locations, capital cost scaling parameters, and transportation cost scenarios. We characterize the sensitivity of cost to scale. We also find the optimal scales of multiple facilities across Illinois. Our results highlight the importance of economies of scale for BECCS system design, with implications for entrepreneurs, power plant designers, policymakers, and power system planners.

2. Materials and methods

2.1. Problem statement

2.1.1. Multiple facility case

Our first formulation of the optimization problem minimizes the net present value (NPV) of the total cost ($) of operating a set of BECCS facilities over the entire project lifetime (Table 1a). Costs include capital, variable operations and maintenance (O + M), fixed O + M, biomass purchase, fixed transportation, and variable transportation costs. Our problem is constrained by county-level biomass availability, and a constraint ensuring that sufficient biomass is delivered to meet expected electricity demand at the facility (Table 1b). We also enforce a constraint on the minimum size of the sum of the portfolio of BECCS facilities; this constraint can be interpreted as a total size goal, or portfolio standard, for a set of facilities throughout the study area.

This optimization problem chooses the size (S) of a set of potential facilities at several different locations, as well as biomass supplied from each county to each location (A), that minimizes total costs, subject to constraints. Decision variables include the size, S, of each facility, and amount of biomass supplied, A, from each county to each facility to satisfy demand. Capital costs are determined using a scaling parameter, $\alpha \leqslant 1$, which represents economies of scale. Biomass price, P, is a function of biomass supplied (A). Our sets include counties with available biomass, c, and a set of facility locations, l.

2.1.2. Single facility case

Our second optimization problem minimizes the NPV of the average cost ($/W) of operating a BECCS facility at a given location over the entire project lifetime. For a fixed capacity factor, minimizing capacity and energy are equivalent. This "average cost" minimization problem determines the optimal scale of a single BECCS facility. This framework is similar to prior studies of optimal scale for bioenergy facilities that are not spatially explicit [33,34,14]. Constraints are identical to the multiple facility case, except no scaled size goal is enforced. We restrict our set of facility locations, l, to a single facility. Decision variables and parameters are identical between the two optimization problems.