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A review of the potential impacts of climate change on bulk power system planning and operations in the United States

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ABSTRACT

Climate change might impact various components of the bulk electric power system, including electricity demand; transmission; and thermal, hydropower, wind, and solar generators. Most research in this area quantifies impacts on one or a few components and does not link these impacts to effects on power system planning and operations. Here, we advance the understanding of how climate change might impact the bulk U.S. power system in three ways. First, we synthesize recent research to capture likely component-level impacts of climate change in the United States. Second, given the interconnected nature of the electric power system, we assess how aggregated component-level impacts might affect power system planning and operations. Third, we outline an agenda for future research on climate change impacts on power system planning and operations. Although component-level impacts vary in their magnitude, collectively they might significantly affect planning and operations. Most notably, increased demand plus reduced firm capacity across generation types might require systems to procure significant additional capacity to maintain planning reserve margins, and regional declines in renewable resources might need to be offset by increasing zero-carbon investment to meet decarbonization targets. Aggregated impacts might also affect operations, e.g., through shifts in dispatching and increased operational reserve requirements. Future research should aggregate component-level impacts at operational timescales, quantify impacts on wind and solar variability, and contextualize climate change impacts within ongoing shifts in the electric power system.

1. Introduction

While weather and climate have impacted power systems since their inception, two ongoing trends could fundamentally reshape this relationship. First, climate change will alter climate and weather during the next decades, inducing nonstationary trends in air temperature and precipitation [1] that might present power systems with new conditions and challenges [2]. In fact, utilities in Europe [3], Canada [4], the United States [5], and elsewhere have already started formulating plans to address these impacts. Second, because of declining costs [6] and decarbonization efforts [7], power systems are increasingly shifting toward variable wind and solar technologies (among other zero-carbon technologies).

Given these forces, a growing body of literature estimates how climate change might affect electric power systems. Most literature focuses on impacts to one or more components of the power system, including electricity demand [8]; transmission infrastructure [9]; and hydroelectric [10], thermal [11], wind [12], and solar [13] generation. Others during the last decade review aspects of climate change impacts on power system components. Stanton and Dessai [14] summarize supply-side impacts of climate change for each European country, Chandramowli and Felder [15] detail the models and methods used to assess climate impacts, Schaeffer et al. [16] describe the mechanisms by which climate change might affect each component of the electric power system, and Mideksa and Kallbekken [17] qualitatively summarize supply- and demand-side impacts globally. None of these prior reviews link component-level or aggregated component-level impacts to power system planning and operation impacts. Additionally, prior reviews do not quantitatively assess component-level impacts in the United States or other regions. Quantitative assessments indicate likely absolute and relative magnitudes of component-level impacts, which are crucial for prioritizing research and adaptation efforts. Despite increasing publications on individual power system components, a dearth of research exists translating climate change impacts on these

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components into impacts on power system planning and operations. Of most relevance, McFarland et al. [18] and Larsen et al. [19] assess how climate change impacts on electricity demand and thermal plant efficiency will drive increased investments and generation. Notably, both papers consider only a small subset of potential component-level impacts; however, because of the interconnected nature of the power system, concurrent impacts on multiple components might yield reinforcing effects on planning and operations. Thus, aggregating impacts and interactions of climate change across components of the power system and linking them to planning and operations is crucial to understand what actions, if any, need to be taken to maintain economic, resilient, and reliable electricity delivery in the future.

A challenge to this endeavor is the significant uncertainty in future climate change and its impacts on power systems. Uncertainty in future climate change arises primarily from a combination of model uncertainty (i.e., models imperfectly represent climate), future emissions pathway uncertainty (i.e., how quickly will economies decarbonize), and climate dynamics uncertainty (e.g., how do aerosols and clouds interact and what is the resulting radiative forcing) [20,21]. Even with perfect climate change foresight, the impacts of climate change on power systems would be uncertain because decarbonization and economic forces might reshape the composition and operation of the generator fleet in the coming decades. For one, retirements of fossil-fueled thermal units due to economic and environmental factors [22,23] will need to be compensated by other sources, particularly wind and solar [23,24]. Growth in wind and solar power might occur in resource-rich areas far from load, requiring significant transmission expansions [25,26]. Additionally, electrification of transportation and other services could significantly increase demand and alter temporal demand patterns [27].

Uncertainty in climate change and its power system impacts does not preclude its consideration in power system planning and operations, as planning and operations already account for large uncertainties. Planning accounts for uncertain load growth, retirements, investments, and emerging technologies, whereas operations account for uncertainty induced by short-term weather variability, e.g. in wind and solar generation [28] and forced thermal generator outages [29,30]. In this context, climate change impacts and associated uncertainty do not pose a fundamentally new problem to planning and operations, but rather add to the complexity and uncertainty they already account for.

In this article, we further the understanding of how climate change might affect bulk, i.e., transmission-scale, power systems by examining individual and aggregated component-level impacts on bulk power system planning and operations. Because studies on climate change impacts typically rely on data from Global Climate Models (GCMs), in Section 3 we briefly describe GCMs and discuss challenges with their use. In Section 4, we focus on climate change impacts on individual components of power systems. We review the results of recent research, then provide our assessments of research gaps and how component-level impacts may affect power system planning and operations. In Section 5, we focus on climate change impacts on power system planning and operations. We first provide our assessment of how aggregated component-level impacts of climate change might affect power system planning and operations, then outline our proposed future research agenda. Given recent publications in this area, we conduct our review for the United States. Additionally, we focus on the bulk power system, so we ignore distribution-level and upstream impacts (see [16] for the latter).

2. Methods

To conduct our literature review, we searched Scopus for peer-reviewed publications on climate change impacts on individual power system components and on power system planning and operations. Given the nascent stage of such research, we limited our search results to publications since 2010 that pertain to the United States. Table 1 provides our Scopus search terms and the number of publications

Table 1
For each component-level impact, our Scopus search terms, the number of publications returned by each search, and the number of publications returned by each search filtered for relevance.

Component-level impact	Scopus search terms	Number of returned publications	Number of filtered publications
Demand	Electricity AND climate change impacts	188	26
Thermal generators	Thermal plants AND power systems AND United States AND climate change impacts	11	19
	Fossil fuel* and power plant* AND United States AND climate change impacts	32	
	Power plant AND (coal OR gas OR oil OR fossil) AND United States AND climate change impacts	69	
Hydropower	(Hydropower OR hydrolog* OR hydro-climat*) AND United States AND climate change	1500	29
	Hydropower AND United States AND climate change impacts	45	
Wind	Wind generation AND United States AND climate change impacts	36	28
	Wind speed AND (wind power OR wind energy) AND climate model	562	
	Wind speed AND (wind power OR wind energy) AND United States AND climate model	252	
Solar	(Solar OR photovoltaic) AND power systems AND United States AND climate change impacts	21	22
	Solar generation AND power systems AND United States AND climate change impacts	13	
	Solar generation AND United States AND climate change impacts	27	
	Solar photovoltaic OR concentrating solar power) AND generation AND climate change impacts	120	
	(Solar power OR solar energy) AND United States AND climate model	130	
	Solar resource AND United States AND climate model	55	
Transmission	Transmission AND electric* AND climate change	485	19
	Transmission AND electric* AND United States AND climate change	37	
Planning and operations	Power systems AND United States AND climate change impacts	166	24