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Long-term implications of sustained wind power growth in the United States: Potential benefits and secondary impacts

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HIGHLIGHTS

- We model a scenario of the U.S. electric sector with wind reaching 35% in 2050.
- Scenario yields potential greenhouse-gas benefits of \$85–\$1230 billion.
- Air-pollution-related health benefits are estimated at \$52–\$272 billion.
- Electric-sector water use is lower by 15% (withdrawals) and 23% (consumption).
- Implications for risk of energy supply, local economic development, and land use.

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ABSTRACT

We model scenarios of the U.S. electric sector in which wind generation reaches 10% of end-use electricity demand in 2020, 20% in 2030, and 35% in 2050. As shown in a companion paper, achieving these penetration levels would have significant implications for the wind industry and the broader electric sector. Compared to a baseline that assumes no new wind deployment, under the primary scenario modeled, achieving these penetrations imposes an incremental cost to electricity consumers of less than 1% through 2030. These cost implications, however, should be balanced against the variety of environmental and social implications of such a scenario. Relative to a baseline that assumes no new wind deployment, our analysis shows that the high-penetration wind scenario yields potential greenhouse-gas benefits of \$85–\$1,230 billion in present-value terms, with a central estimate of \$400 billion. Air-pollution-related health benefits are estimated at \$52–\$272 billion, while annual electric-sector water withdrawals and consumption are lower by 15% and 23% in 2050, respectively. We also find that a high-wind-energy future would have implications for the diversity and risk of energy supply, local economic development, and land use and related local impacts on communities and ecosystems; however, these additional impacts may not greatly affect aggregate social welfare owing to their nature, in part, as resource transfers.

1. Introduction

Wind energy's role in global [1] and U.S. [2] electricity supply is rising, driven by policy measures as well as technology advancements and associated cost reductions [3]. The underlying policies helping motivate growth in wind energy are often predicated on the stated benefits of wind energy relative to fossil energy sources, including carbon and air-pollution emissions reductions, limited or no water requirements, potential benefits from energy diversity and risk reduction, and local economic-development activity. These benefits, however, are not always evaluated quantitatively, described fully, or qualified appropriately. Moreover, wind's benefits must be compared with the potential costs and risks introduced by adding wind energy to the electric system—such as changes in energy costs and increased planning and operating reserve requirements—as well as the potential negative impacts of wind on local ecosystems, local communities, and economic development elsewhere in the economy.

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Table 1
Summary of co-benefits, co-costs, and co-impacts covered in analysis.

Category	Brief description
Greenhouse-gas emissions reductions	*Coverage and method:* Quantifies life-cycle GHG emissions reductions, and values those reductions based on "social cost of carbon (SCC)" estimates *Caveats and limitations:* Considerable uncertainty exists on the SCC, so 4 trajectories spanning a wide range are applied; these reflect *global* carbon damage estimates.
Air-pollution impacts	*Coverage and method:* Estimates combustion-related criteria air pollution emissions reductions, and values those reductions based on avoided health outcomes *Caveats and limitations:* Focuses on 3 combustion-related pollutants; given uncertainty, develops 3 benefit estimates; assumes presence of MATS and CSAPR
Water use reduction	*Coverage and method:* Estimates operational water withdrawal and consumption impacts, including on a regional basis, and discusses benefits qualitatively *Caveats and limitations:* Does not quantify monetary value of water use reductions; makes assumptions about cooling-technology requirements for new power plants
Energy diversity and risk reduction	*Coverage and method:* Estimates impacts based on: (1) reduced sensitivity of future electric-system costs to uncertain fuel prices; and (2) reduced natural gas prices *Caveats and limitations:* Generalized methods to value diversity and risk reduction are controversial; neither impact estimated here represents a societal benefit
Workforce and economic development	*Coverage and method:* Estimates *gross* wind-related employment needs, based on input-output model *Caveats and limitations:* Develops 2 estimates based on range of manufacturing assumptions; does not consider *net* impacts, and no societal benefit claimed
Land use and local impacts	*Coverage and method:* Estimates land requirements from wind deployment considering wind project boundaries and the amount of disturbed land within that *Caveats and limitations:* Does not consider *net* impacts given reduced land needs associated with displaced generation; qualitatively discusses other local impacts

Transitioning to a future electricity system in which wind plays a more prominent role will have direct and significant impacts on the wind industry, cascading effects through the rest of the electricity system, and implications for local and global environments, human health, and the broader economy. In this and a companion paper [4], we evaluate these myriad potential impacts, costs, and benefits within the context of a *Wind Vision* scenario in which wind energy increases from its 2013 contribution of 4.5% of U.S. annual electricity demand to 10% by 2020, 20% by 2030, and 35% by 2050. As described in DOE [5], we view this modeled scenario as plausible but ambitious. We then compare this scenario with an alternative baseline scenario that assumes no new wind deployment.

The analysis described here assesses the potential implications of achieving a high-wind future. Lantz et al. [4] and DOE [5] summarize the electric-sector modeling approach and its advantages and limitations, the scenario framework, and the key input assumptions; the envisioned transitions to future power systems based on scenario results; direct electric-sector costs and impacts on electricity consumers; and transmission-expansion and grid-integration needs. The current paper analyzes a subset of the possible environmental and social co-benefits, co-costs, and co-impacts of this high-wind scenario. Specifically, it covers greenhouse-gas (GHG) emissions reductions, air-pollution impacts, water-use reduction, energy diversity and risk reduction, workforce and economic-development impacts, and land-use and local impacts. Table 1 summarizes, in brief, the impacts covered, methods used, and key caveats that apply to our analysis.

Our research uses a scenario-analysis approach where the 10%/20%/35% *Wind Vision* "study" scenario is compared with a "baseline" scenario in which no new wind is deployed post-2013. Though somewhat unconventional, this framework enables us to assess the costs, benefits, and impacts of *all incremental* wind deployment beyond 2013. Whereas Lantz et al. [4] and DOE [5] evaluate these scenarios (as well as more-traditional business-as-usual scenarios) using the National Renewable Energy Laboratory's (NREL) ReEDS model under a range of future fossil and wind energy costs, the present paper focuses on the central study assumptions. For each benefit, impact, and cost category, we take the modeled output from the ReEDS capacity-expansion model and then apply additional tools to assess benefits, costs, and impacts in physical and, where feasible, monetary terms. We qualify the study results appropriately—highlighting areas of uncertainty—and objectively address their policy implications. The U.S. Department of Energy's *Wind Vision* report provides further detail on the assumptions, methods, and results [5], as does the companion paper by Lantz et al. [4]. In particular, see Lantz et al. [4] for a summary of the ReEDS model and why that model is well-suited for the present analysis, and for more information on the remaining limitations and uncertainties in both the modeling approach and assumptions.

The approach used in the present study contributes to and builds on past literature. Previous work has found that the increasing maturity of wind technology [6] and the size of the global resource [7] could enable wind energy to play a significant future role in electricity supply [8–12]. That role, however, is uncertain, and is found to be affected by wind energy cost reductions, the scale of greenhouse gas emissions mitigation efforts, and other factors [10–12]. Some of this research has focused specifically on wind energy's role in the U.S. electricity mix. MacDonald et al. [13], for example, find significant potential for wind energy supply in the U.S., as does an earlier report from the U.S. Department of Energy [14].

Other past research has explored a subset of the potential benefits and impacts of wind energy. For example, McCubbin and Sovacool [15] compare the health and environmental impacts of wind to natural gas, while Yang and Chen [16] provide a sustainability evaluation of wind power systems. Siler-Evans et al. [17], Buonocore et al. [18], and Cullen [19] explore these health and climate benefits on a regional basis, while Arent et al. [20] assess a small subset of benefits associated with a high-penetration renewable energy scenario in the U.S. primarily in physical (not financial) terms. Others have explored the impacts of renewable (and wind) energy deployment on water use, on land use, on risk and diversity, and on employment – with citations provided later in this paper.

The present work and that described in Lantz et al. [4] substantially builds on these past efforts in several ways. First, and most importantly, ours is a comprehensive assessment of important impacts, costs, and benefits of a high-penetration wind energy future. Rather than focusing on a small subset of important