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Integrating rooftop solar into a multi-source energy planning optimization model

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HIGHLIGHTS

- There is significant technical capacity for rooftop solar installations.
- Rooftop solar generation is heavily dependent on key parameters.
- Rooftop solar should be one of several options for increasing renewable energy.
- Renewable energy planning should consider both cost and benefits.

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ABSTRACT

This research uses an optimization model to compare the role of rooftop solar generation versus large-scale solar and wind farm installations in renewable energy planning. The model consists of competing objectives, minimizing annual generation costs and minimizing annual greenhouse gas emissions. Rather than focus on the individual consumer's investment decision, over 20 scenarios were developed which explored key input parameters such as the maximum penetration level of rooftop solar installations, pricing of equipment, tax credits, and net-metering policy to determine what role rooftop solar plays in renewable energy investment at an aggregate level. The research finds that at lower levels of penetration, such as those currently found in the United States, other renewable energy sources remain viable options, thus rooftop solar should be just one option considered when increasing development of renewable energy sources. The research also shows that a balanced approach taking into account both of the opposing objectives will lead to greater levels of rooftop solar generation than focusing solely on cost or emissions. Therefore, rooftop solar should be considered as part of an overall balanced approach to increasing renewable energy generation.

1. Introduction

In efforts to combat climate change and reduce carbon emissions, renewable energy planning and development has been an increasing popular topic in governments, environmental organizations, and academic research in the past decade. Though much of the early work focused on large-scale developments such as wind farms, there has been increasing interest in distributed forms of generation, such as rooftop solar installations, due to the success of this approach in several countries [1,2]. With respect to solar rooftop generation, the previous research has been focused on individual choices [3–5], as the cost of the rooftop installations and associated paybacks or rates of return, have a big impact on the decision of individuals to invest in this technology. Moving beyond the individual decision, the ability to determine the amount of rooftop area available for installations on a large scale has proven difficult. There have been attempts at using satellite or radar images and quantifying rooftop area using geographic information systems techniques [6–8], but these applications are very time-consuming and are manageable only at the city or county level. A new technique based on statistical sampling has been developed to estimate rooftop area in larger areas, such as a state or region [9]. This approach is applied to a region in the Appalachian mountains of the United States to determine the potential for electricity to be derived from distributed rooftop solar installations.

In addition to quantifying rooftop solar availability, the research in this paper integrates this information into a regional energy planning multi-objective optimization model that has been used previously [10,11] to assess the economic viability and environmental impact from wind and solar farm developments in comparison to the existing energy infrastructure within the region. The integration of rooftop solar into this model allows for another option in renewable energy planning, as well as providing an

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assessment of cost-effectiveness for rooftop solar versus large-scale wind and solar farm installations within the region. The integration of multiple sources into this model provides additional information that would not be obtained through an analysis devoted solely to rooftop solar development in the region.

2. Rooftop solar background

Rooftop solar installations have been used around the world as an effective way to increase the amount of renewable energy. The two most commonly used policies to encourage rooftop solar are feed-in tariff and net-metering. A typical feed-in-tariff policy is based on a long-term contract that guarantees a price for electricity generated from renewable sources. Net-metering does not offer a guaranteed price for generation, as producers are often compensated at the current retail rate. Most net-metering policies do not allow for net producers of electricity to be paid for the excess generation, instead it is carried forward to future billing cycles and an expiration is often placed this credit. Although there have been attempts to implement feed-in-tariff policies in the United States [12], net-metering is the most common approach with 42 of the 50 states implementing this style of policy [13].

Several attempts at quantifying the amount of rooftop space available have been performed in previous research. Some of the efforts to address this issue have utilized satellite and aerial data sets, such as LiDAR, and performed GIS analysis to quantify rooftop space available for solar installations. Accomplishing this task requires not only defining the rooftop areas, but accounting for aspect, shading, and other factors that can decrease the amount of usable rooftop space. To date most research along these lines has focused on individual cities [6–8], and applying these approaches to larger areas is infeasible. Another approach [13] utilized an expensive non-geographic database containing information about buildings located in the United States. Beyond the cost of this information, factors such as aspect and shading must still be accounted for, requiring a set of assumptions to accurately define the amount of rooftop area available for solar installations. However, unlike in the detailed analysis associated with the first approach, these assumptions are created independently of other geographic data. A more sophisticated approach was developed to address rooftop availability over a wide area [9]. The south eastern region of Ontario province in Canada was analyzed through a five-step process that included sampling from different locations within the region, extrapolation through roof area-population relationships, and reduction due to shading, uses, and orientation. The result of this procedure was an estimated 13.1 m^2/capita ±6.2% available for rooftop solar installations, a statistic that can be carefully applied to other areas. By using a sample-based approach, this methodology did not require the extensive processing associated with the complete analysis of an entire region, and it ties all of the geographically-based data together throughout the process. By focusing on the differences and similarities between locations within the region, the result is the creation of a statistic that can be carefully applied to other areas, as implemented in Section 3.2 of this research.

Most of the research focused on rooftop solar installations has looked at this technology from a stand-alone perspective [13–15], analyzing the ability to increase generation without comparing it to other technologies. In addition, this research has focused on the impact that policies [4] or financial measures [3] have on investment decisions. The research presented in this paper takes a different approach, integrating rooftop solar installations as just one option to increase the use of renewable energy sources, as well as focusing on the overall costs of generation within the region instead of focusing on individuals.

With respect to rooftop solar on a larger scale, the difficulty has been estimating the level of market penetration, or number of consumers willing to adopt the technology. Previous research has attempted to solve this through techniques such as the development of a fuzzy-logic model for consumer acceptance based on surveys [5], or through the creation of adoption curves [13,14]. While this research has been beneficial, the survey approach relies too heavily on individual consumer's behavior to be useful in a regional model, and the methods creating adoption curves do not provide calculations that can be applied to other models. As such, the development of scenarios and reporting of penetration levels in [13] will provide the starting point for the values used in this research.

3. Methodology

3.1. Previous research

This research is the built on previous work [10,11,16] chronicling the development of a multi-source renewable energy planning model as applied to the greater southern Appalachian mountains region (Fig. 1), which comprises large portions of North Carolina (NC), Virginia (VA), and West Virginia (WV), along with smaller sections of Kentucky (KY) and Tennessee (TN). At the time of this research, the region was dominated by coal generation for electricity [17], accounting for 84.39% of total generation, while only 3.37% of electricity in this region is generated from renewable sources. However, the region has some of the best on-shore wind potential in the eastern United States, along with good levels of solar insolation [18].

The first portion of this research [16] created a geographic information system (GIS) model to determine potential locations for wind and solar farms. There were 203 potential wind farm sites and 477 potential solar farm sites discovered, representing 3.24% and 3.33% of baseline generation, respectively. The cost of full installation for wind farm sites, including new transmission infrastructure, is $13.7 billion, with an average generation cost of $0.1487/kW h, while solar farms would cost $32.6 billion, at an average cost of $0.2219/kW h. In addition, the model analyzed potential solid wood waste resources that could be used for co-fire at coal plants within the region. Approximately 8.7% of coal used within this region could be replaced by solid wood waste biomass, at a cost of $164.9 million. The total estimated capital cost for new renewable energy projects is $46.16 billion.

The results of this GIS model were incorporated into a mathematical model containing data for the existing electricity generation infrastructure [10]. The multi-objective linear programming optimization model consists of two competing objectives, minimizing emissions and minimizing cost, which are often in direct conflict with each other. The decision variables in the model include each of the potential wind and solar farm locations, with the generation and cost information from the GIS model utilized as parameters. Existing infrastructure decision variables were also included, allowing for costly or heavily polluting plants to be scaled back or shut down and replaced with cheaper or non-polluting renewable resources. There were several constraints within the model, including a limit on the amount of capital investment, which was set at $15 billion. An analysis of the tradeoffs between the objectives was illustrated through five different optimizations: (1) minimizing cost (without regard for emissions), (2) minimizing emission (without regard for cost), (3) equal importance of cost and emissions, (4) relatively more preference for minimizing cost, and (5) relatively more preference for minimizing emissions.

The third stage of this research focused on modifications to the optimization model based on three public policies: a renewable