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LETTER

Compounding climate change impacts during high stress periods for a high wind and solar power system in Texas

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Abstract

Power system planning aims at ensuring that sufficient supply- and demand-side assets exist to meet electricity demand at all times. For a Texas electric power system with high wind and solar penetrations, we quantify how climate change will affect supply and demand during three types of high stress periods for the power grid: high demand hours, high net demand hours, and high system ramp hours. We specifically quantify effects on demand, reductions in available thermal capacity (i.e. thermal deratings), wind and solar generation, and net demand. We estimate each using meteorological variables from five climate change projections (2041–2050) assuming Representative Concentration Pathway 8.5 and from a reference period (1996–2005). All five projections indicate that climate change will increase demand by up to 2 GWh during high demand hours (4% of demand in the reference period) and increase net demand by up to 3 GWh during high net demand periods (6% of net demand in the reference period). All five projections also indicate thermal deratings will increase during high demand and net demand periods by up to 2 GWh and high net demand ramps will increase by up to 2 GW. Overall, our results indicate compounding effects of climate change in Texas will necessitate greater investment in peak and flexible capacity.

Introduction

Power system planning primarily aims at maintaining system adequacy, or at ensuring that sufficient assets will be available to meet future electricity demand at all times. These assets include demand- and supply-side resources, such as thermal, wind, and solar generators. Because of their variability and uncertainty, wind and solar generation poses new challenges to the planning process. For instance, planning traditionally focused on procuring capacity to meet demand in high demand periods, but increasing wind and solar penetrations are elevating other high stress periods in planning (Lew *et al* 2013, Milligan *et al* 2017).

A growing consensus indicates climate change will likely affect the demand for and supply of electricity (Chandramowli and Felder 2014, Stanton and Dessai 2016, Craig *et al* 2018). In the United States, climate change will increase the frequency and magnitude of peak demand primarily because increased ambient air temperatures under climate change increase air conditioning loads (Dirks *et al* 2015, Auffhammer *et al* 2017, Fonseca *et al* 2019). Climate change will also decrease available thermal capacity (i.e. increase thermal deratings) particularly in the summertime (van Vliet *et al* 2012, Bartos and Chester 2015, Liu *et al* 2017, Miara *et al* 2017, Loew 2018), when electricity demand also peaks in many systems. Climate change will increase deratings of thermal plants with once-through cooling using freshwater through increased water temperatures or reduced water availability (van Vliet *et al* 2012, Liu *et al* 2017), and increase deratings of combustion turbines and plants with recirculating and dry cooling through altered meteorological conditions, e.g. increased air temperatures (Bartos and Chester 2015, Loew 2018). Although less certain than prior impacts, climate change will also likely cause regional increases or decreases in average annual wind and solar generation through altered resources, with larger changes at sub-regional and sub-annual timescales (Wild *et al* 2015, Haupt *et al* 2016, Craig *et al* 2018, Carreño *et al* in review, Karnauskas *et al* 2018).

Little research has combined these demand- and supply-side impacts of climate change to understand their potential aggregate effect on power system planning. Larsen *et al* (2017) and McFarland *et al* (2015) used long-term planning models to quantify how increased annual and peak demand and decreased available thermal capacity alter power plant investments and operations across the United States by 2050. Tobin *et al* (2018) estimated aggregate multi-year changes in wind, solar, hydropower, and available thermal capacity by country in Europe by end of century. Parkinson and Djilali (2015) used a long-term planning model to optimize generator builds given possible increases in hydropower generation in British Columbia by 2050. Notably, these studies did not jointly quantify climate change impacts on electricity demand, thermal deratings, and wind and solar generation, which will be crucial to planning in the high wind and solar penetration power systems expected by midcentury.

Here, we assess how climate change might affect power system planning by quantifying electricity demand and supply during three high stress periods for the power system: high demand hours, high net demand hours, and high system ramp hours. We conduct our study on a Texas power system with high wind and solar penetrations of 26% and 23% of total installed capacity, respectively. We estimate synchronous electricity demand, thermal deratings, wind and solar generation, and net demand in a reference period (1996–2005) and under five climate change projections under Representative Concentration Pathway (RCP) 8.5 by midcentury (2041–2050).

Methods

Weather variables under reference period and climate change projections

To estimate electricity demand, thermal deratings, and wind and solar generation in a reference period and under climate change, we first obtain weather variables for a reference period (1996–2005) and five climate change projections (2041–2050) under RCP 8.5. Among RCPs, RCP 8.5 has the greatest projected warming by end of century, so we select it to estimate an upper bound on climate change impacts. However, RCPs 4.5, 6.5, and 8.5 result in similar projected warming through midcentury (Stocker *et al* 2013), our period of analysis.

We use highly spatially and temporally-resolved weather variables for the reference period and climate change projections from Carreño *et al* (in review), who generate those variables using the Weather Research and Forecasting (WRF) model version 3.8, a numerical weather prediction model (Skamarock *et al* 2008). Carreño *et al* configured WRF by centering its grid at 31.00°N and 100.00°W and using 340 points in the latitudinal and longitudinal directions spaced 4 km apart (see supplemental information available online at stacks.iop.org/ERL/15/024002/mmedia (SI) section SI.1 for domain). To better estimate parameters that drive solar generation, they configured WRF with the Rapid Transfer Radiative Model (RRTM) for longwave radiation and activate direct aerosol effects in WRF with high-resolution climatology of aerosol optical depth at a 550 nm wavelength from WRF-Solar (Jimenez *et al* 2016).

To generate atmospheric variables for the reference period, Carreño *et al* used data from the North American Regional Reanalysis (NARR) (Mesinger *et al* 2006) to specify WRF's boundary conditions every 6 h from 1995 through 2005. Since we used 1995 as a spin up year, we exclude it from our analysis.

To generate atmospheric variables under climate change projections, Carreño *et al* modified NARR data from the reference period using Global Climate Model (GCM) output dynamically downscaled with the Regional Climate Model version 4 (RegCM4) (Giorgi *et al* 2012), then used that modified NARR data to specify WRF's boundary conditions every 6 h. Thus, to generate climate change projections, Carreño *et al* used two dynamical downscaling steps, in each of which a higher-resolution atmospheric model (RegCM4 and WRF in the 1st and 2nd steps, respectively) was forced by time-varying boundary conditions that were based on a coarser-resolution model (GCM and RegCM4 in the 1st and 2nd steps, respectively). To run WRF for climate change projections, Carreño *et al* modified 6 h NARR sea surface temperature (SST) and atmospheric temperature and moisture on a cell-by-cell basis at all levels. To do so, they first calculated average monthly changes between 1995–2005 and 2040–2050 for each year and variable for RCP 8.5 from an ensemble of five GCMs (ACCESS1-0, CCSM4, IPSL-CM5A-LR, MPI-ESM-MR, and GFDL-ESM2M) dynamically downscaled with RegCM4, then disaggregated these average monthly changes via linear interpolation to 6 h changes. Thus, to each unique 6 h NARR SST and atmospheric temperature and moisture value they added a unique 6 h interpolated RegCM4 value. The five selected GCMs captured the range of annual mean precipitation projections in Texas across 11 GCMs dynamically downscaled with RegCM4 by Ashfaq *et al* (2016).

Carreño *et al* validated wind and solar resources in our reference period against high-resolution wind and solar integration datasets (Draxl *et al* 2015, Sengupta *et al* 2018) and against two long-term observed datasets from Texas. Validation indicated our reference period had similar errors as the integration datasets for global horizontal irradiance and wind speed relative to the observed data. Validation also indicated our reference period tended to underestimate wind speeds and global horizontal irradiance and overestimate direct normal irradiance. Averaging across years from our reference period to climate change projections, Carreño *et al* found average surface temperatures increased by 0.5 °C–2.3 °C across Texas and average wind and solar capacity factors changed by 1.3%–3.5% and −0.6% to 2.5%, respectively, across Texas. For more details, see Carreño *et al* (in review).

Overall, this process generates ten years of hourly time series of atmospheric and solar irradiance variables from WRF for 4 × 4 km grid cells covering Texas for one reference period and five climate change projections. The reference period corresponds to 1996–2005 meteorology, while each climate change projection corresponds to 1996–2005 meteorology superimposed with climate change for 2041–2050 under RCP 8.5 from one GCM dynamically downscaled with RegCM4.

Estimating electricity demand, thermal deratings, and wind and solar generation

To calculate how climate change affects electricity demand, thermal deratings, and wind and solar generation, we estimate each on an hourly basis using WRF outputs for the reference period and five climate change projections. For our study system, we use the Electric Reliability Council of Texas (ERCOT), which serves 90% of electric demand in Texas (Electric Reliability Council of Texas 2017a). Given hydropower's small installed capacity in ERCOT (less than 1% of total installed capacity (Electric Reliability Council of Texas 2017b)) and limited research quantifying climate change impacts on the transmission network, we exclude hydropower and transmission from our analysis.

Electricity demand

Electricity demand has a strong nonlinear dependence on ambient air temperature (Bramer *et al* 2017, Wang and Bielicki 2018, Fonseca *et al* 2019): increased air temperatures tend to increase demand for air conditioning except at low temperatures, when increased air temperatures reduce demand for electric heating. To capture this nonlinear relationship, we estimate hourly electricity demand (D (MWh)) as a function of air temperature (T (°C)) using a piecewise linear regression model that enforces continuities at its breakpoints (see SI.2.3) (Fonseca *et al* 2019):

$$D_t = \sum_{i=1}^{N} (\alpha_i * T_{i,t}) + \delta_t + \gamma_t + \beta + \epsilon_t, \quad (1)$$

where t and i index hours and piecewise linear segments, respectively; N = number of piecewise linear segments (provided below); α = slope of the relationship between temperature and demand (MWh/°C); δ = fixed effect for all possible combinations of hour of day, weekday versus weekend, and season (MWh); γ = fixed effect for year (MWh); and β and ε are intercept and error terms, respectively (MWh). Time fixed effects δ and γ capture systematic changes in electricity demand across days (e.g. demand tends to peak in early evening as people arrive home), weeks (e.g. demand tends to be greater on weekdays than weekends due to high commercial and residential consumption), seasons (e.g. Texas is a summer peaking season), and years (e.g. due to long-term climatic variability and fuel price variability) (Fonseca *et al* 2019).

To isolate the impact of climate change on demand, we ignore all other potential demand impacts over our study period. Including interactions between temperature and relative humidity within each segment only marginally improves our regression's fit, so we use our simpler and clearer model. Other approaches, e.g. heating and cooling degree days, can forecast demand under climate change (Sailor and Pavlova 2003), but at coarser temporal resolution than needed here.

We obtain historic hourly demand for ERCOT divided into eight weather zones for 1996 through 2005 excluding 2001, for which no demand data publicly exists (Electric Reliability Council of Texas 2018). To better capture local demand responses to air temperature, we fit equation (1) separately for each weather zone. To fit each regression, we regress historic hourly binned demand against hourly WRF air temperatures from the relevant weather zone for all 9 years in the reference period (SI.2) (Fonseca *et al* 2019). By regressing historic demand against WRF outputs instead of against historic meteorology, we avoid potential biases in WRF outputs relative to historic meteorology that could bias our regression results (Fonseca *et al* 2019). Based on the relationship between demand and WRF air temperature in each weather zone, we use the following piecewise segments in equation (1) for each weather zone (in degrees Celsius): [−18.44, 10], (10, 15], (15, 20], (20, 25], and (25, 42.67], where −18.44 and 42.67 are the minimum and maximum temperatures in our dataset. In fitting equation (1) in each weather zone, we use the temperatures closest to each weather zone's largest demand, which we assume is the largest city (SI.2). In-sample R-squared values of our fitted regressions range from 0.76 to 0.85, while cross-validation indicates that in-sample and out-of-sample root mean square errors of predicted demand are similar (SI.2).

With the fitted regressions, we estimate hourly demand in each weather zone for all nine years of the

Table 1. Number and installed capacity of generators in our thermal fleet by plant type and cooling technology, which drive a generator's vulnerability to deratings, and cooling technology we use to calculate deratings. ST, CC, and CT stand for steam turbine, combined cycle, and combustion turbine, respectively. OT, RC, and DC stand for once-through, recirculating, and dry cooling, respectively.

Plant type	Cooling technology	Number of generators	Total installed capacity of generators (GW)	Cooling technology used to calculate deratings
Coal ST	None/OT/RC/DC	0/0/25/0	0/0/15.5/0	RC/RC/RC/DC
Gas ST	None/OT/RC/DC	6/15/19/0	0.2/4.4/5.8/0	RC/RC/RC/DC
Gas CC	None/OT/RC/DC	14/8/61/10	2.9/3.1/2.5/2.3	RC/RC/RC/DC
Gas CT	NA	67	4.6	NA

reference period and of each climate change projection using hourly WRF air temperatures, then sum hourly demand across weather zones to estimate hourly ERCOT demand. The correlation between hourly observed and predicted ERCOT demand in the reference period is 0.93.

Thermal deratings

Thermal power plants' vulnerability to deratings (or reductions in available capacity) depend on the type of power plant and cooling technology (see Introduction). We calculate deratings of natural gas combustion turbines (Bartos and Chester 2015) and of coal- and other gas-fired generators with recirculating and dry cooling systems (Loew 2018) as linear functions of air temperature, relative humidity, and air pressure (see SI.3). We do not quantify deratings for generators with once-through cooling for two reasons. First, strict environmental regulation enforcement largely drives once-through cooling deratings (Henry and Pratson 2016, Liu *et al* 2017, Yearsley *et al* 2017), but enforcement is unlikely when power system reliability is at stake. Second, once-through cooling is phasing out nationwide (Loew 2018), so has little relevance to midcentury analyses.

To estimate the impact of climate change on thermal deratings, we calculate thermal deratings for the 2017 ERCOT generator fleet (Electric Reliability Council of Texas 2017b) in the reference period and in each climate change projection using WRF output and linear equations. By using the 2017 generator fleet, we ignore the effects of continued thermal plant retirements and any adaptation measures taken to reduce the vulnerability of existing thermal generators. Thus, our research likely provides an upper bound on (i.e. pessimistic estimate of) how climate change will affect thermal deratings. Future research should forecast interaction between climate change, thermal deratings, and thermal generator fleet changes.

Since recirculating cooling is largely replacing once-through cooling, we model deratings for generators with once-through cooling as if they had recirculating cooling. Table 1 provides the number and total installed capacity of generators for which we estimate deratings by plant and cooling type. We estimate deratings for each generator using relevant variables, which vary by plant and cooling type (SI.3), from the nearest available WRF output. Given the hot Texas climate, we assume cooling system designs that are robust to high air temperatures (Loew 2018), but test the sensitivity of our results to more and less robust designs (SI.3).

Wind and solar generation

To isolate climate change impacts on wind and solar generation, we calculate generation by the same wind and solar generator fleet in the reference period and in each climate change projection. Given expected growth in wind and solar installed capacity and our midcentury timeframe, we use a high wind and solar generator fleet with wind and solar installed capacities of 35 and 31.5 GW (26% and 23% of total installed capacity), respectively, and energy penetrations of 25% and 15%, respectively. Absent climate change, studies in other parts of the US indicate that this level of renewable penetration can be integrated from a technical perspective, but doing so might require market design reform and investment in transmission and flexible assets (Hand *et al* 2012, Bloom *et al* 2016). As of July 2019, ERCOT has 22 and 1.8 GW of installed wind and solar, respectively (ERCOT 2019). We site this wind and solar capacity at locations of wind and solar plants deployed by the Regional Energy Deployment System (Cohen *et al* 2019), a capacity expansion model, for a similar wind and solar penetration scenario. Generally, our wind plants are sited in the Panhandle, Central, and Southern Texas, while our solar plants are sited in the Panhandle, Central, and Houston areas (see SI.4 for map). In the reference period, the wind and solar generator fleets have average fleet-wide capacity factors of 0.39 and 0.18, respectively, indicating they are sited in high quality resource areas.

To estimate hourly electricity generation by each wind and solar plant in the reference period and climate change projections, we input WRF outputs into the System Advisor Model (SAM) (US National Renewable Energy Laboratory 2017), which includes a wind and solar performance model. Specifically, we input into SAM hourly air temperature, wind speed (at 10 m), direct normal irradiance, and direct horizontal irradiance from WRF to estimate hourly solar electricity generation. In so doing, we capture the effect of temperature on solar PV generation. To estimate hourly wind electricity generation, we input into SAM wind speed, air pressure, and air temperature (all at

100 m) from WRF. We assume fixed tilt solar panels tilted at latitude and IEC-2 composite wind turbines at 100 m hub height and with 90 m rotor diameter and use the nearest WRF output to each wind and solar plant. We ignore wake effects for wind generation.

Defining high stress periods

We quantify the effect of climate change on demand, thermal deratings, and wind and solar generation during three types of high stress periods for the power grid: high demand, high net demand, and high system ramps. Net demand equals demand plus thermal deratings minus wind and solar generation, which we calculate on an hourly basis using the synchronous time series generated above. System ramps equal the change in demand or net demand between each pair of hours. Upward ramps typically pose greater operational challenges than downward ramps, as excess renewable generation can be curtailed to meet the latter. Consequently, we quantify system ramps as upward changes in demand or net demand on an hourly basis, the temporal resolution of our data.

To analyze patterns in demand- and supply-side impacts of climate change, we define 'high' as the top 20 h values per year, e.g. high demand periods are the hours with the top 20 demand values in each year. ERCOT also uses top 20 h in planning, for the calculation of wind and solar capacity values (Electric Reliability Council of Texas 2019). We find similar results when defining 'high' as the top 10 and 30 h values annually (SI.5).

Power systems must continually balance supply and demand. High demand stresses power grids by requiring utilization of most of their installed capacity. High net demand stresses power grids by requiring utilization of most of their installed dispatchable capacity, as net demand already accounts for non-dispatchable generation (namely wind and solar generation and thermal deratings). High net demand periods poses a particular challenge to high wind and solar systems because wind and solar might displace dispatchable capacity. Because net demand factors out wind and solar generation, high net demand rarely coincides with high demand. Finally, high system ramps stress power grids by requiring utilization of most of their installed flexible capacity, or capacity that can quickly respond to changes in supply or demand.

Results

For each high stress period, we first quantify demand, thermal deratings, wind and solar generation, and net demand (where relevant) in our reference period, then quantify the effect of climate change on each. Since demand increases annually over our reference period (figure 1), we treat each year as an independent observation in our analysis and compare median climate change effects across the nine years in each climate change projection.

High demand hours

In our reference period, demand varies from 46–47 GWh to 53–54 GWh across years (figure 1) and high demand hours (i.e. the top 20 demand hours annually). Also during these hours, thermal deratings range from 1–5 GWh across years (which corresponds to 2%–7% of total thermal capacity) and wind plus solar generation ranges from 17 to 45 GWh with large variability between and within years.

For each climate change projection, we quantify the median climate change impact on demand, thermal deratings, and wind and solar generation in each high demand hour by taking the median impact across years for each hour (figure 2). During high demand hours, all five climate change projections indicate climate change will increase median demand by 1–2 GWh (up to 4% of demand in the reference period). We do not find climate change will change when high demand occurs, typically between June and August in the late afternoon (2–4 p.m.). During high demand hours, all five climate change projections also indicate climate change will increase median thermal deratings by 0–2 GWh (up to 40% of deratings in the reference period) (figure 2). Increased demand and thermal deratings compound each other by reducing thermal plants' potential contribution to meeting the increase in demand during high demand periods. Increases in demand and thermal deratings also occur across high demand hours in individual years (SI.6).

No consistent impact of climate change on wind or solar generation during high demand hours emerges across climate change projections or across high demand hours within each projection. Median changes in wind generation range from a 5 GWh decrease to 7 GWh increase while median changes in solar generation range from a 5 GWh decrease to 3 GWh increase across climate change projections and high demand hours. Greater variability in wind and solar generation changes under climate change occur across high demand hours within each year (SI.6).

High net demand

In the reference period, net demand ranges from 31–35 GWh to 40–46 GWh across years during high net demand hours (figure 3). High net demand generally coincides with moderate demand (36–53 GWh), low wind and solar generation (less than 17 GWh), and low thermal deratings (less than 3 GWh). Consequently, high net demand hours do not coincide with high demand hours.

Across all five climate change projections, we find climate change will increase median net demand by 0.5–3 GWh in high net demand hours (figure 4), or by up to 6% of median net demand in the reference period (i.e. the median across years for each high net

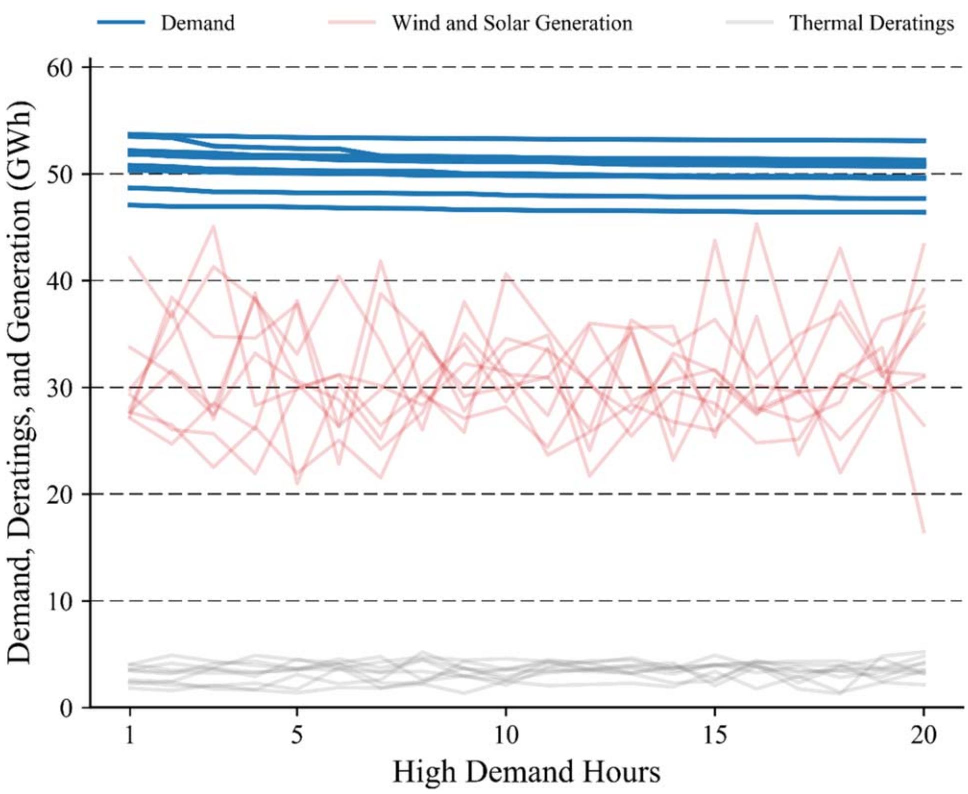

Figure 1. Demand, wind plus solar generation, and thermal deratings in high demand hours in the reference period. Lines represent individual years. Demand is sorted from greatest to least, while thermal deratings and wind and solar generation are synchronous with sorted demand.

demand hour) (figure 3). We found a similar increase of 1–2 GWh in demand during high demand hours under climate change (figure 2). We do not find climate change will shift when high net demand occurs, typically in the early evening (6–8 p.m.) between June and September.

In high net demand periods, we find climate change will increase net demand primarily through increases in demand and thermal deratings (figure 4). Net demand increases in each high net demand hour, but contributing increases in demand and thermal deratings do not occur in each high net demand hour, indicating their compounding nature. Climate change will have a mixed impact on wind generation and little impact on solar generation during high net demand hours (figure 4). High net demand tends to occur in the early evening, when solar generation is small.

High system ramps

In the reference period, high system ramps in demand range from 3.5 to 5 GW while high system ramps in net demand range from 9 to 17 GW across years (figure 5). Greater ramps in net demand (relative to just demand) are driven primarily by greater variability introduced by wind and solar power; deratings have little effect on high system ramps. Thus, variability in wind and solar generation increases system flexibility requirements from roughly 5 to 17 GW in our reference period.

We quantify climate change impacts on high system ramps as the median change in high hourly system ramps across years in each climate change projection. We examine high system ramps in demand, demand plus thermal deratings, and net demand. All five climate change projections indicate climate change will decrease the median of high system ramps in demand by up to 0.1 GW (up to 3% of reference period values) (figure 6). Conversely, all five climate change projections indicate climate change will increase the median of high system ramps in demand plus thermal deratings by up to 0.2 GW (up to 6% of reference period values). Climate change has larger and more variable effects on high system ramps in net demand. Specifically, all five climate change projections indicate climate change will increase the median of high system ramps in net demand by up to 2 GW (up to 10% of reference period values). We find similar results for 4 h ramps (SI.7).

Discussion

This paper analyzes how climate change might affect power system planning at high wind and solar penetrations. We quantified climate change effects on supply (specifically thermal deratings and wind and solar generation) and demand during three types of high stress periods for the power system: high demand, high net demand, and high system ramps. To quantify

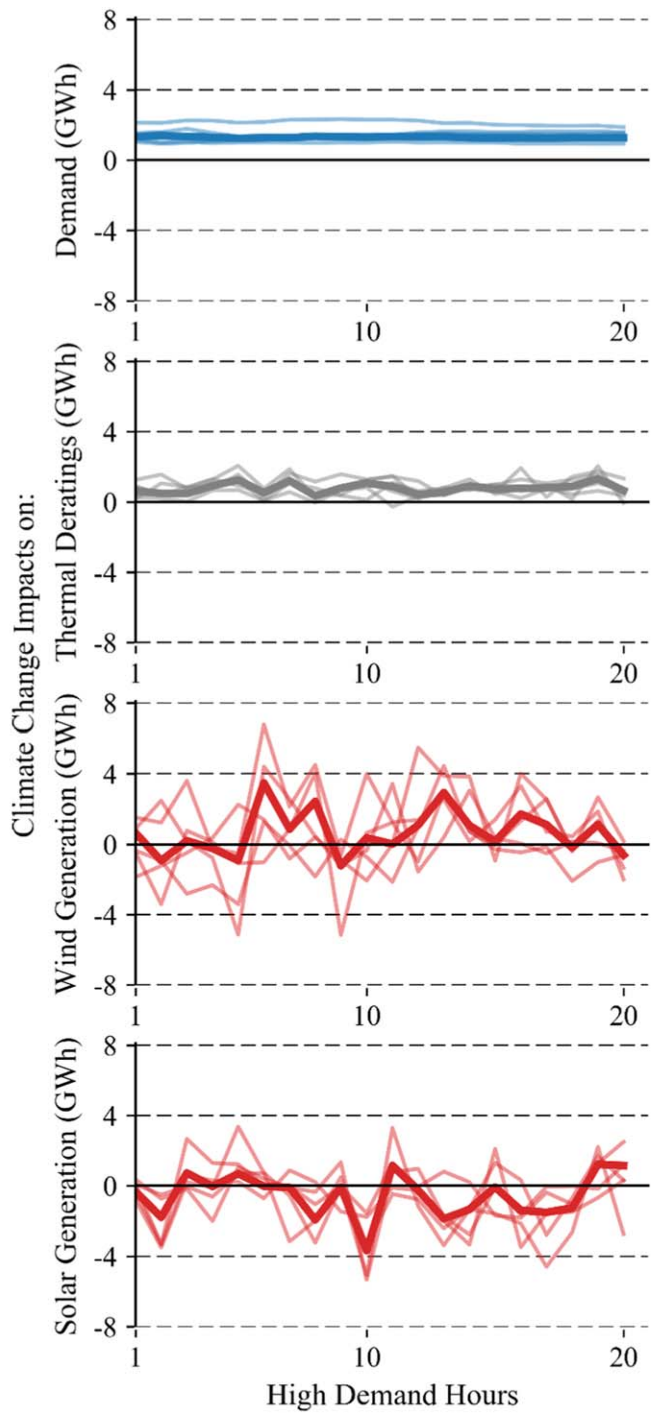

Figure 2. Climate change impacts on demand, thermal deratings, wind generation, and solar generation during high demand hours. Each faded line corresponds to a single climate change projection, and indicates the median climate change impact across years for each high demand hour. Bold lines are the median values of those faded lines, i.e. the median values across climate change projections.

climate change effects, we compared five climate change projections representative of 2041–2050 impacts under RCP 8.5 in Texas against a reference period of 1996–2005.

We found agreement across climate change projections that climate change will increase demand by up to 2 GWh in high demand periods (4% of demand in the reference period), increase net demand by up to 3 GWh in high net demand periods (6% of net demand in the reference period), and increase system ramps in net demand by up to 2 GW in periods with high system ramps in net demand (10% of system ramps in net demand in the reference period). Our climate change projections also agree that climate change will increase thermal deratings by up to 2 GWh (40% of thermal deratings in the reference period) during high demand periods.

Our finding that climate change will increase demand during high demand periods agrees with prior work (Auffhammer *et al* 2017, Craig *et al* 2018,

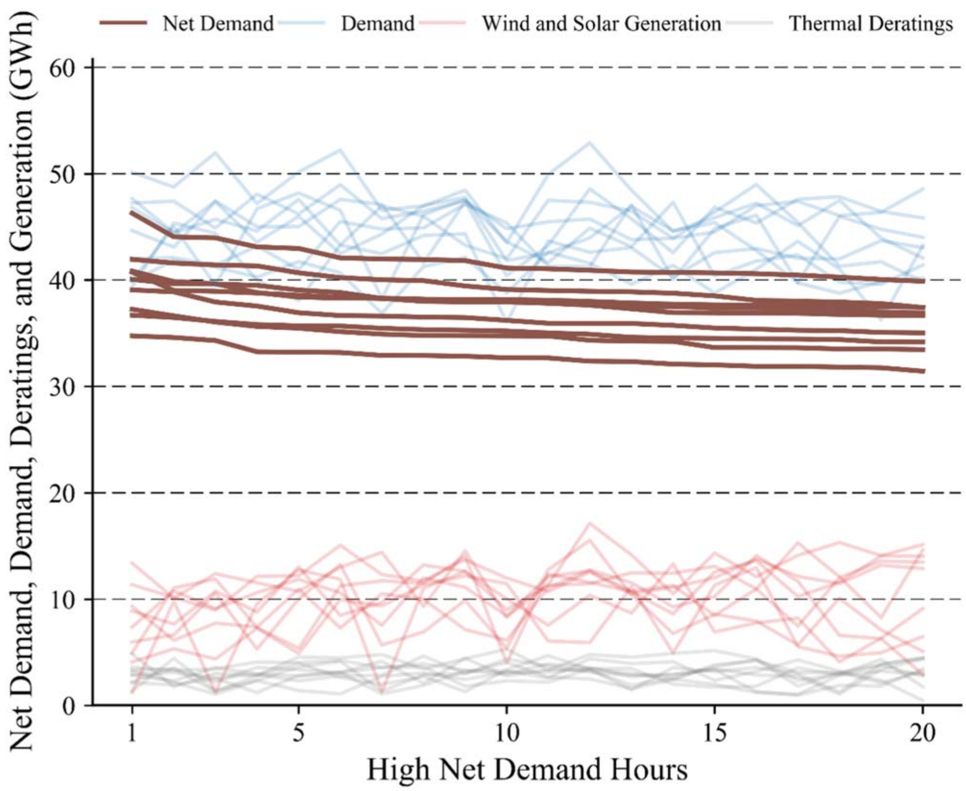

Figure 3. Net demand, demand, wind plus solar generation, and thermal deratings in high net demand hours in the reference period. Lines represent individual years. Net demand is sorted from greatest to least, while demand, thermal deratings, and wind and solar generation are synchronous with sorted net demand.

Fonseca *et al* 2019). As power systems increasingly shift towards renewable energy, high net demand periods will become increasingly important in planning. We demonstrated that climate change will exacerbate high net demand periods in all five climate change projections, indicating climate change will increase peak capacity investment needs in Texas with and without high wind and solar penetrations. Peak capacity refers to firm capacity that can dependably contribute to meeting high demand periods, such as dispatchable thermal capacity or derated wind and solar capacity. In other words, our results suggest shifting towards wind and solar power does not avoid increased peak capacity investment needs imposed by climate change. Peak capacity investments aimed at meeting the increase in high demand due to climate change might also meet the increase in high net demand due to climate change, as we found those increases similar in magnitude.

We also found agreement among climate change projections that climate change will exacerbate thermal deratings during high demand and net demand periods. Consequently, system planners should carefully consider potential future deratings when procuring additional capacity to meet expected increases in demand and net demand under climate change. While our study focuses on Texas, this will likely affect all US power systems as their thermal generator fleets and loads experience warming. An important mediating factor in how climate change will affect future thermal fleets is how those fleets evolve over time (Wang *et al* 2019). We found that shifting to robust cooling technologies nearly eliminates thermal deratings in high demand hours (SI.3.2), indicating adaptation potential within the existing generator fleet (van Vliet *et al* 2016). Additionally, retiring all coal-fired generators (without replacement) would reduce thermal deratings by 41%–45% in high demand hours across climate change projections, indicating the importance of future changes in the generator fleet composition.

Instead of investing in more thermal peaking capacity, non-generation technologies, such as grid-scale storage (via batteries or pumped hydropower) or demand response, could compensate for increased demand and net demand. In fact, investment in these types of technologies will likely continue to grow to handle variability of wind and solar generation and due to falling costs (Kittner *et al* 2017). However, climate change may also affect the performance of these technologies, which future research should examine.

We also found agreement across our five projections that climate change will increase system ramps in demand plus thermal deratings during high demand ramps and will increase system ramps in net demand during high net demand ramps. In our study system, this means system flexibility requirements would need to increase with and without high wind and solar penetrations. Increasing wind and solar penetrations

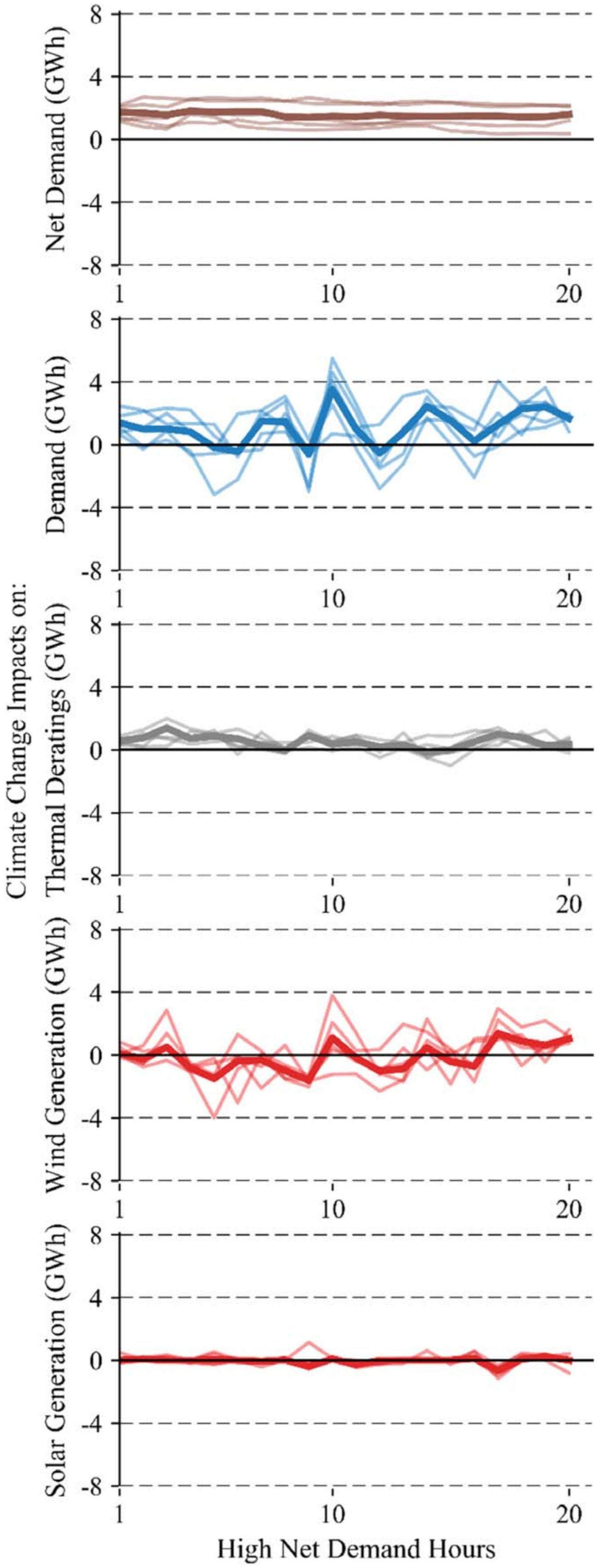

Figure 4. Climate change impacts on net demand, demand, thermal deratings, wind generation, and solar generation during high net demand hours. Each faded line corresponds to a single climate change projection and indicates the median climate change impact across years for each high demand hour. Bold lines are the median values of those faded lines, i.e. the median values across climate change projections.

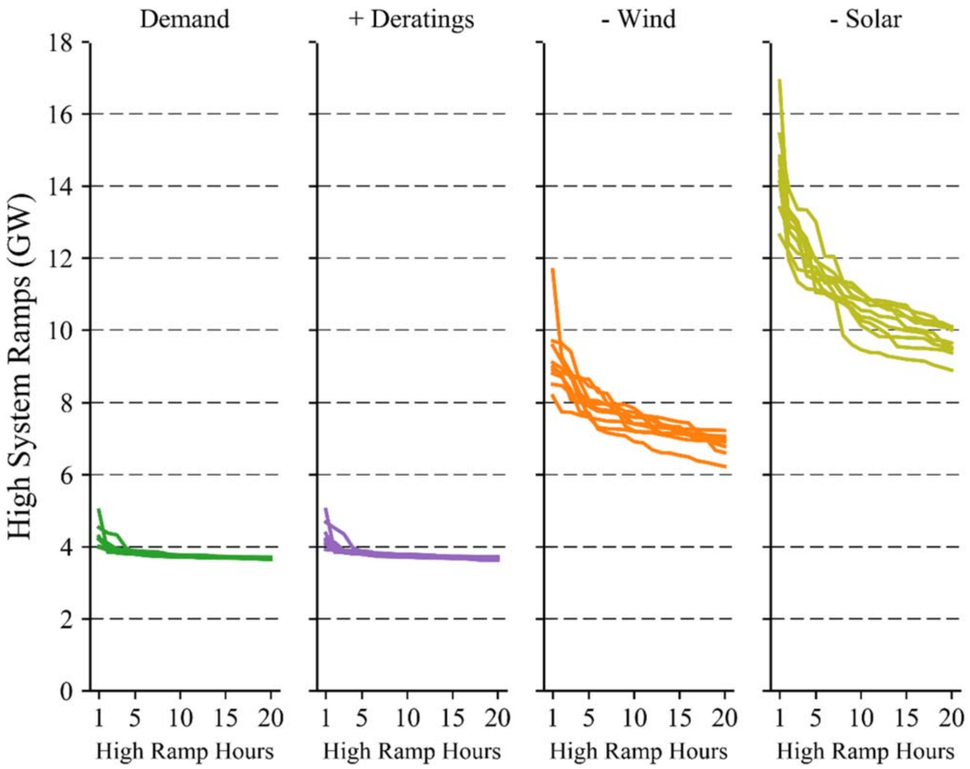

Figure 5. Top 20 high system ramps in demand (left) plus thermal deratings (second to left) minus wind generation (second to right) minus solar generation (i.e. net demand) (right) per year in the reference period. Lines represent individual years.

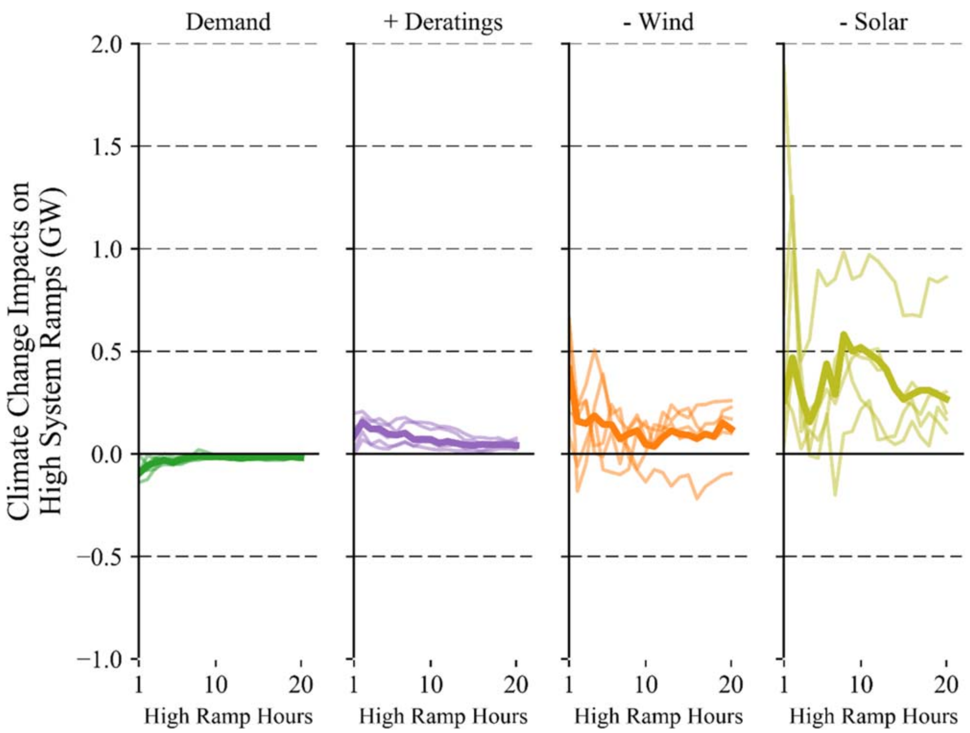

Figure 6. Climate change impacts on high system ramps in demand (left) plus thermal deratings (second to left) minus wind generation (second to right) minus solar generation (i.e. net demand) (right). Faded lines are median values across years for each climate change projection. Bold lines are the median values of those faded lines, i.e. the median values across climate change projections.

have already pushed some power systems to procure flexibility products (California ISO 2018). Such products could be used to compensate for increasing flexibility requirements under climate change. Additionally, we found increases in high demand and net demand values will likely be larger than increases in system flexibility requirements, so the same resources could be used to compensate for both increases if planning accounts for system flexibility needs (e.g. by procuring flexible capacity resources). Storage technologies like batteries are particularly well suited to meet increased flexibility needs due to their fast response time.

One limitation of our analysis is that by conducting our analysis over nine years, we might not capture decadal variability that could yield more extreme climate change impacts in some years. Including more years, e.g. thirty, would better capture long-term climate variability, which future research should explore. Other opportunities for future research also exist. First, we assess climate change impacts on a generator fleet that was deployed (in the case of thermal units) and optimized (in the case of wind and solar units) without considering climate change. Different siting or technology decisions could mitigate the climate change impacts we quantified, which future research should explore. Second, to understand the generalizability of our results, future research should study synchronous and highly temporally resolved impacts of climate change across a broader geographic scope. Third, future research should consider climate change impacts on transmission, which we do not capture. Transmission will play a crucial role in integrating high wind and solar penetrations through connecting generators to loads and through enabling sufficient system flexibility to accommodate their generation (Bloom *et al* 2016). By limiting transmission capacities (Craig *et al* 2018), climate change could lead to greater curtailment of wind and solar or inhibit their growth absent additional transmission investment.

Conclusions

In our study system, we found climate change will exacerbate periods of high demand, net demand, and net demand ramps. In response, our study system would need to invest in more peak and flexible capacity with and without high wind and solar penetrations. These increased investment needs are partly driven by compounding supply- and demand-side effects of climate change, illustrating the importance of including both in planning. Given long lifespans of power system investments, planning should start incorporating climate change effects to safeguard the reliability of future power systems.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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