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Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time

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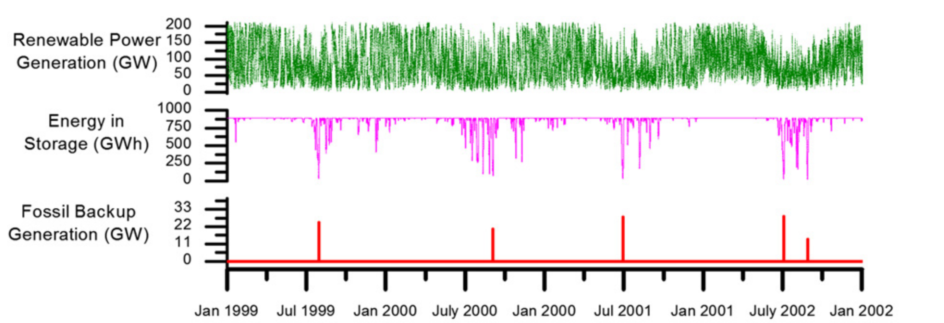
HIGHLIGHTS

- ► We modeled wind, solar, and storage to meet demand for 1/5 of the USA electric grid.
- ► 28 billion combinations of wind, solar and storage were run, seeking least-cost.
- ► Least-cost combinations have excess generation (3× load), thus require less storage.
- ► 99.9% of hours of load can be met by renewables with only 9–72 h of storage.
- ► At 2030 technology costs, 90% of load hours are met at electric costs below today's.

GRAPHICAL ABSTRACT



Load was met with renewable generation and storage 99.9% of hours over 4 years; fossil backup needed on five occasions

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ABSTRACT

We model many combinations of renewable electricity sources (inland wind, offshore wind, and photovoltaics) with electrochemical storage (batteries and fuel cells), incorporated into a large grid system (72 GW). The purpose is twofold: 1) although a single renewable generator at one site produces intermittent power, we seek combinations of diverse renewables at diverse sites, with storage, that are not intermittent and satisfy need a given fraction of hours. And 2) we seek minimal cost, calculating true cost of electricity without subsidies and with inclusion of external costs. Our model evaluated over 28 billion combinations of renewables and storage, each tested over 35,040 h (four years) of load and weather data. We find that the least cost solutions yield seemingly-excessive generation capacity—at times, almost three times the electricity needed to meet electrical load. This is because diverse renewable generation and the excess capacity together meet electric load with less storage, lowering total system cost. At 2030 technology costs and with excess electricity displacing natural gas, we find that the electric system can be powered 90%–99.9% of hours entirely on renewable electricity, at costs comparable to today's—but only if we optimize the mix of generation and storage technologies.

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1. Introduction

What would the electric system look like if based primarily on renewable energy sources whose output varies with weather and sunlight? Today's electric system strives to meet three requirements: very high reliability, low cost [1], and, increasingly since the 1970s, reduced environmental impacts. Due to the design constraints of both climate mitigation and fossil fuel depletion, the possibility of an electric system based primarily on renewable energy is drawing increased attention from analysts. Several studies (reviewed below) have shown that the solar resource, and the wind resource, are each alone sufficient to power all humankind's energy needs. Renewable energy will not be limited by resources; on the contrary, the below-cited resource studies show that a shift to renewable power will increase the energy available to humanity. But how reliable, and how costly, will be an electric system reliant on renewable energy? The common view is that a high fraction of renewable power generation would be costly, and would either often leave us in the dark or would require massive electrical storage.

Here we model the hourly fluctuations of a large regional grid, PJM Interconnection, in order to answer these questions. PJM is a large Transmission System Operator (TSO) in the eastern United States. It is located geographically in Fig. 1, and described in more detail in Appendix A. To obtain a multi-year run with constant system size we analyze calendar years 1999–2002, before its recent growth, when PJM managed 72 GW of generation, with an average load of 31.5 GW_a [2].

To evaluate high market penetration of renewable generation under a strong constraint of always keeping the lights on, we match actual PJM load with meteorological drivers of dispersed wind and solar generation (Fig. 1) for each of the 35,040 h during those four years. We created a new model named the Regional Renewable Electricity Economic Optimization Model (RREEOM). Our model is constrained (required) to satisfy electrical load entirely from renewable generation and storage, and finds the least cost mix that meets that constraint. The model is computationally-constrained, so we did not include additional computing-intensive considerations, such as how much additional transmission is optimum, or reliability issues not related to renewable resource fluctuations.

2. Prior studies

We do not find the answers to the questions posed above in the prior literature. Several studies have shown that global energy demand, roughly 12.5 TW increasing to 17 TW in 2030, can be met with just 2.5% of accessible wind and solar resources, using current technologies [3–5]. Specifically, Delucci and Jacobson pick one mix of eight renewable generation technologies, increased transmission, and storage in grid integrated vehicles (GIV), and show this one mix is sufficient to provide world electricity and fuels. However, these global studies do not assess the ability of variable generation to meet real hourly demand within a single transmission region, nor do they calculate the lowest cost mix of technologies.

Ekren and Ekren analyzed a small-scale system with batteries, PV, wind turbines, and auxiliary power [6]. The study assumes near-constant load (for communications), calculates only an energy capacity for the batteries and not power limits, and optimizes the configuration for minimum capital cost, not minimum total cost. Unfortunately, Ekren and Ekren only report their optimized system cost and area of solar and wind rotor as well as battery size so it is difficult to analyze these results. In a real grid, we must satisfy varying load, and with high-penetration renewables, charging and discharging storage will at times be limited by power limits not just by stored energy. More typical studies combining wind and solar do not seek any economic analysis and/or do not look at hourly match of generation to load (e.g. Markvart, 1996).

Hart and Jacobson determined the least cost mix for California of wind, solar, geothermal and hydro generation [7]. Because their mix includes dispatchable hydro, pumped hydro, geothermal, and solar thermal with storage, their variable generation (wind and photovoltaic solar) never goes above 60% of generation. Because of these existing dispatchable resources, California poses a less challenging problem than most areas—elsewhere, most or all practical renewable energy sources are variable generation, and dedicated storage must be purchased for leveling power output. We cannot draw general conclusions from the California case's results—for example, one might plausibly infer from this study that it is possible to have a power system with 60% variable generation, but not a higher fraction; or, we might conclude that a grid based exclusively on variable generation would require prohibitively expensive amounts of storage.

We can also compare our model with the HOMER micropower optimization model [8], which takes hourly load and resource data and calculates the most cost effective mix of generation. Much like HOMER, the present work employs a more valid storage cost model than other studies, because it distinguishes cost per MWh (cost per stored energy unit) from cost per MW (cost per power transfer rate). The difference between our study and HOMER is that we examine a regional power system, whereas HOMER has been used primarily for small isolated grids such as islands or single residences or buildings. One of our main objectives is to incorporate the power-leveling effects of meteorological and resource diversity on a regional scale.

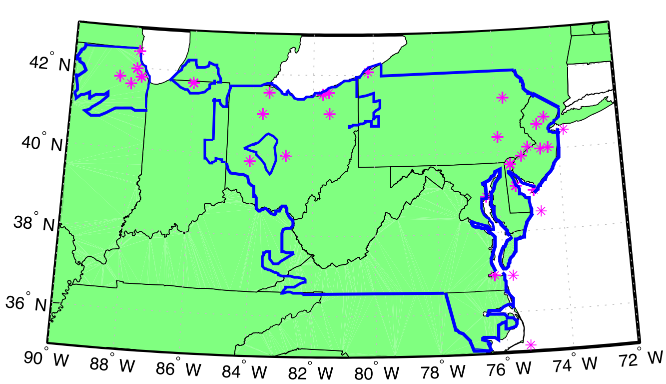

Fig. 1. A map showing the outlines of the current PJM system (blue line) and of the inland and offshore meteorological stations used for the wind data (pink asterisks). (For interpretation of the references to color in this figure legend, the reader is referred to the web or PDF version of this article.)

3. Enough power to meet load

Current electric power systems use fossil fuels as a form of stored energy, burning fuel at variable rates to generate power matched to fluctuating power demand. The operating principle of fossil generation is "burn when needed", a principle simple enough that it could be followed without computers, digital high-speed communications, or weather forecasting—precisely the conditions when today's electric system was created, early in the 20th century.

The ability to reliably meet load will still be required of systems in the future, despite the variability inherent in most renewable resources. However, a review of existing literature does not find a satisfactory analysis of how to do this with variable generation, nor on a regional grid-operator scale, nor at the least cost. We need to solve for all three.

In order to manage variable generation, there are four known options: geographical expansion, diversifying resources (e.g. solar plus wind), storage, and fossil backup. All four are employed in this study.