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"Enhancing America's Grid Security and Resilience"

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Major points/synopsis:

One of the best ways to understand and protect against grid vulnerabilities is to perform "stress tests" of our current systems, and the systems we hope to build in the future. However, as the grid expands into other economic sectors; as we add less controllable sources of generation to the mix; and as climate change alters the likelihood of extreme events occurring, it is becoming more difficult to characterize the plausibility (let alone the likelihood) of different future scenarios and extreme events.

Good morning, Committee Chairman Rodgers and Sub-committee Chairman Duncan, other members of the Committee. Thank you for the invitation to speak today.

My name is Jordan Kern. I am an assistant professor at North Carolina (NC) State University in the Edward P. Fitts Department of Industrial and Systems Engineering. I also have appointments in the Departments of Civil, Construction, and Environmental Engineering, and Operations

Research. I have been a faculty member at NC State for 5 years, and before that I was a faculty member at the University of North Carolina Chapel Hill, where I am also a three-time graduate.

At NC State I conduct research on bulk electric power systems. The overarching goals of my group's research are to:

1. Build computational models (software) capable of accurately simulating the behavior of real-world systems (for example, the North Carolina grid; the Duke Energy grid; and/or the entire Eastern Interconnection).

2. Use these models to measure system performance (e.g., in terms of cost, reliability, environmental impacts), especially during periods of stress, and conduct experiments that allow us to understand how the performance of the power grid might change in the future.

3. Communicate the results of our research to help inform optimal decision making around the building of new infrastructure and real-time management and control of the power grid.

My group's research has received consistent funding support from the National Science Foundation, including NSF's prestigious early career award, and five different offices within the U.S. Department of Energy, including the Office of Science, the Office of Energy Efficiency and Renewable Energy, and the Advanced Research Projects Agency, or ARPA-e.

We collaborate with researchers at many other universities in the U.S. and some abroad. In the last several years, my most consistent and productive collaborations have been with national laboratories, and first among those, Pacific Northwest National Laboratory. I consider the national lab system to be a critical hub due to the talented scientists and engineers who work there combined with its mission to do research in the U.S. national interest. My first exposure to the national lab system was after graduating from college, when I served as a contractor at the U.S. Department of Energy in the Hydrogen and Fuel Cells program. My more recent experience collaborating directly with lab researchers has only strengthened my gratitude and belief in the national lab system, and I want to state this clearly for the record.

In addition, my group's research frequently involves the participation of key stakeholders in the electric power industry, especially electric utilities (investor owned, federal, municipal, and local cooperative), but also merchant power generators, system operators, and regulators (utility commissions). Explicitly involving these entities' perspectives helps ground our research in the complex realities of planning and operating the power grid. It has helped make our research more impactful. Personally, it has also given me appreciation for the employees of electric utilities and system operators who play such an important role in keeping our society functioning. I also appreciate the great challenges that they face – and, by extension, that we all face—in the next two decades and beyond.

Technical needs for the power sector

There is a narrower set of analytical needs I see for electric utilities and system operators that mirror ones I have observed within the research community and have experienced firsthand in my own work. This is not an exhaustive list, but a few examples include:

- Faster and more accurate computational tools to support system simulation, risk analysis and decision-making

- Improved representation of uncertainty in research and real-world decision-making

- Better forecasting capabilities, from hours-to-days in advance (e.g., about electricity demand and the availability of variable renewable energy like wind and solar)

- More effective ways to incorporate forecasts into short term operations and long term planning

- A better understanding of how failures and successes in the electricity sector impact other sectors, and vice versa

- New techniques for balancing multiple "zero-sum" objectives in decision-making

There are smarter people than me working on all of these. I'm optimistic that with time and continued funding, these are issues we'll collectively solve.

A two-front challenge for the power grid: weather risk and decarbonization

There are other important challenges for grid planners and operators in which I have comparatively little expertise. These include but are not limited to: global supply chains; cyber security and terrorism; regulatory, permitting and market reforms.

I am more qualified to provide insight about the challenge of protecting the grid against more frequent and extreme weather, while also reducing greenhouse gas emissions to very low levels.

Decarbonizing the broader U.S. economy is probably necessary by 2050 to avoid the worst impacts of climate change. To that end, a low-to-zero carbon grid --combined with electrification of major parts of the transportation, heating, industrial sectors-- is often cited as the cheapest, fastest way to decarbonize the broader economy[1-3].

At the same time, the grid should also prepare to withstand increasingly frequent and severe weather due to climate change that is already "baked in" due to the cumulative emissions of greenhouse gases over the past 150 years.

Solving both problems simultaneously is important, and solving both problems would require significant changes in electric power system infrastructure and operational capabilities (i.e., large investments in physical and human capital). Although there are many technical challenges involved in decarbonizing the power grid, it is feasible with technologies that are available today. Many researchers have essentially proven this[3].

A more open question is whether we will be willing and able to pay to rapidly accelerate what would otherwise be a more gradual grid transition towards clean energy. Continued advances in low and zero carbon technologies will be extremely important in reducing those up-front costs.

Before I touch on more technical aspects of this challenge, I will note that it is likely that grid expansion and evolving workforce demographics will open new professional opportunities (and necessities) for highly skilled scientists and engineers to enter the power sector. Universities will continue to play a vital role in training students to help fill these jobs. None of my own graduate students wish to become academics. I'm not surprised by this -- they want to get out in the real world and have a more direct impact.

Extreme weather and the grid

Extreme weather events already pose a significant risk for society, with costs approaching $400 billion per year in the U.S. alone[4-6]. A significant share of annual costs from extreme weather in the U.S. (estimates range from $25 to $75 billion per year) comes from impacts to the electric power sector in the form of damaged equipment and service outages[7,8].

Aging electric power systems are particularly vulnerable to extreme weather. Over the past 20 years, more than 80% of major power outages (affecting at least 50,000 people) were caused by extreme weather. In order, the most damaging weather events to the grid have been from: severe thunderstorms (rain, wind, lightning); winter weather (extreme cold, snow, ice, freezing rain); hurricanes and tropical storms (wind and flooding); extreme heat; and wildfires. Outages were significantly higher over the period 2010-2020 than they were over the period 2000-2010[9].

The U.S. grid is divided into three major interconnections (Eastern, Western, and the Electric Reliability Council of Texas), and each is essentially operated as a single, massive, synchronous machine. System operators must perfectly match constantly fluctuating electricity demand with equal supply through coordinated operations of power plants, transmission lines, and other critical infrastructure like electrical substations that (among their other functions) ramp the voltage of electricity flows up and down to facilitate delivery throughout the grid. Each component of this system (i.e., generation, high voltage transmission, substations, and low voltage distribution) is vulnerable in a different way. Even with physical redundancy built-in and emergency protocols in place, extreme weather events regularly (if overall, quite rarely) overwhelm these measures, causing blackouts. Americans average 7-8 hours of interrupted service per year, although those numbers are increasing.[38]

Power systems across the U.S. are not uniformly exposed to extreme weather. Likewise, Americans are not uniformly exposed to power outages. From 2018-2020, 1-hr and 8-hr power outages (the latter are designated as medically-relevant) were most prevalent in Northeastern, Southern, and

Appalachian regions of the U.S.[10] The impacts of power outages can also pose very different risks for different people. Interruptions in electricity service pose life-threatening risks for people who depend on electricity-powered medical devices (e.g., oxygen concentrators, ventilators, nebulizers, CPAP and BiPAP, mobility aids). These risks can be exacerbated if power outages are caused by (or occur at the same time as) conditions that pose risks for public safety, including flooding, wildfire, or extreme temperatures.

In addition to public safety risks associated with lost electricity service, these events can pose significant direct economic costs for retailers, manufacturers (as high as $5 million/hour), data centers ($9000/minute), and health care facilities[11].

Disruptions to the tenuous balance between electricity supply and demand can also cause extreme price shocks in competitive wholesale markets for electricity, which exist in regions of the U.S. that are “re-structured” or “deregulated”. Before 2000, most electric utilities were vertically integrated (i.e., they owned electricity generators and power lines). Today, only one third of U.S. electricity demand is serviced by regulated monopoly utilities[12]. The rest of the U.S. is served by utilities participating in competitive markets. Competitive markets are economic mechanisms for determining (in real-time) which power plants should generate and sell electricity, based on each plant’s marginal cost of production (fuel cost). The cheaper plants are supposed to outcompete the expensive ones. Like any other commodity, the wholesale price of electricity goes up and down based on available supply and demand.

During certain extreme weather events (especially those involving extreme temperatures), prices can increase dramatically for retail utilities (i.e., the primary "buyers" in wholesale markets). This has occurred repeatedly in the last 10 years, including in the Mid-Atlantic in 2013 (polar vortex), in the Northeast in 2018 (winter "bomb" cyclone), in California in 2020 (heat waves)[13-14] and Texas in February 2021 (cold snap and winter storm)[15–17]. Policies in different markets control how high wholesale prices can reach during periods of extreme scarcity. The Electric Reliability Council of Texas, which manages an "energy only" electricity market, uses high prices during periods of scarcity to incentivize market entry (i.e., construction of new power plants), so prices are allowed to rise to very high levels ($9,000/MWh). In most other markets, system operators implement price caps at $1,000 – 2,000/MWh. For reference, the average retail price of electricity in the U.S. is currently $0.22/kWh, equivalent to $220/MWh.

So, during extreme events, retail utilities can end up buying electricity from the wholesale market for more than 10 times the price for which they are selling that same electricity to retail consumers.

My group has spent many years studying the impacts of extreme weather on the functioning of electricity markets and electric utilities, including financial risk for electric utilities. In general, electric utilities are extremely capital intensive and employ relatively high debt-to-equity ratios. A consequence of this structure is that some utilities have financial exposure to large sudden increases in costs that make it more difficult for them to make regular debt service payments. Risk profiles of electric utilities can vary widely, depending on their market and regulatory environment, and their idiosyncratic exposure to extreme weather. I will touch on the topic of financial risk again later in my testimony.

Climate change

Today, even without factoring in the potential long-term impacts of climate change, extreme weather represents the largest driver of major grid outages and poses significant economic costs to society. Based on my experience researching this topic, I am often asked how climate change will impact the U.S. electric power grid. The answer is it's complicated, and somewhat uncertain.

What risks for the grid seem more likely and will be broadly felt across the U.S.?

Heat waves. There is high confidence within the scientific community about the likelihood of continued increases in global average temperatures and an increased frequency and severity of heat waves[19]. Extreme heat is frequently responsible for causing the periods with the highest (or "peak") electricity demand, and that demand dictates how much generation and transmission capacity an electric utility needs to build. In addition, periods of extreme heat can cause equipment performance to degrade, making failures more likely. When failures do occur during heat waves, it leaves vulnerable populations exposed to dangerous conditions.

What climate risks for the grid seem more likely but may be region dependent?

Hurricanes. Hurricanes can knock out power for hundreds of thousands of people at a time, with most outages caused by tree damage to low voltage distribution lines, and smaller (but longer duration) outages caused by flooding.

From NASA: "Due to global warming, global climate models predict hurricanes will likely cause more intense rainfall and have an increased coastal flood risk due to higher storm surge caused by rising seas. Additionally, the global frequency of storms may decrease or remain unchanged, but hurricanes that form are more likely to become intense."[18]

Drought. Across the U.S., drought poses important risks for hydropower production and for many thermal electric power plants (nuclear, coal and natural gas) that use large amounts of water for cooling. However, in general, the water intensity of the power sector is declining, due to widespread adoption of wind and solar and the retirement of older, water intensive power plants. In some respects, this may make parts of the power sector less vulnerable to water shortages in the future.

Large scale changes in regional precipitation patterns are uncertain across much of the U.S., but for the Southwestern U.S. specifically, there is a clear historical trend, stretching back to 1890, of a gradually worsening drought[20]. It is widely believed that climate change will exacerbate this trend by further reducing water availability in the Southwest.

Moving forward, one region of the U.S. power grid that could be most damaged if significant changes in water availability occur is the West Coast (and particularly the Pacific Northwest, where hydropower meets >50% of regional demand).

Although future precipitation amounts in the Pacific Northwest and larger West Coast are uncertain under climate change, higher air temperatures are very likely to change the *timing* of when water is available during the year. More precipitation will fall as rain instead of snow, and snow that does fall will melt earlier. This will shift the timing of when hydropower is available to earlier in the year, and away from summer, when electricity demands are highest throughout the west. The result will be less hydropower being available when people need it the most[21].

Decarbonization

At the same time, to prevent the worst effects of climate change, it is increasingly accepted that the electric power sector (responsible for around 27% of greenhouse gas emissions in the U.S.[22]) must decarbonize before 2050, while also expanding to facilitate electrification of other critical sectors like transportation, industry, space heating, and agriculture[1-3]. Estimates of the capital investment needed to transform the U.S. grid in this manner reach into the trillions of dollars[2-3,23-24].

Although there are a range of different technology pathways in which the U.S. achieves adequate cuts in greenhouse gas emissions, the lowest cost scenarios look likely involve dramatically increased reliance on variable renewable energy, with wind and solar power potentially generating upwards of 75% of total electricity generation in the U.S., and 50% of total U.S. energy use across all sectors[2-3].

Weather related risks of wind and solar

A growing number of tools are available for managing variability in wind and solar power, which can fluctuate significantly (and not always predictably) across space and time. There have been large investments at the federal level in the development and adoption of these critical tools, and more would be needed to facilitate very deep penetration of wind and solar in the generation mix. These include, but are not limited to:

- Energy storage
- Flexible and interruptible demand
- Maintaining responsive generators (e.g., natural gas and hydropower) as "back up"
- Increased transmission and coordination across system operators
- Improved forecasting

Renewable energy has been documented to perform well during some periods of extreme grid scarcity (e.g., solar farms produced energy as expected during a cold snap experienced this past December in North Carolina, when rolling blackouts had to be enacted for the first time in recent memory), though both wind and solar can be vulnerable to extreme weather in several ways (e.g., freezing, wind speeds above cutoff points, flooding, etc.).

Solar in particular can serve as a critical "distributed" source of electricity (i.e., consumed where it is produced, "behind" substations). When upgraded to "island", paired with a battery, and/or incorporated within microgrids, solar can be a resilient source of electricity, and it may be instrumental in withstanding weather disasters in some areas.

Nonetheless, tying a majority of the U.S. electricity supply to variable renewable energy could alter the exposure of the grid to weather risk[23-30]. Some of these risks pertain to system reliability. In particular, concerns about the reliability of deeply decarbonized grids during extreme events are not fully answered.

We can turn off wind and solar farms when they are producing "too much" electricity, but we cannot turn them on (or ramp them up) when they are not producing enough. Both wind and solar availability is somewhat seasonal, and historical data can allow system operators to form probabilistic expectations about how much they will be able to count on wind and solar over a particular month, or on a particular day. However, we have no ability to, with precision, predict how much wind and/or solar power will be available during the next major heat wave to impact California; or the next big cold snap to affect the Eastern U.S.

Adding wind and solar proportionally reduces the amount of generation we need from fossil fuel resources (i.e., one megawatt-hour produced from a solar farm generally reduces the amount electricity needed from a natural gas power plant by the same amount). This means lower carbon emissions and lower emissions of other air pollutants, such as fine particular matter, sulfur dioxide, and nitrogen oxides, which have direct human health impacts.[37]

However, adding 1000 megawatts of solar capacity does not necessarily mean we can retire a 1000 MW natural gas plant, because a large part of that capacity may still be needed to provide “firm” (backup) capacity to the solar farm.

Based on my group’s research[31], I believe that due to uncertainty in weather conditions, the amount of back up capacity that will be needed in decarbonized grids could be more than what some recent studies suggest. This additional backup capacity could come from many different sources: existing hydropower, natural gas, interruptible demand, and/or emerging low and no emission resources, including small modular nuclear reactors.

There are other open questions about how large additions of wind and solar will impact the electric power sector, including how they will impact the financial incentive for market participants to build new infrastructure. In general, large amounts of renewable energy depress wholesale market prices. This can reduce revenues for other producers, including renewable energy developers themselves and low-carbon technologies like hydropower and nuclear. These issues highlight a potential need for changes in regulatory frameworks and market structures to facilitate private sector investment in fully decarbonized power grids.

Potential Risks from electrification

There are other important ways in which a rapid transition to clean energy could increase risks associated with extreme weather. While I think these will be manageable, they are probably not explored enough today.

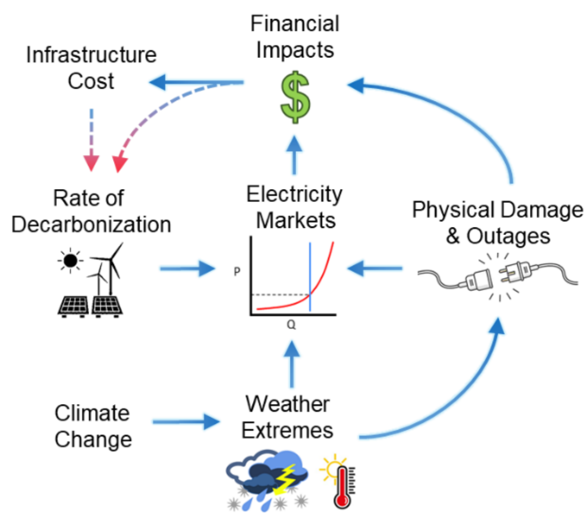
A key tenet in many decarbonization plans is the electrification of significant parts of the transportation sector, along with residential and commercial space heating, and parts of industrial energy use. Weather disasters in a fully electrified world will pose different (and potentially more serious) risks for some Americans by simultaneously knocking out multiple critical services at once.

For example, part of what made Winter Storm Uri (the event that impacted Texas in 2021) so dangerous was that it did not just interrupt electricity service for a prolonged period (exposing people to dangerously low temperatures and removing a critical lifeline for people who rely on electricity powered medical devices); it also led to knock-on effects to water systems across the state, including a reduced ability to treat and distribute potable water. More than 2,300 boil water notices were issued across the state, affecting approximately 14 million people. This was probably the largest boil water notice event in U.S. history. Meanwhile, due to hazardous road conditions, no one could leave[32].

Similarly, I worry that we don’t fully understand the potential for reduced mobility of vulnerable or impacted communities during weather disasters if we largely electrify light duty transportation in the U.S. This is not an argument against vehicle electrification. It is an argument for the federal government, states, and utilities to study this issue in depth now and build these risks into both infrastructure planning and emergency management strategies.

Greater risk = greater costs

At a time when rising interests have dramatically increased the cost of capital for everyone (including electric utilities), the power grid's increasingly complex exposure to weather risk could make it even more expensive to build new infrastructure (**figure at right)**.



For electric power utilities and other power providers, extreme weather events can manifest as large, unexpected increases in costs[33]. In some cases, the resulting financial instability can make it more difficult for utilities to meet debt service obligations (i.e., make "mortgage" payments) on existing infrastructure. Recent examples include the utility PG&E in California, regarded to have incurred the first major "climate driven" bankruptcy from its liabilities related to wildfires[34]; and energy companies in Texas, bankrupted by a 100x increase in market prices during extreme winter weather in 2021[35]. Even in cases that do not end in bankruptcy, utilities that experience weather-caused financial stress can be downgraded (negatively assessed) by credit rating agencies[36], the institutions charged with scoring the financial health of large, institutional borrowers. Credit rating downgrades equate to a higher “cost of capital” for utilities (interest rates on future borrowed sums)—making new infrastructure projects much more expensive.

Failure to understand and manage financial risks posed by extreme weather could increase the already substantial investment needed to simultaneously harden the grid against extreme weather and decarbonize it.

Conclusions

Based my own group’s research, along with my assessment of the current state of the art from the broader research community, and my experience interacting with a wide range of grid participants, I don’t think we currently understand the full scope of our exposure to the dynamics that I’ve discussed today. The grid is complicated and differs greatly by region. The overlapping public, private, local, state, and federal institutions in charge of the grid are complicated. Climate science is complicated, and uncertain.

One of the best ways to protect against some of the dangers I’ve highlighted today is to perform “stress tests” of our current systems, and the systems we hope to build in the future, similar to the process that the Federal Reserve requires of large financial institutions that are important to the U.S. economy. There are already established practices in place at utilities, system operators, and regulators to do this.

However, as the grid expands into other economic sectors; as we add less controllable sources of generation to the mix; and as climate change alters the likelihood of extreme events occurring, it is becoming more difficult to characterize the plausibility (let alone the likelihood) of different future scenarios and extreme events. As a result, stress testing the grid is becoming a more difficult exercise to perform (and the results more difficult to interpret).

Whether it happens quickly or more gradually, the clean energy transition will put more pressure on electric utilities, system operators, and regulators to understand these difficult-to-quantify risks and manage them on behalf of the people who depend on the electrical grid, which is becoming more and more critical to modern life.

Thanks for allowing me to speak today, I hope it has been helpful.

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