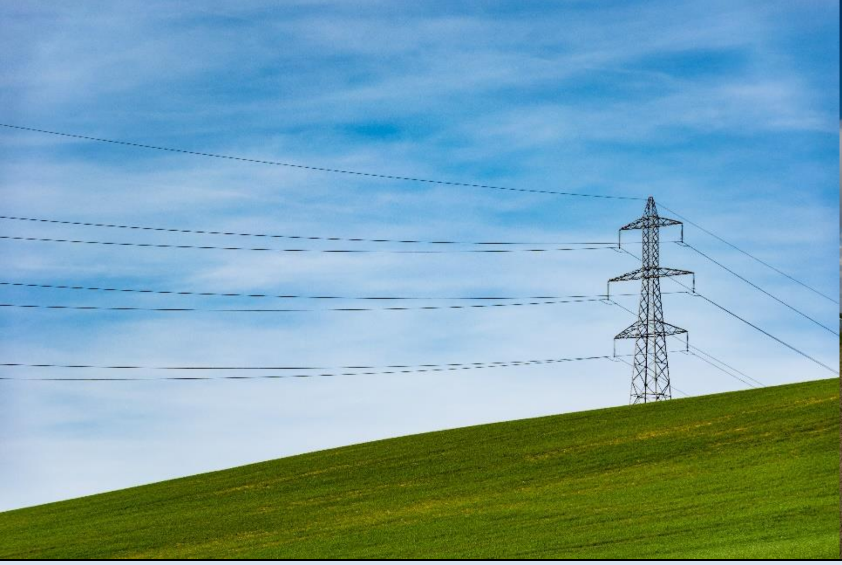


Actionable Scientific Assessments for the Energy Sector


American Meteorological Society
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AMS

Actionable Scientific Assessments for the Energy Sector

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Executive Summary

There is an innate and critical relationship between energy and weather, water, and climate (WWC). As the deployment of renewable energy, particularly wind and solar energy, increases, so too does dependence on weather and weather variability. Understanding, accounting for, and communicating weather and climate variables is therefore critical for the planning and optimization of the energy system—especially as the deployment of renewables will need to expand even more rapidly in the future in order to meet national goals. This puts increasing pressure on the scientific community, and particularly those working on the weather and climate aspects of renewables, to provide the right information to meet the key decision-making needs of the energy sector. Moreover, this information must be accessible and usable to those who need it—in other words, actionable.

This American Meteorological Society (AMS) Policy Program study is the second of two pilot projects on the provision of actionable information for decision-making through the tailored and targeted assessment of weather and climate science. Through conversations with professionals across the operational energy production and distribution sector as well as those from the WWC community, we identify seven key findings on the key decisions and information needs of the energy sector as they relate to weather and climate.

Findings:

- Effective development of wind, solar, and hydro power at the scales needed to foster a resilient and reliable renewable-based energy system will require accurate modeling of the availability of each resource. Some such datasets (such as an updated Wind Integration National Dataset [WIND] toolkit) are currently in development, but additional datasets are needed that fully merge solar capacity and wind potential in ways that allow for possible correlations or anticorrelations.
- There is a need for a comprehensive and continuously-updated high-resolution reanalysis dataset. This would ideally be at 1 km horizontal resolution with adequate boundary-layer vertical resolution to provide good hub-height wind data, and fully integrate not only meteorological data (with high-quality wind and solar capabilities) but also coincident energy data.
- Projections for how climate change will affect river basin runoff, wind and solar generating capacity in specific geographic regions, and weather extremes that impact generating infrastructure and distribution networks are still not sufficiently robust to allow confidence in long-term planning.
- Trustworthy and quality-controlled sources of data can be challenging for utilities to find and navigate, particularly when looking to visualize user-selected threshold-defined events. There is a need for a validated database that ties objective extreme events in the power infrastructure to the weather events that caused them so that projections of frequency changes in weather events can be used to project infrastructure impacts.

- Improved understanding of potential future conditions stemming from various impacts of climate change, especially changes in weather extremes, will be crucial to optimize the infrastructure needed for the generation and delivery of energy.
- While future energy generation will rely heavily on probabilistic forecast approaches, there is still much to be done to ensure the operational energy community is prepared to effectively utilize this information, as well as increasingly sophisticated measures of uncertainty in delivering firm power.
- While weather and climate information is crucial to deploying energy efficiently where it is needed, developing new regulatory and policy frameworks for energy delivery may be the most critical need at this time in allowing a larger penetration of renewables.

The transition to an efficient, resilient, and reliable energy system built primarily on renewables is an example of a “wicked” problem—inherently complex and uncertain with no optimal solution. As such, it necessitates bringing together a variety of stakeholders, sectors, and disciplines to develop multiple approaches to address the different components of the challenge in a comprehensive fashion. Actionable scientific assessments are useful mechanisms to aid the development of these approaches; they may not only reveal gaps in climate science knowledge but also the instances where these gaps might be bridged through the reframing of available information or through new convergence research.

This study confirmed that excellent progress is being made on a variety of fronts associated with renewable energy, from better understanding of turbine wakes to improve future wind farm siting to using artificial intelligence and machine learning (AI/ML) for better short-term forecasts of generation variabilities. Each of these areas of enhanced understanding and improved capabilities is critically important as we move to increase use of renewables. A consistent theme in the discussions under this study, however, is the need to bring together many disparate types of data, modeling, and analyses toward convergent tools that adequately address the complex interconnectedness of a national power system built on renewable sources. In many ways, the most significant finding of this study is the need for major convergence research efforts to build the necessary historical reanalysis datasets, integrated weather-energy forecast models, and policy and regulatory frameworks that can leverage current disciplinary research efforts.

1. Introduction

1.1 Background

Weather, water, and climate (WWC) present myriad challenges and opportunities to every part of society, influencing decisions at every scale and timeframe. This is demonstrated particularly strongly within the energy sector. Weather conditions are central to energy demand, and the industry has incorporated this knowledge into demand forecasts for years. However, the energy system is also transforming in response to climate change mitigation requirements and related policies as well as the need to adapt to the impacts of emerging changes, both gradual and extreme, in weather and climate.

As the deployment of renewable energy, particularly wind and solar energy, increases, so too does dependence on weather and weather variability (Hooke et al. 2021). Indeed, weather and climate may themselves be considered as "fuel" for the production of energy. Understanding, accounting for, and communicating weather and climate variables is therefore critical for the planning and optimization of the energy system—especially as the deployment of renewables will need to expand even more rapidly in the future in order to meet national goals. For example, to meet the Biden administration's 2035 targets for decarbonizing the power sector, the U.S. will need to have about 600 GW of wind installed by 2035, compared to the approximately 136 GW currently operational (Wiser et al. 2022). This puts increasing pressure on the scientific community, and particularly those working on the weather and climate aspects of renewables, to provide the right information to meet the needs for proper siting and operation of renewables at much larger scales than we have seen in recent years. Moreover, this information must be accessible and usable to those who need it—in other words, actionable.

This American Meteorological Society (AMS) Policy Program study represents an effort to provide actionable information for decision-making through the tailored and targeted assessment of weather and climate science for key decisions. It is the second of two planned pilot projects; the first, completed in 2021, considered decision support needs relating to coastal resilience (Tipton 2021). The pilot approach consisted of convening a small working group of information providers and information users to first identify a set of needs and decision points, and second to evaluate whether actionable science can be readily provided to inform those decision-support needs. Virtual discussions took place throughout early 2022, with stakeholders drawn from the public, private, and academic sectors.

Renewable energy is an area of extensive ongoing research, and new studies and datasets are being released continuously. It is very possible, and perhaps probable, that some of the types of data, analysis, or tools that participants of this study identified as being needed or desirable are already in process or have recently become available. In fact, we would not expect any of the recommendations or conclusions of this study to necessarily be a surprise given how often we heard similar answers to the question "What kind of weather or climate information would help you in your work that you do not have now?" We do feel, however, that this study has value in bringing the voices of professionals across the operational energy production and distribution sector together with those from the weather and climate community applying their knowledge to the renewable energy issue.

1.2 The U.S. energy landscape

The process of effectively delivering power to the nation is a multijurisdictional and complex concern. The U.S. energy system is highly decentralized, consisting of federal, state, regional, and local entities. Around 3,000 utilities—which may be investor-owned, publicly-owned, or a cooperative—distribute electricity to customers. Many states require utilities to prepare integrated resource plans (IRPs) in order to develop strategies to meet future energy demand. Though requirements vary by state, an IRP typically looks out 10 or 20 years at expected supply and demand. In some areas, regional transmission organizations (RTOs) or independent system operators (ISOs) coordinate and monitor power system operations to ensure reliability. States may develop their own energy strategies independently or in conjunction with RTO/ISO policies. The Federal Energy Regulatory Commission (FERC) regulates the transmission and wholesale sale of electricity in interstate commerce and may promote the formation of RTOs/ISOs (although only RTOs are directly regulated by FERC). Under the oversight of FERC and Canadian authorities, the North American Electric Reliability Corporation (NERC) regulates the reliability of bulk power transmission, encompassing the various major and minor grids that form the overall North American power transmission grid.

Ensuring "firm" energy for customers (i.e., ensuring that the energy source can meet the demand) is a high priority within the sector. Historically, providing firm energy mostly required having good estimates of expected load and using those estimates to ensure adequate generation to meet the load. As the deployment of renewables increases, ensuring firmness becomes more challenging since the generating capacity is variable and outside operator control. This variability means that the needs of energy providers relating to weather and climate information, particularly when planning for decades in advance, are therefore inherently complex and may differ by resource.

2. Key Issues and Information Needs in Renewable Energy

2.1 Wind

The U.S. has high potential for onshore and offshore wind, with technological advances further increasing turbine capabilities; as such, wind energy development is rapidly increasing across the nation (Brooks 2022). The ability to assess and characterize available wind resources is a critical factor in this development, namely in the siting and operation of wind plants. At present, wind resource data for integration analyses and power planning are available from the Wind Integration National Dataset (WIND) toolkit maintained by the National Renewable Energy Laboratory (NREL). The toolkit consists of a meteorological dataset, a wind power production dataset, and a wind forecast dataset, representing over 126,000 existing and potential wind facilities in the continental U.S. (Draxl et al. 2015). However, the wind community has noted that the toolkit solely utilizes data from 2007 to 2013, and is consequently limited in its representative capacity.

Development of an updated 20-year dataset for the WIND toolkit is currently underway (Brooks 2022). Developers stated that having high resolution boundary layer observations (high spatial resolution and sub-minute temporal resolution) would significantly aid this process, particularly in terms of better incorporating offshore wind data. Satellite observations may be one tool to help accomplish this. Ideally, the updated dataset would also provide information to evaluate uncertainty; however, it was noted that uncertainty is generally not well understood by toolkit users, potentially limiting the effectiveness of this feature.

As investment in wind energy grows, optimization of wind turbine placement will be crucial to effectively meet developmental and operational goals. It is well-known that the operation of a turbine produces a wake, reducing downstream wind speed. The wake effects generated by a wind farm can therefore impact a downstream farm's power generation (and in turn revenue generation and CO_2 emission saving) capabilities, presenting a critical challenge when siting new wind farms (Lundquist et al. 2019). This is all the more true as large (e.g., 1+ GW) wind plants are being planned with wakes that may extend for kilometers. However, the dynamics of wake effects from wind turbines and their impacts on power production are still not fully understood. Research is ongoing in this area, including the American WAKE experimeNt (AWAKEN) field campaign intended to gather data about the atmosphere and wind around and within operational wind farms.[1]

Additionally, understanding how long-term climate change may affect the availability of wind resources is a high priority. Changes in atmospheric and oceanic conditions are likely to alter wind speeds and patterns; as such, there is a need for wind and oceanographic information at more granular levels than are generally currently available. Climate data at the level of a wind turbine may also be valuable in building an understanding of what design conditions will be necessary for future turbines to function through extreme occurrences as well as "new normal" operating conditions in a warming climate. There is also an ongoing question of how to

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[1] See: https://www.nrel.gov/wind/awaken.html

represent wind turbines themselves within climate simulations: large-scale deployments may exert influence on factors such as albedo or surface roughness that need to be accounted for.

In addition to shifts in baseline conditions, individual weather events can present an array of operational concerns for turbines. Extreme winds require turbines to be shut down, while very cold temperatures or icing can affect mechanical systems. Hail or lightning can also damage equipment. Forecasts at 5-min or hourly intervals may allow operators to take partial action to mitigate impact in such instances; however, as these events can be highly localized, more precise knowledge of where they occurred would also be useful to enable quick and effective post-event maintenance.

2.2 Solar

Solar energy has the largest potential for renewable electricity production in the U.S., with much of that potential concentrated in the Southwest (Brooks 2022). Photovoltaic (PV) systems can range from centralized, utility-scale plants to distributed installations that are located close to where the energy is used. While energy has traditionally been fed into the grid before being distributed to users by an electric provider ("in front of the meter"), behind-the-meter (BTM) PV generation (e.g., rooftop solar panels) is rapidly growing in popularity. In the region covered by ISO-NE, for example, there is currently almost 5,000 MW of BTM PV, with that number on the rise. Customer-installed BTM PV generation brings both opportunities and challenges for ensuring system robustness. From the grid operator perspective, BTM PV is not seen as a generation source, but as a load reduction. Forecasting load gets more difficult as more BTM PV is added to the grid, and during a traditionally low-load period (such as a sunny weekend day in April), BTM PV generation can lead to minimum load challenges.[2] Insufficient load on a portion of the grid can lead to instabilities.

The variability of cloud cover can make load management even more difficult since it can initiate ramp events in BTM PV. For example, on a sunny day with high BTM PV generation, load on the grid may suddenly increase as diurnal clouds form in the afternoon and quickly reduce BTM PV generation, requiring that load to be met by other sources. The timing and extent of this kind of cloud cover is typically not forecast well enough to allow operators to actively manage the ramp event.

Snow cover on solar arrays presents particularly challenging operational problems, as noted by more than one interviewee. After a snowstorm, the solar panels in the array may have several inches of snow cover that reduces power generation (in some cases to near zero). Meanwhile, while the array panels are covered in snow the skies may be clear, and programs that provide forecasts of generating capacity based on predicted weather conditions may be projecting significant generating capacity. Energy distribution plans made using those forecasts can be seriously in error. Eventually, the snowpack on the panels will begin to melt and slide off, allowing generation to resume immediately. Since the panels in a given array are all typically at

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[2] This is described as the "duck curve", see: https://www.energy.gov/eere/articles/confronting-duck-curve-how-address-over-generation-solar-energy

the same angle, the snow will often slide off all the panels at nearly the same time, leading to a major ramp event in generation that is nearly impossible to predict accurately at present.

For long-term planning, reliable estimates of seasonal weather conditions are needed. Energy providers often use the “standard weather year” provided by NREL, which was released in 2012, but based on data from 1991-2010.[3] That data may not adequately reflect operating conditions in the coming decades.

Providers also noted that it would be helpful to have a dense network of real time irradiance monitors in use across a region that were available to aid near-real-time forecasting for solar farms. These could be as part of home or business weather stations or independent from them. An example of the concept as an independent data source, but for air quality monitoring, is the Purple Air network.[4] Even though the data sources are of varying quality, NOAA could ingest the data and do the required quality control to have it still add significant value.

2.3 Integration of wind and solar

A hybrid wind/solar installation can generally more reliably meet power demand than either solar or wind alone, and adding storage to the system can increase its ability to generate firm power. Importantly, if local needs are met by a firm hybrid plant, the need for increased transmission on the grid is reduced. Recent research (Stanley and King 2022) has shown that for hybrid power plants, one can achieve greater firmness by either adding storage or having a better weather forecast.

It would also be widely beneficial to have a dataset that provides solar and wind resource information together in order to better understand their interactions in various weather regimes.

2.4 Hydro

A significant fraction of U.S. power comes from hydro, mostly in the west and Pacific Northwest, and pumped hydro still represents the largest component of energy storage in the U.S. Hydro is also currently the cheapest form of energy. However, given recent long-term droughts and projections of further droughts as a result of climate change, there are increasing concerns about hydro’s long-term viability.

Understanding whether the current drought situation in the western regions of the U.S. is an anomaly or the “new normal” is critical to estimating the potential energy production by hydro power in the future. Those responsible for future planning have been frustrated by the lack of clear consensus of projections for runoff in the climate change projections for various river basins. For example, while the majority of projections suggest decreasing runoff for the Colorado River Basin, there are large differences among projections regarding the amount and

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[3] See: https://www.nrel.gov/docs/fy12osti/54824.pdf

[4] See: https://map.purpleair.com/1/mAQI/a10/p604800/cC0#4.61/35.68/-102.63

seasonal impacts. For the Bonneville Basin, projections range from decreases to increase overall, and again with differences among seasonal components.

In assessing the potential impact of climate change on the future potential capacity for hydro power, a key element appears to be runoff efficiency. With higher temperatures, the surface will have more evapotranspiration and the drier conditions at the surface can impact runoff efficiency. Currently, runoff efficiency is about 8% (by contrast, in the very wet year of 1984, when the ground was more saturated, the runoff efficiency was about 16%). There appear to be some important differences in the models being used for the climate change projections in terms of their incorporation of this runoff efficiency issue, and that may account for the differences in projections for future hydro capacity. There is concern that the surface modeling in climate models is not being updated at the same extent as it has been for weather prediction models and the climate projections are therefore not adequately capturing possible changes in runoff efficiency. Changing snow-to-rain ratios may also alter snowmelt and runoff timing, further complicated by the fact that snow is challenging to model as snowpack may contain varying amounts of water (also known as the snow water equivalent).

Another form of energy generation falling under the hydro banner is marine generation (wave, current, or tidal generation). Marine generation is an area of increasing development and may be of particular value to island communities; however, marine energy technologies are not yet commercially viable. As development continues, there is a need to evaluate the impact of weather and climate on waves and ocean currents. Certainly, coastal storms represent significant impacts, but the potential impacts of sea level rise have also not been well-studied.

2.5 Data

2.5.1 High-resolution reanalysis

A key concern from study participants was that the energy industry on the whole does not yet fully appreciate that the multivariant components of weather's impact on energy are also fully interdependent. For example, weather conditions that impact wind generating capacity are also related to solar capacity in complicated ways, while also impacting load. Resource adequacy studies (i.e., evaluations of whether there is enough generating capacity to cover loads) are still mostly done in the "old way" looking at the average of each form of generation and estimating averages and expected peak needs and using that to determine the potential contribution from that form of energy at that location. Simply adding these together for multiple locations and generating types fails to account for the geographic variability and the correlations between solar and wind.

The renewable industry needs time-coincided datasets of weather and energy that are verifiable and that include uncertainty data. This suggests the need for a high resolution reanalysis dataset. This needs to be of resolution no coarser than 4 km, but ideally more like 1 km. The dataset needs to include all the usual weather variables, but also good verification data on episodes of snow and icing, and integrated gridded data from the energy system that shows episodes of cold or heat impacts on the renewable generation systems. A high-resolution model like NOAA’s High-Resolution Rapid Refresh (HRRR) at 1 km would be ideal, and this has sufficient vertical resolution in its boundary-layer scheme to produce acceptable hub-height wind data as part of the reanalysis. This sort of integrated weather and energy modeling system would provide the nationwide dataset that could help place renewable generating capacity in planning for the next 30 years.

It was acknowledged that using the HRRR for a rolling reanalysis at 1 km resolution would be expensive, but the need for this kind of integrated weather and energy impact model data came up in multiple discussions with the participants and there was a sense that the benefits would be quickly realized and far outweigh the costs.

2.5.2 Observational data quality

It was noted that the observational datasets available from the National Centers for Environmental Information (NCEI), including those from the National Climatic Data Center (NCDC) archive, are hard to use and do not have adequate quality control. Currently each user is forced to do additional QC on the data, flagging potentially bad observations and cleaning up the data overall, before using it. Some may do this well, and others may not, but ultimately each user is forced to reinvent that wheel and proceed at their peril. Those doing the additional QC without strong meteorological knowledge are likely to be left with substandard datasets and may make poor decisions based on them. Careful QC of the native datasets in the NCEI system would be helpful, but given that this is probably prohibitively resource intensive, even the creation of a list of the most reliable observation stations would be a real value since observations from those stations could be weighted more heavily than those from less reliable stations.

2.5.3 Data sharing

An additional challenge in obtaining usable data has been that private companies may collect observational data on their networks but be reluctant to share it. In some European countries, policies require sharing of observations by even commercial entities. This open data can be beneficial to all, so similar policies in the U.S. would be helpful. For example, being able to obtain individual turbine performance in real time and ingest that into modeling systems could be powerful.

2.5.4 Incorporating uncertainty

Users of weather data often request measures of uncertainty, but may not have the knowledge on how to use that information effectively. Several participants in this study suggested that more needs to be done to educate renewable energy operators on how to utilize probabilistic forecast output and measures of uncertainty in forecast products.

2.5.5 AI and ML

Artificial Intelligence and machine learning (AI/ML) are playing increasingly important roles in the development of tools for the renewable energy industry. Deterministic models are necessary for forecasts beyond about 6 hours, but AI/ML techniques can add considerable value to the deterministic forecast. For less than 6 hours, AI/ML techniques are critical to providing best predictions at the high time resolution required for operations.

Given model limitations, any forecasts at high resolution in space or time will need to be probabilistic. Weather experts who were part of this study indicated that there is still a lot of work to be done in the renewable world to educate operational people in renewable energy to know how to use the probabilistic forecasts effectively and to appreciate what the community can provide (Haupt et al. 2019).

2.6 Infrastructure and resilience

Issues related to the limitations of the existing power grid came up in nearly every conversation with energy experts. There is broad recognition that successful integration of renewables to provide the majority of the nation's power requirements will require load balancing over larger geographic regions than can be supported by the current grid infrastructure. With a grid that can use HVDC to efficiently move electricity large distances, renewable energy has the potential to be reliably load balanced across the country. It was noted that even at the current level of penetration of renewables, the grid is often the limiting factor in using the power generated by them effectively. Many current ISO transmission policies between states are not conducive to increased integration of renewables and there is therefore a critical need for major policy review with an eye to being more strategic toward a goal of full integration of renewables.

Building the optimal mix of renewables across the nation to take advantage of potential load balancing if a highly efficient grid was built will require high resolution observational datasets that can help provide the needed information for optimal renewable placement.

More discussion is needed on power resilience. Most electricity disruption is a result of weather-related events, so understanding the frequency of extreme events is of high importance. Relatedly, there is a need for guidance on how to define “extreme events” since the impact on the power industry may not align with definitions used in other contexts. For example, one such definition might be that the event causes a load increase at the 90th percentile or higher. It is not easy to get the right sort of data to connect the weather events with the load impacts, but doing so could allow weather forecasts to be much more useful in planning. There are similar issues in terms of “extreme events” on the power distribution side with weather events that impact the distribution infrastructure. While forecasts are getting better and companies are getting better at prepositioning assets based on weather forecasts, there are challenges with longer term planning, and having a solid database that ties objective measures of extreme events in the power infrastructure with weather data would allow analyses that improve future plans.

A key question, of course, is whether climate change will result in more extreme events and what types of events, and where, will be impacted. Understanding the nature of the changes is critical, so for any particular type of event, will it happen more often, last longer, be more severe, shift geographically to a different region, etc. Perhaps organizations (like AMS) could form partnerships (e.g. with the Edison Electric Institute [EEI]) to create a resource that was well-vetted, validated, and seen as trustworthy to provide the current state of the science to answer questions related to "Is the weather getting more extreme?" This sort of resource would allow all utilities to plan better and operate under a common framework.

2.7 Policy and regulation

2.7.1 Transmission

Throughout the discussions reported on in this study, long-distance transmission was highlighted as a key element to moving power at the scales needed to make renewable energy a feasible replacement for fossil fuels. However, it was also noted that the primary challenges with building out transmission were on the policy front rather than the technological one, and that much of the difficulty was political in nature. Cross-region connectivity will play a huge role going forward, but is happening too slowly at present. Most impediments to better regional connectivity are self-imposed, at the ISO level and in terms of the politics, and a lot of work needs to be done to get past the current inertia. State policies are often not adequately strategic in terms of transmission infrastructure, but the Competitive Renewable Energy Zones in Texas were mentioned as a potential example of an effective practice.[5]

2.7.2 Regulation

New requirements from the Securities and Exchange Commission (SEC) mean that management must certify that reports include expected impacts on business due to climate change.[6] With the information currently available, it is very hard to complete these requirements with high confidence despite their being federally mandated by the SEC. Related to this SEC policy, there is currently little consistency in event attribution which makes it difficult to assess climate change impacts. After an event, questions about whether the event was enhanced due to climate change, and if so by how much, are not easily answered; consequently, it is hard to use past events to gauge future impacts due to climate change. Clear and consistent guidance on those issues for past events would be very helpful in assessing future impacts.

2.7.3 Equity and environmental justice issues

The transition to renewable energy offers opportunities for communities to proactively address issues of equity and environmental justice. Many fossil fuel facilities have historically been sited in less developed neighborhoods and have been demonstrated to contribute to poorer air quality

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[5] See: https://poweringtexas.com/wp-content/uploads/2018/12/Transmission-and-CREZ-Fact-Sheet.pdf

[6] See: https://www.sec.gov/news/press-release/2022-46

in those areas, with associated health problems for residents (Massetti et al. 2017). As older power plants are decommissioned in the wake of increased renewable energy production capacity, states and communities can make it a priority to revitalize those neighborhoods by increasing the amount of green space in them, which can improve air quality and reduce urban heat island impacts.

2.7.4 Challenges of successful inter/transdisciplinary work

Building a resilient and firm energy infrastructure based primarily on renewable energy generation is a complicated problem that relies on both technical and political action. As such, it falls into the category of "wicked problems" (Rittel and Webber 1973) that rely on inter- and transdisciplinary approaches (increasingly being referred to as convergence research). Few professionals have been trained in transdisciplinary approaches, so building teams which extend beyond traditional disciplinary silos becomes critically important.

There are examples of collaborative efforts that show the potential power of these approaches, such as the collaboration between NCAR scientists and Xcel Energy integrating artificial intelligence and NWP for wind power forecasting (Kosovic et al. 2020). They require, however, significant effort to establish and serious commitment by all involved in order to be successful. A challenge in these sorts of collaborative efforts is that academic researchers look toward publication of results as part of their reward structure, while corporations may feel the need to protect new tools and techniques as proprietary for their competitive advantage.

3. Conclusion

Key decisions within the energy sector, particularly those relating to the deployment of renewable energy, involve both short-term operations and long-term planning. As such, these decisions may be aided by several different forms of weather and climate information. Notably, discussions with information providers and users from across the energy sector yielded seven main findings relating to the availability and use of such information:

- Effective development of wind, solar, and hydro power at the scales needed to foster a resilient and reliable renewable-based energy system will require accurate modeling of the availability of each resource. Some such datasets (such as an updated WIND toolkit) are currently in development, but additional datasets are needed that fully merge solar capacity and wind potential in ways that allow for possible correlations or anticorrelations.
- There is a need for a comprehensive and continuously-updated high-resolution reanalysis dataset. This would ideally be at 1 km horizontal resolution with adequate boundary-layer vertical resolution to provide good hub-height wind data, and fully integrate not only meteorological data (with high-quality wind and solar capabilities) but also coincident energy data.
- Projections for how climate change will affect river basin runoff, wind and solar generating capacity in specific geographic regions, and weather extremes that impact generating infrastructure and distribution networks are still not sufficiently robust to allow confidence in long-term planning.
- Trustworthy and quality-controlled sources of data can be challenging for utilities to find and navigate, particularly when looking to visualize user-selected threshold-defined events. There is a need for a validated database that ties objective extreme events in the power infrastructure to the weather events that caused them so that projections of frequency changes in weather events can be used to project infrastructure impacts.
- Improved understanding of potential future conditions stemming from various impacts of climate change, especially changes in weather extremes, will be crucial to optimize the infrastructure needed for the generation and delivery of energy.
- While future energy generation will rely heavily on probabilistic forecast approaches, there is still much to be done to ensure the operational energy community is prepared to effectively utilize this information, as well as increasingly sophisticated measures of uncertainty in delivering firm power.
- While weather and climate information is crucial to deploying energy efficiently where it is needed, developing new regulatory and policy frameworks for energy delivery may be the most critical need at this time in allowing a larger penetration of renewables.

The transition to an efficient, resilient, and reliable energy system built primarily on renewables is an example of a “wicked” problem—inherently complex and uncertain with no optimal solution. As such, it necessitates bringing together a variety of stakeholders, sectors, and disciplines to develop multiple approaches to address the different components of the challenge in a comprehensive fashion. Actionable scientific assessments are useful mechanisms to aid the development of these approaches; they may not only reveal gaps in climate science knowledge but also the instances where these gaps might be bridged through the reframing of available information or through new convergence research.

This study confirmed that excellent progress is being made on a variety of fronts associated with renewable energy, from better understanding of turbine wakes to improve future wind farm siting to using AI/ML for better short-term forecasts of generation variabilities. Each of these areas of enhanced understanding and improved capabilities is critically important as we move to increase use of renewables. A consistent theme in the discussions under this study, however, is the need to bring together many disparate types of data, modeling, and analyses toward convergent tools that adequately address the complex interconnectedness of a national power system built on renewable sources. In many ways, the most significant finding of this study is the need for major convergence research efforts to build the necessary historical reanalysis datasets, integrated weather-energy forecast models, and policy and regulatory frameworks that can leverage current disciplinary research efforts.

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Appendix

List of experts who contributed to this study in alphabetical order. The organizations listed represent primary employers at the time of the interview/presentation.

Gregory Brinkman, NREL
Adria Brooks, DOE
Randy Cain, First Energy Corp
Julia Dumaine, Connecticut Department of Energy and Environmental Protection
Caroline Draxl, NREL
Paul Fleming, NREL
Sue Haupt, NCAR
Bri-Mathias Hodge, University of Colorado and NREL
Rebecca Johnson, Western Area Power Administration
Meghan F Klee, American Electric Power
Edward Kieser, American Electric Power
Jennifer King, NREL
Ryan King, NREL
Christopher G Leopold, American Electric Power
Julie Lundquist, University of Colorado and NREL
Michael Malmrose, Connecticut Department of Energy and Environmental Protection
Peter Manousos, First Energy Corp
Melinda Marquis, NREL
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Brent Osiek, Western Area Power Administration
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Connor Reardon, Littleton Electric Light & Water Departments
Joe Roberts, ISO-New England
Amy Robertson, NREL
Manajit Sengupta, NREL
Justin Sharp, Sharply Focused
Marcus R Smith, American Electric Power
Bradley Udal, Colorado State University
Connie Woodhouse, University of Arizona
Thomas Workoff, First Energy Corp


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