Evaluating and Strengthening Iowa's Power Grid for High Wind/Solar Penetration Levels

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Evaluating and Strengthening Iowa's Power Grid for High Wind/Solar Penetration Levels

Project Report #2
High-Risk Conditions and Events

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Executive summary

The focus of this work is to identify conditions and events that pose high risk to Iowa's power system. Assuming a very high penetration of wind and solar generation in the future, extreme conditions are defined by weather conditions that include simultaneously low wind and low solar irradiance. Furthermore, the most extreme condition is when wind and solar irradiance are both low during high temperatures. This results in a high load, low generation condition, making it challenging to balance load and generation.

In order to quantify the potential risk for the Iowa power system due to extreme conditions, the NREL Sup3rCC weather data was used to simulate wind and solar output under historical weather conditions and under future conditions predicted by a climate model. The weather data was used in conjunction with wind turbine and solar collector models to predict renewable generation output. Simulations of a large set of existing and planned wind and solar facilities across the state of Iowa indicate that wind and solar generation are simultaneously below 10% of their rated output for 721 hours under 2022 weather conditions. Further simulations were performed by varying solar generation from none to 100% of the wind and solar generation mix. The results indicate that the number of hours of low generation (hours of risk) reach a minimum when solar generation is around 40% of the total renewable generation mix.

The most severe weather conditions are when low renewable generation occurs at high temperatures. Our simulations indicate that Iowa would experience low renewable generation at high temperatures for a significant number of hours each year under 2022 weather conditions. In addition, the hours of risk are predicted to be higher under 2050 conditions because Iowa is subject to longer durations of hot weather. However, the results again indicate that the hours of risk can be somewhat minimized by increasing the solar fraction of generation so that solar generation is approximately 60% of the total renewable generation mix.

As opposed to the general nature of extreme conditions, extreme events are specific times and places in which the cost impact of weather, climate, or environmental conditions exceeds a historical threshold. Analysis of a database maintained by the National Centers of environmental Information (NCEI), indicates that both count and average cost of extreme weather events in Iowa have increased between 1980 and 2022. These events include severe storms, droughts, floods, and freezes, but the most common extreme event in Iowa is a severe storm, where severe is defined as having an impact exceeding $1B. In Iowa, the number of severe storms per decade has increased for the past four decades and the state is projected to experience 30 of them in the current decade. These observations are consistent with simulations of future weather events using climate models, which project increased storm activity over the U.S. Midwest, especially during the March-April-May timeframe. However, the study of future weather using climate models contains significant uncertainty, and the prevalence of certain effects such as tornadic activity are difficult to determine.

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1 Introduction

The focus of this work is to identify conditions and events that pose high risk to Iowa's power system. The basic approach is to assume that by 2050, generation in Iowa will fundamentally shift from fossil fuel sources to predominantly renewable forms of generation such as wind and solar. Thus, weather related conditions such as low wind and low solar irradiance become major concerns in making sure that future generation is adequate to meet demand. But what are the specific risks? How many hours per year would wind and solar generation be simultaneously low? How many hours per year would low renewable generation occur at high temperatures (and therefore high loads)? What is the right mix of solar and wind generation? Furthermore, weather patterns are prone to be altered by climate change. Will the weather conditions in 2050 be more severe than the conditions we are already experiencing? Chapter 2 addresses these questions by presenting a detailed analysis of the high-risk conditions imposed by weather and climate change.

Beyond weather conditions, specific weather events may place Iowa's generation, transmission, and distribution systems at risk. As it turns out, the frequency of serious weather events may also be affected by climate change. What can we expect from climate change and what are the specific risks we should prepare for? Chapter 3 of this report presents an in-depth analysis of the history of severe weather events in Iowa and the potential implications for long term expansion planning.

2 Extreme conditions

When the generation mix transitions from predominately fossil fuels to a high penetration of renewable generation, the definition of extreme conditions also changes. Whereas fossil-fueled power plants are largely unaffected by wind and solar irradiance, these factors become critical to adequate wind and solar generation. Thus, in this chapter, extreme conditions are defined by weather conditions that include simultaneously low wind and low solar irradiance. Furthermore, the most extreme condition is when wind and solar irradiance are low during high temperatures. This results in a high load, low generation condition, making it challenging to balance load and generation.

2.1 Overview of datasets

Since the extreme conditions mentioned above are weather related, we need good ways to consider weather in our analysis. But in doing so, we must consider climate change, which may fundamentally change future weather patterns relative to those of the past. Furthermore, in choosing weather data, we require data that has good spatial and temporal resolution. Such resolution is generally derived using a combination of sensor data (measurements) and a computational model, such as the Weather Research and Forecasting (WRF) model[1].

To consider typical weather itself, we have several options. We could use historical data, such as the high-resolution rapid refresh HRRR dataset provided by the NOAA; the NREL wind toolkit (WindTK) data; or the NREL national solar radiation database (NSRDB). But to consider climate change, weather data options are currently very limited. One option currently available is the NREL Super-Resolution for Renewable Energy Resource Data with Climate Change Impacts (Sup3rCC). Sup3rCC is a dataset obtained from downscaling the output of a climate model using machine learning (ML), where the ML is trained using data obtained from NREL's WRF-generated NSRDB and WindTK datasets. Sup3rCC provides high temporal (hourly) and spatial (4 × 4 km) resolution, for time periods decades into the future. The dataset covers a time span from 2015 to 2059, but with the caveat that, "the historical years represent the historical average climate, not the actual historical weather that we experienced."[2] An added benefit of the Sup3rCC data is that it can easily be used with NREL reV, which provides physical models of wind turbines and solar collectors, so that their time-varying power output can be calculated based on variation in weather.

In summary, the Sup3rCC data is an appropriate resource for use in this analysis of extreme conditions posed by weather. It provides good spatial and temporal resolution, it includes both historical weather and future weather based on a GCM, and it accommodates usage of NREL reV for calculating the time-varying power output of renewable generation. However, Sup3rCC is a relatively new dataset; conclusions derived from it should be considered together with those from alternatively-derived datasets of future weather conditions.

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[1] National Center for Atmospheric Research (NCAR) Mesoscale & Microscale Meteorology Laboratory, "Weather Research & Forecasting Model (WRF)." [Online]. Available: https://www.mmm.ucar.edu/models/wrf.
[2] The National Renewable Energy Lab (NREL). (2023). Super-Resolution for Renewable Energy Resource Data with Climate Change Impacts (Sup3rCC) [data set]. Retrieved from https://dx.doi.org/10.25984/1970814.

2.2 Calculation of hourly wind and solar output

Prior to the analysis described in this section, a list of currently installed wind and solar generators was compiled using publicly available information[3]. In addition, future installations of wind and solar generators were obtained from the MISO Generator Interconnection Queue – Active Projects Map[4]. These lists and this analysis only pertains to installations in the state of Iowa.

Once the generator lists were compiled, the hourly output of all wind and solar generators was derived using the process outlined in Figure 2-1 below. Weather parameters such as wind and irradiance are both spatially and temporally variable. Therefore, each generator is matched to the nearest available weather data location. For wind farms, it was often the case that several generators were matched to the same weather data location. In these cases, the turbines were combined by summing their capacity. Subsequently, a single instance of the turbine model is simulated in order to calculate the time varying output in terms of an hourly capacity factor. Then the sum of turbine capacities at that location could be multiplied by the hourly capacity factor in order to find the time-varying output in MW. However, in this analysis, the goal was to obtain a single time-varying response for all the wind turbines in the state, and another time-varying response for all the solar installations in the state. These net responses were calculated using a weighted sum based on the nameplate power capacity at each location. Wind farm losses and solar inverter losses are included in the analysis, and these losses are reflected by a reduction in the hourly capacity factor.

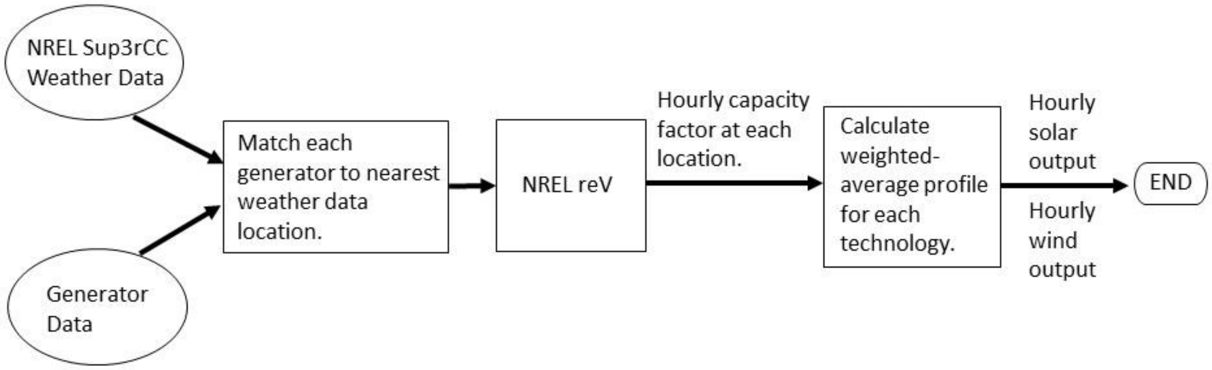

Figure 2-1: Flow chart of process of calculating hourly net output of wind and solar generation.

Table 2-1 below shows summary statistics for all renewable generators included in this analysis. These generators represent a diverse set of locations across the state. Therefore, the net wind and solar output profiles (time-series) derived in the process described above reflect the variation of weather over practically the whole state. These results are much different than if we assumed that all generator installations were in a single location and only affected by the weather in a single location. The idea is that the analysis reflects the reading we would see at any point in time if we had a single meter to indicate the net output of all wind generation or of all solar generation in the state of Iowa. This analysis was completed for 2022 and 2050 weather conditions. The 2022 case

[3] Hoen, B.D., Diffendorfer, J.E., Rand, J.T., Kramer, L.A., Garrity, C.P., and Hunt, H.E., 2018, United States Wind Turbine Database v6.0 (May 31, 2023): U.S. Geological Survey, American Clean Power Association, and Lawrence Berkeley National Laboratory data release, https://doi.org/10.5066/F7TX3DN0.
[4] MISO logoGenerator Interconnection Queue – Active Projects Map [Online], Available: https://giqueue.misoenergy.org/PublicGiQueueMap/index.html.

represents weather conditions that we have already seen and the 2050 case represents weather conditions that could occur under the influence of climate change.

Table 2-1: Summary of Iowa wind and solar generation used in this study.

Count	Generator Type	Total Nameplate Capacity (MW)
6220	Existing Wind Turbines	12,406.4
31	Wind Farms in MISO Queue	5,690.2
10	Existing Solar Installations	168.6
23	Solar Installations in MISO Queue	3,267.0

2.3 Analysis of results: times of low renewable generation

As mentioned in the introduction to this chapter, renewable generation is subject to weather variation, and if we assume a very high penetration of wind and solar, the most extreme conditions will occur when both wind and solar irradiance are low. In the simplest case, we could look at a single year and ask how many hours solar and wind generation are simultaneously low. For example, if we analyze the solar and wind output for 2022, we can see that for 721 hours both solar and wind are below 10% of their rated output; for 1410 hours, both are below 20% of their rated output; and for 2212 hours, both are below 30% of their rated output. These results are summarized in Table 2-2 below.

Table 2-2: Analysis of low renewable generation under 2022 weather conditions.

Hours both wind and solar generation are below:		
10% output	20% output	30% output
721	1410	2212

This analysis is a cause for concern. It indicates that both sources of generation are simultaneously low for a significant amount of time in a single year. If both were of equal capacity, the total renewable generation would be below 20% of its nameplate output for 721 hours in a year and we would need to plan accordingly by providing energy storage, load curtailment, or other forms of generation to avoid load interruption.

By totaling the hours that both wind and solar output are low, the analysis above assumes that both are of equal capacity. But what if that is not true? What happens when the mix of renewable generation is varied? Figure 2-2 below illustrates what happens when solar generation is varied from 0 to 100% of the total generation. The solar fraction is defined as the fraction of the total generated energy that is from solar.

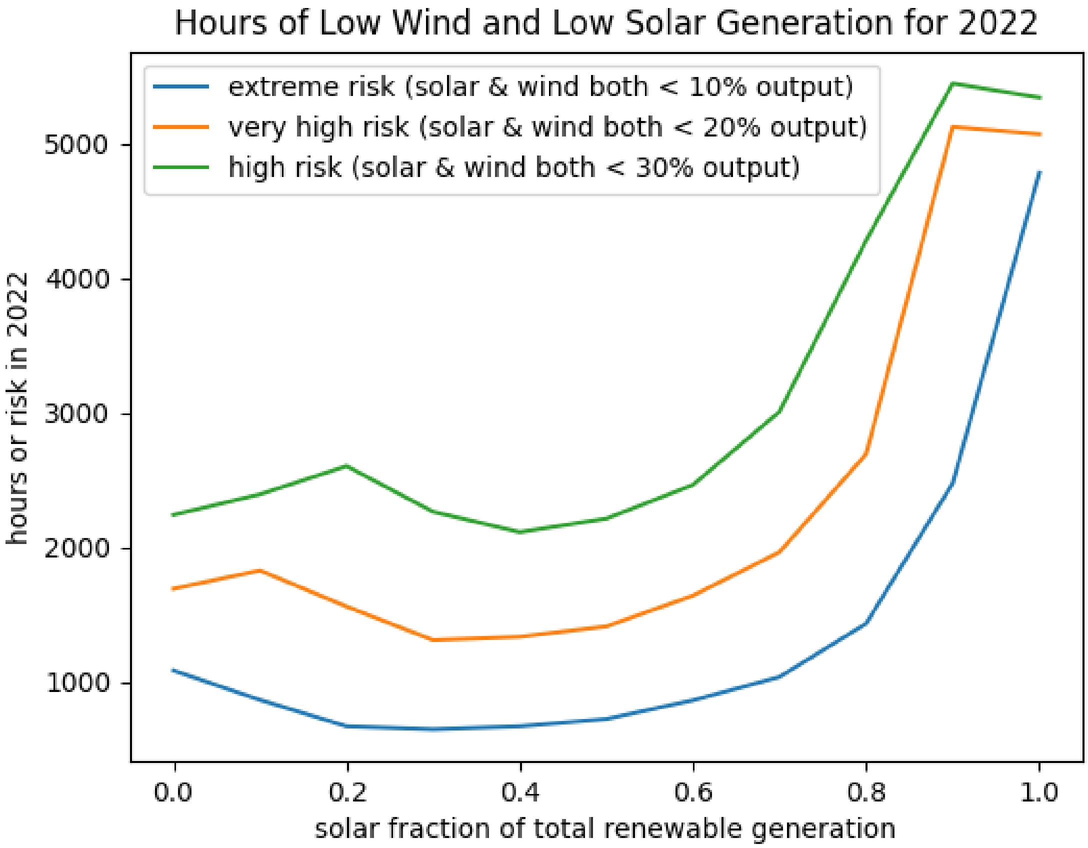

Figure 2-2: Hours of simultaneously low wind and solar generation under 2022 weather conditions.

The most pervasive feature of Figure 2-2 above is that the hours of low generation rise steeply and approach 1.0 as the solar fraction goes above 0.5. This makes sense because solar generation goes to zero at night. Beyond that, the results indicate that the hours of low generation are minimized when the solar fraction is somewhere around 0.4, or when solar generation is around 40% of the total renewable generation mix.

To illustrate the potential effects of climate change on these results, Figure 2-3 shows the results of the same analysis under 2050 weather conditions. While the hours of risk appear to be somewhat higher for low solar fractions, the results for 2050 weather conditions are not radically different than the 2022 results.

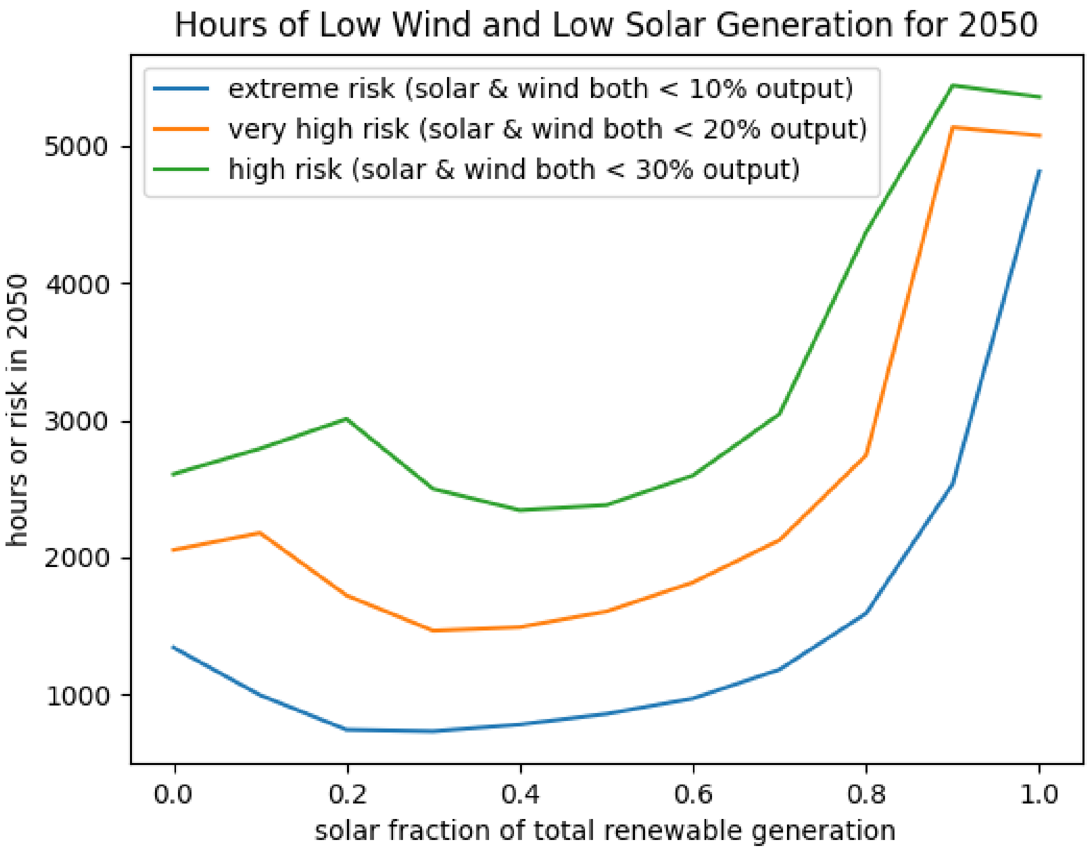

Figure 2-3: Hours of simultaneously low wind and solar generation under 2050 weather conditions

2.4 Analysis of results: low renewable generation at high temperatures

In the foregoing analysis, we found conditions where wind and solar irradiance were simultaneously low, causing low renewable generation. This was useful and instructive, but the most extreme conditions are when low wind and irradiance occur at high temperatures. The high temperatures would be coupled with high air conditioning load, so these conditions would imply low renewable generation under high load conditions. Assuming that wind and solar penetration are very high in the future, it is paramount to the frequency of such situations and to develop plans accordingly.

Figure 2-4 shows how many hours low renewable generation occurs at high temperature under 2022 weather conditions. As indicated by the legend, each line represents a different level of risk. For example, high risk is defined as being when the combined renewable output is below 60% of capacity and the ambient temperature in the load centers is above 26 ℃. The seriousness of the conditions increases as the combined renewable generation (power production, not capacity) decreases but the temperature increases. For this analysis, the ambient temperature was taken to be the weighted average of the 12 most populous cities in Iowa weighted according to population.

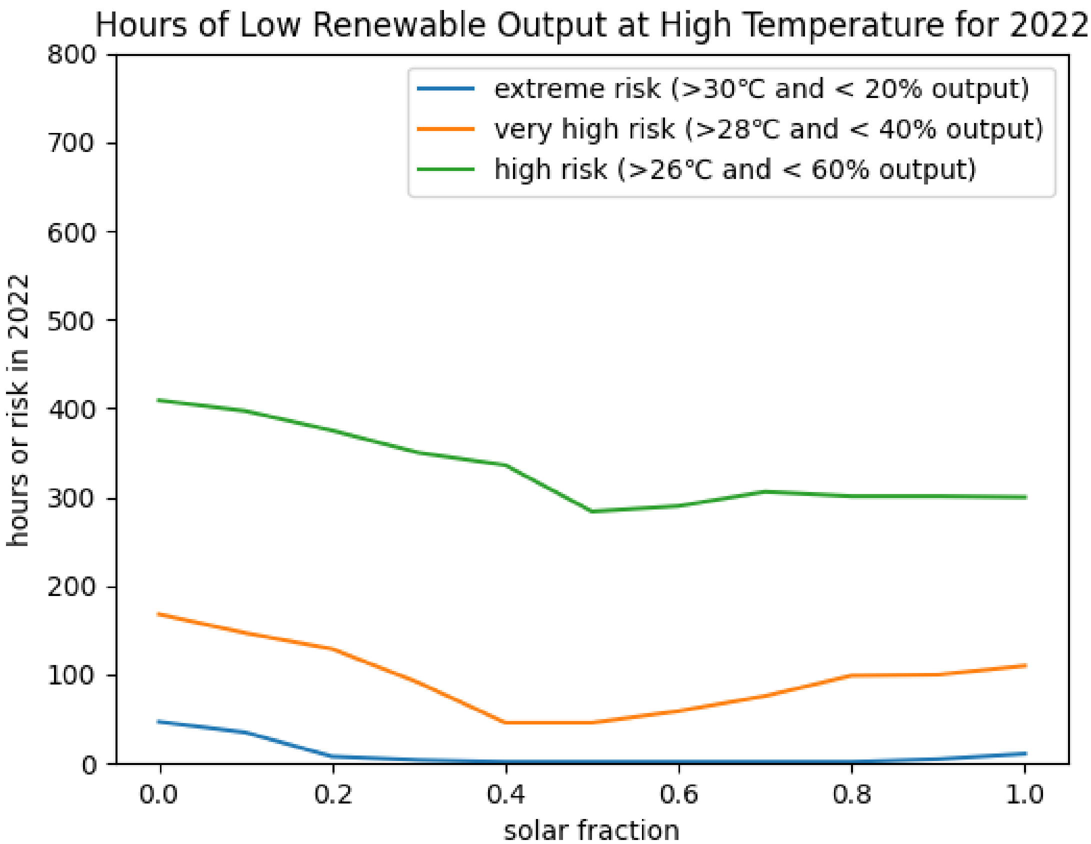

Figure 2-4: Hours of low renewable generation at high temperatures under 2022 weather conditions.

As Figure 2-4indicates, the hours of risk generally tend to decrease as the solar fraction of generation increases. This is a result of the fact that the hottest times of the year tend to be during the day when solar generation is more likely to contribute to serving the load. However, the results do show that an optimal solar fraction is around 0.5, where hours of risk reach a minimum.

There is an important difference between 2022 and 2050 weather conditions. Figure 2-5, below, shows a histogram of temperatures for both years. The plot indicates that Iowa will experience less extreme cold, but longer durations of relatively hot weather. Interestingly, the GCM does not predict an elevation in the highest temperatures, just longer durations of the same higher temperatures that were seen in 2022.

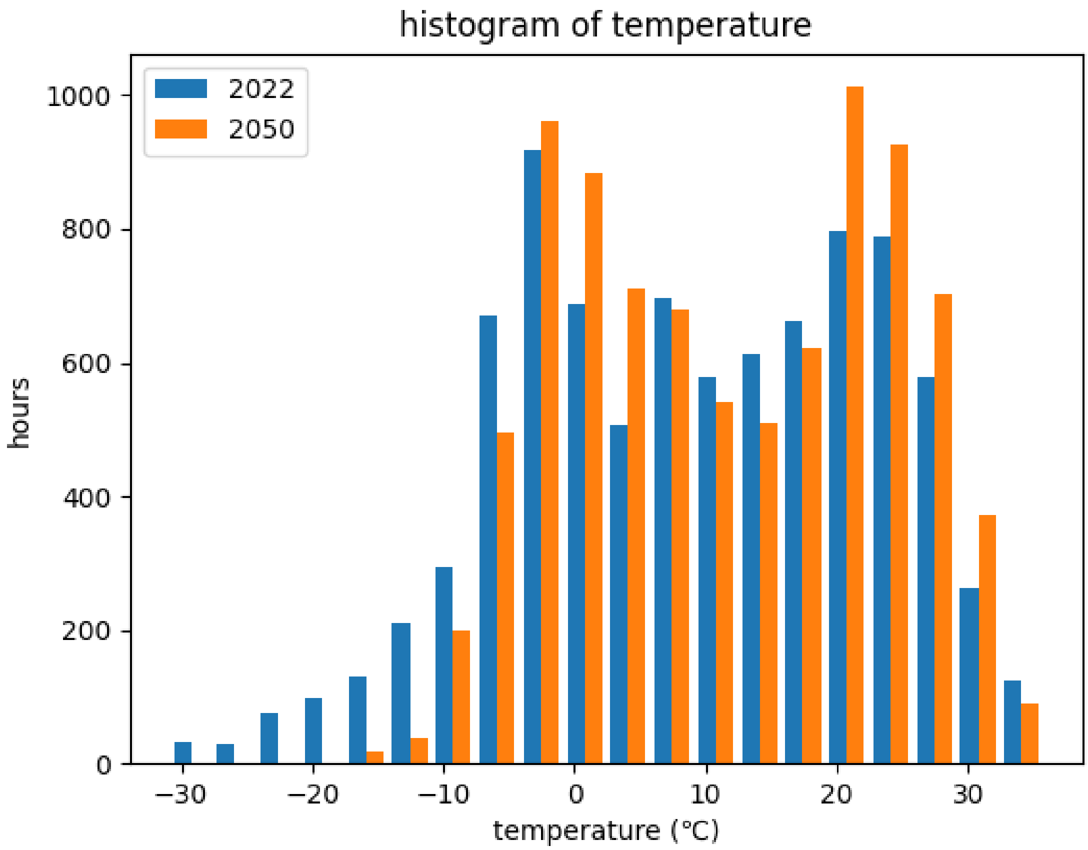

Figure 2-5: Histogram of temperature for 2022 and 2050.

Finally, Figure 2-6 shows how many hours low renewable generation occurs at high temperatures under 2050 weather conditions. Again, we see that the hours of risk tend to decrease as the solar fraction increases and that a somewhat subtle minimum occurs when the solar penetration is around 0.6. However, in comparing these results with those shown for 2022 weather conditions (Figure 2-4), we see that 2050 entails many more hours of risk, especially at low solar fractions. This is due to the longer duration of hot weather predicted by the GCM. Thus, the effectiveness of adding a significant amount of solar generation to the renewable mix is even more apparent in the 2050 results.

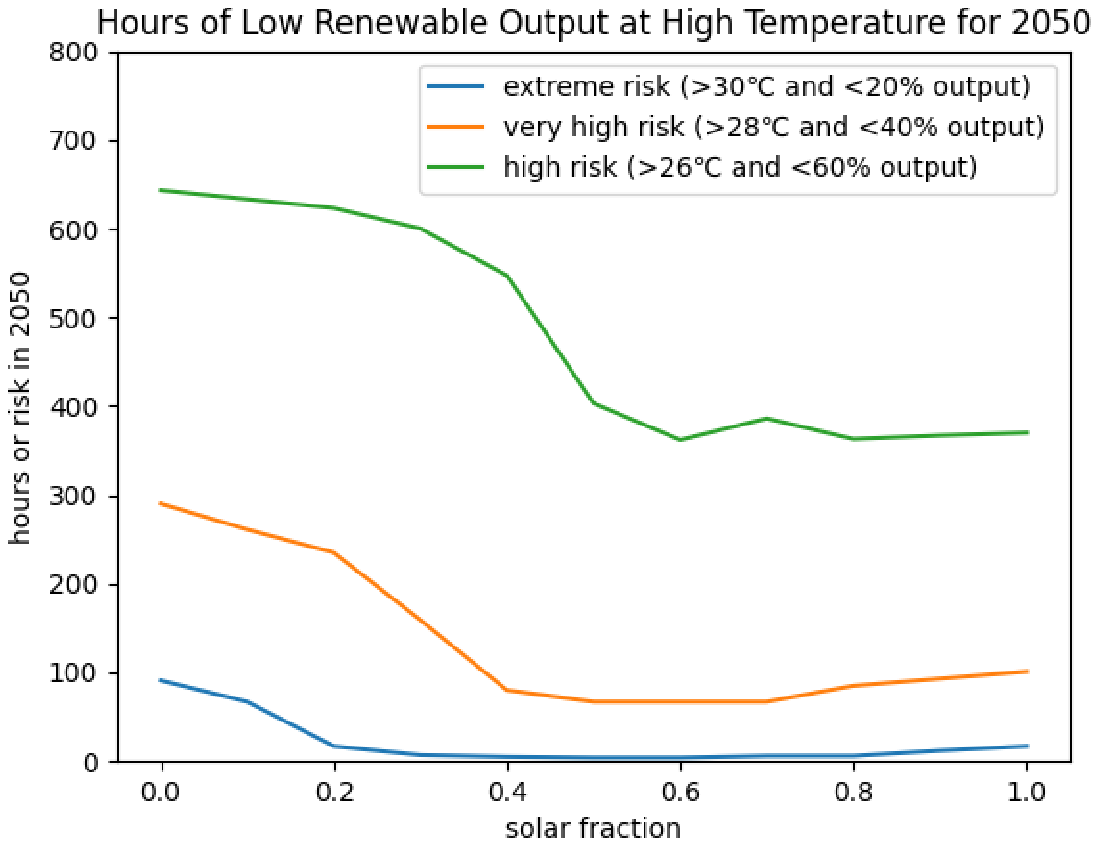

Figure 2-6: Hours of low renewable generation at high temperatures under 2050 weather conditions.

2.5 Future work

We intend to extend this work in three ways. First, we will repeat this analysis using an actual load prediction instead of the weighted average of temperatures in the largest cities. While it is true that temperature is closely related to load, other factors such as humidity and day of the week also affect load. Increased accuracy in load prediction would account for these other factors and increase the accuracy and utility of the results.[5]

Second, it was meaningful to refer to the MISO queue for the location of future renewable generation sites. However, the time frame of the queue is somewhat limited, so for long term simulations it would be better to include other sites, based on their potential for economic energy production. Selection of such sites is possible by using the NREL reV software, which also includes a database of local regulations and restrictions on land usage.

Finally, although the Sup3rCC weather data is based on well-known datasets (WindTK and NSRDB), it is still relatively new and unproven. It would be useful to compare the 2022 results

[5] National Renewable Energy Laboratory (NREL), "NREL Releases Comprehensive Databases of Local Ordinances for Siting Wind, Solar Energy Projects," 2023. [Online.] Available: www.nrel.gov/news/program/2022/nrel-releases-comprehensive-databases-of-local-ordinances-for-siting-wind-solar-energy-projects.html.

presented here with results obtained using different sources of weather data, such as the NOAA HRRR dataset and others. If the results are very similar for past years, this would help to validate usage of the Sup3rCC data. In addition, while the Sup3rCC dataset is developed using a climate model, the climate model used is just one of several possible ones, s, and other such datasets may become available in the future. Some of these models may provide more optimistic results than others, and long-term expansion planning should include some way to address the uncertainty of climate change modelling.

3 Extreme weather events

The notion of "extreme events" has been one that has been of interest in the literature of power system reliability and resilience for many years and includes, besides weather-related events, other types such as earthquakes, tsunamis, volcanic eruptions, geomagnetic disturbances, human intentional, cyber-related, and cascading outages. Of these, the first three are of little interest in considering threats to Iowa infrastructure, but the last four are. However, none of these are weather or climate related.

This chapter focuses on extreme weather events. Interest in this focus arises because it is possible, even likely, that climate change will result in a near-future where the frequency of such events increases significantly. This increased frequency motivates the development of solutions that mitigate associated consequences.

It is useful at the outset to define the term "extreme weather event" as used in this chapter. A widely quoted definition provided in Chapter 1 of the 2021 publication "Global change research needs and opportunities for 2022-2031," by the National Academies of Sciences, Engineering, and Medicine,[6] is as follows:

> An extreme [weather] event is a time and place in which weather, climate, or environmental conditions, such as temperature or precipitation, rank above a threshold value near the upper or lower ends of the range of historical measurements.

To this meteorologically-sound definition, we integrate the notion of the additional societal costs associated with such events, resulting in the following definition that we embrace in this chapter.

> An extreme weather event is a time and place in which the cost impact of weather, climate, or environmental conditions, such as temperature or precipitation, ranks above a threshold value near the upper end of the range of historical values.

In Section 3.2, we will use $1B as our "threshold value."

The essence of power system reliability at the transmission level is captured by Standard TPL-001 of the National Electric Reliability Corporation (NERC). Version 4 of this standard, TPL-001-4, referred to extreme weather events as those that could result in "loss of two generating stations," giving examples of wildfires and "severe weather, e.g., hurricanes, tornadoes, etc.".[7] Version 5 of this standard, TPL-001-5.1, makes no change in this sense.[8]

On June 23, 2023, the Federal Energy Regulatory Commission (FERC) published Rule 88 FR 41262 which motivates better articulation on how to handle extreme weather events within transmission planning performance criteria.[9] In its summary statement, it said, "The Federal Energy Regulatory Commission directs the North American Electric Reliability Corporation, the

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[6] A consensus Study Report of the National Academies of Sciences, Engineering, and Medicine, "Global Change Research Needs and Opportunities for 2022-2031," The National Academies Press, 2021. [Online.] Available: https://nap.nationalacademies.org/read/26055/chapter/1

[7] NERC Standard TPL-001-4, "Transmission System Planning Performance Requirements," Effective date: Nov 26, 2014. [Online.] Available: https://www.nerc.com/pa/Stand/Reliability%20Standards/TPL-001-4.pdf.

[8] NERC Standard TPL-001-5.1, "Transmission System Planning Performance Requirements," [Online.] Available: https://www.nerc.com/pa/Stand/Reliability%20Standards/TPL-001-5.1.pdf.

[9] FERC Rule 88 FR 41262, "Transmission System Planning Performance Requirements for Extreme Weather," Published June 23, 2023. Effective date Sept 21, 2023. [Online.] Available: https://www.federalregister.gov/documents/2023/06/23/2023-13286/transmission-system-planning-performance-requirements-for-extreme-weather.

Commission-certified Electric Reliability Organization, to develop a new or modified Reliability Standard no later than 18 months of the date of publication of this final rule in the Federal Register to address reliability concerns pertaining to transmission system planning for extreme heat and cold weather events that impact the Reliable Operation of the Bulk-Power System." Although the focus on "extreme heat and cold weather" may be interpreted more narrowly than the "weather, climate, or environmental conditions" we identify in our "extreme weather event" definition, it is clear that FERC is recognizing the same, or at least a similar need.

3.1 Extreme weather event categories

The National Oceanic and Atmospheric Administration (NOAA) has identified six extreme event categories. We list them as follows, together with a definition:

- *Severe storm*: A storm is "severe" when it produces wind gusts of at least 58 mph and/or hail one inch in diameter or larger and/or a tornado.[10] A tornado is a violently rotating column of air touching the ground, usually attached to the base of a thunderstorm.[11] Derechos, also considered a severe storm, are widespread, long-lived wind storms associated with a band of rapidly moving showers or thunderstorms; if a severe storm causes wind damage extending more than 240 miles and includes wind gusts of at least 58 mph or greater along most of its length, then the event may be classified as a derecho.[12]
- *Tropical cyclone*: A cyclone is a large-scale circulation of winds around a central region of low atmospheric pressure. A tropical cyclone is a warm-core, non-frontal synoptic-scale cyclone, originating over tropical or subtropical waters with organized deep convection and a closed surface wind circulation about a well-defined center.[13]
- *Winter storm*: A winter storm is a combination of heavy snow, blowing snow and/or dangerous wind chills.[14]
- *Drought*: A period of abnormally dry weather sufficiently prolonged for the lack of water to cause serious hydrologic imbalance in the affected area.[15]
- *Flooding*: An overflow of water onto normally dry land; the inundation of a normally dry area caused by rising water in an existing waterway, such as a river, stream, or drainage ditch.[16]
- *Freeze*: A freeze is when the surface air temperature is 32°F or below over a widespread area for a climatologically significant period of time.[17]
- *Wildfires*: A wildfire is an unplanned, unwanted fire burning in a natural area.[18]

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[10] National Oceanic and Atmospheric Administration (NOAA). [Online]. Available, www.noaa.gov/explainers/severe-storms#:~:text=NOAA%20classifies%20a%20storm%20as,larger%20and%2For%20a%20tornado.

[11] National Weather Service. [Online]. Available: www.weather.gov/phi/TornadoDefinition#:~:text=Tornado%20%2D%20A%20violently%20rotating%20column,the%20base%20of%20a%20thunderstorm.

[12] National Weather Service. [Online]. Available: https://www.weather.gov/lmk/derecho.

[13] National Weather Service Glossary. [Online]. Available: https://forecast.weather.gov/glossary.php?word=cyclone.

[14] National Oceanic and Atmospheric Administration (NOAA). [Online]. Available: www.nssl.noaa.gov/education/svrwx101/winter/types/.

[15] National Weather Service. [Online]. Available: www.weather.gov/bmx/kidscorner_drought#:~:text=A%20drought%20is%20defined%20as,Glossary%20of%20Meteorology%20(1959).

[16] National Weather Service. [Online]. Available: https://www.weather.gov/mrx/flood_and_flash.

[17] National Weather Service Glossary. [Online]. Available: https://forecast.weather.gov/glossary.php?word=freeze#:~:text=A%20freeze%20is%20when%20the,or%20other%20conditions%20prevent%20frost.

[18] Federal Emergency Management Agency (FEMA). [Online]. Available: https://community.fema.gov/ProtectiveActions/s/article/Wildfire-What.

3.2 Extreme weather event data

The National Centers for Environmental Information (NCEI), a part of the National Oceanic and Atmospheric Administration (NOAA), has recently developed a website providing information on extreme weather events occurring since 1980 and causing cost-impacts exceeding $1B[19]. Data is available at the national level and also at individual state levels. Figure 3-1 summarizes by year all such extreme weather-events for the state of Iowa. The following comments highlight certain features of this figure.

- The bars indicate the number of events, as indicated on the left axis, where the number of each type of event is specified by colors within each bar. The meaning of colors is identified at the top of the figure. The most common color is green, indicating the most common event type for Iowa is severe storms. The only other event types observed for Iowa are, in order of most common to least, droughts (orange), floods (blue), and freezes (light blue).
- The two red lines indicate the range of cost caused by the extreme events in the given year, as indicated on the right axis.
- The black line indicates the 5-year average of the cost caused by the extreme events.

The event count and the average cost both indicate a general increase from 1980 to 2022. This increase is mainly due to the growing number of severe storms in each year, as indicated in Figure 3-2, which shows event count for severe storms increasing from 1 in the first decade 1980-1989, to 4 in the second decade 1990-1999, to 9 in the third decade 2000-2009, and to 23 in the fourth decade 2010-2019. So far, in the fifth decade 2020-2023, there have been 12 severe storms causing cost impact exceeding $1B, a rate that would, if maintained until 2029, reach 30. The decade-by-decade increase in severe storm events is captured more succinctly in Figure 3-3.

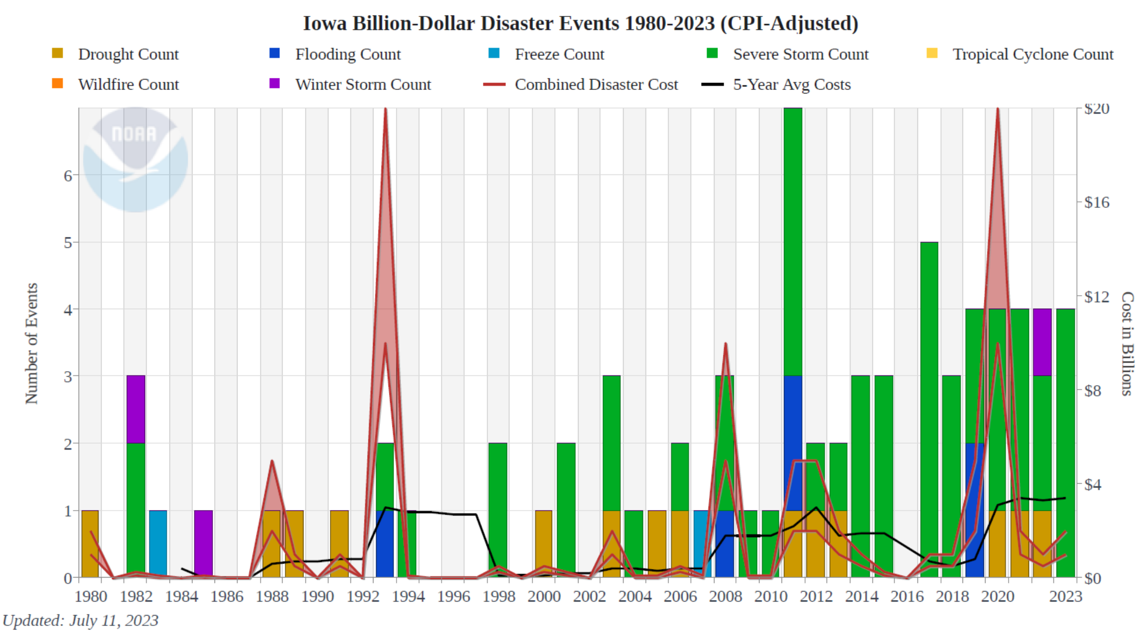

Figure 3-1: Summary of all extreme event disasters in Iowa having cost-impact exceeding $1B since 1980

[19] NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2023). https://www.ncei.noaa.gov/access/billions/, DOI: 10.25921/stkw-7w73

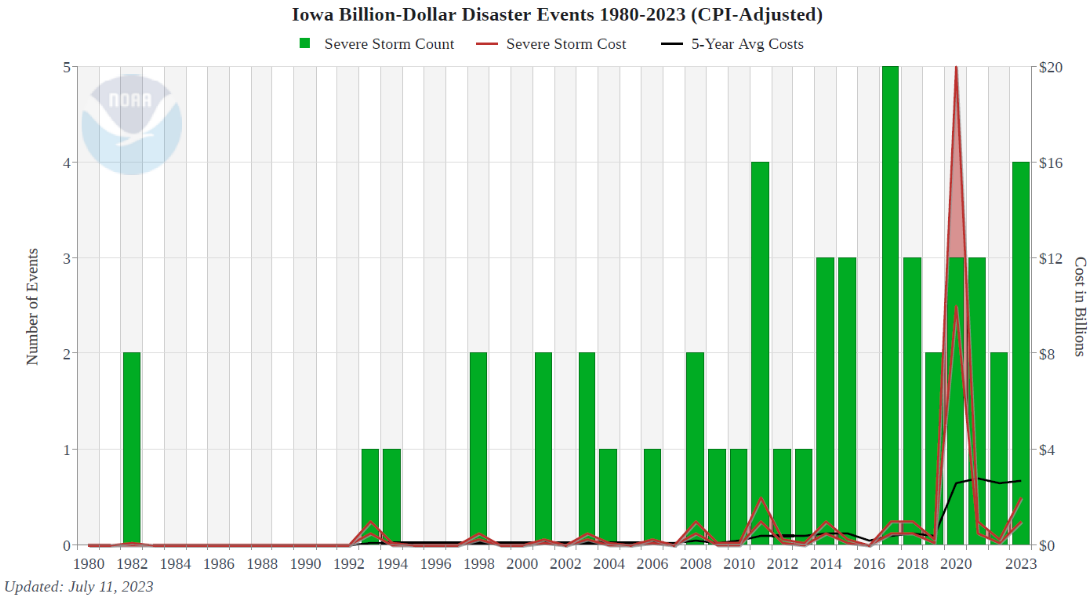

*Figure 3-2: **Summary of all severe storms in Iowa having cost-impact exceeding $1B since 1980***

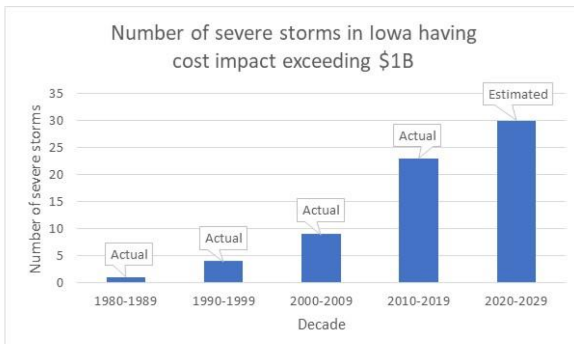

Figure 3-3: Number per decade of severe storms in Iowa having cost-impact exceeding $1B since 1980

The observation that the annual number of high-impact severe storms is growing in Iowa is consistent with predictions based on modeled simulation of the future, except that most of such simulations predict these increases to be a few decades later. The following statement, from the 2017 Climate Science Special Report[20] reflects these findings:

> "…Upon employing global climate models (GCMs) to evaluate CAPE and S06[21], a consistent finding among a growing number of proxy-based studies is a projected increase in the frequency of severe thunderstorm environments in the United States over the mid- to late 21st century…. The most robust projected increases in frequency are over the U.S. Midwest and southern Great Plains, during March-April-May (MAM). Based on the

[20] USGCRP, 2017: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp. [Online]. Available: https://science2017.globalchange.gov/chapter/9/.

[21] Two quantitative measures that characterize the local thunderstorm environments are Convective Available Potential Energy (CAPE) and S06. CAPE is a measure of the amount of energy available for convection; it is directly related to the maximum potential vertical speed within an updraft; thus, higher values indicate greater potential for severe weather. Observed values in thunderstorm environments often may exceed 1000 joules per kilogram (J/kg), and in extreme cases may exceed 5000 J/kg. S06 quantifies the vertical change or "shear" of the environmental horizontal wind vector. It is the magnitude of the vector difference between the horizontal wind at 6 km above ground level and the wind at the lowest model level. See R. Trapp, et al., "Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing," *Proceedings of the National Academy of Sciences*, Dec. 11, 2007, 104 (50) 19719-19723 https://doi.org/10.1073/pnas.0705494104.

> increased frequency of very high CAPE, increases in storm intensity are also projected over this same period."

The above statement from the original report, enumerates several references that we do not include in our quotation here, but the indication is that there have been multiple studies which support that the frequency of severe storm events is likely to increase moving forward. In addition to the fact that this statement is made with respect to predicted future events based on models, it should be also considered that our historical data is for extremely severe events, i.e., those exceeding $1B in impact; the above reference includes all severe storms. In addition, study of future weather using global climate models contains a great deal of uncertainty. For example, in a recent article by well-known climate scientists and meteorologists, although they conclude that "the effects of future climate change have the potential to decrease spring and increase winter and nocturnal tornadic storms, which could lead to a dangerous increase in tornado vulnerability," they also state that "the effects of climate change on tornadic storms have proven difficult to determine and remain uncertain."[22]

[22] E. Bercos-Hickey, C. Patricola, and W. Gallus, "Anthropogenic Influences on Tornadic Storms," *Journal of Climate*, Nov., 2021, Vol. 34, pp. 8989-9006.

4 Conclusions and next steps

For very high penetration of wind and solar generation, extreme conditions are weather oriented. Of particular interest are times when wind and solar irradiance are simultaneously low, causing low renewable generation. In addition, conditions are even more severe when low renewable generation occurs at high temperatures.

NREL Sup3rCC weather data was used to simulate wind and solar output under historical conditions and the future conditions predicted by a global climate model. The weather data was used in conjunction with NREL reV, which employs wind turbine and solar collector models to predict renewable generation output. Simulations of a large set of existing and planned wind and solar facilities across the state of Iowa indicate that wind and solar generation are simultaneously below 10% of their rated output for 721 hours under 2022 weather conditions. Further simulations were performed by varying solar generation from 0 to 100% of the wind and solar generation mix. The results indicate that the number of hours of low generation (hours of risk) reach a minimum when solar generation is around 40% of the total renewable generation mix.

The most severe weather conditions are when low renewable generation occurs at high temperatures. Our simulations indicate that Iowa would experience low renewable generation at high temperatures for a significant number of hours each year under 2022 weather conditions. In addition, the hours of risk are predicted to be higher under 2050 conditions because Iowa is subject to longer durations of hot weather. However, the results again indicate that the hours of risk can be somewhat minimized by increasing the solar fraction of generation so that solar generation is approximately 60% of the total renewable generation mix.

As opposed to extreme weather conditions, extreme weather events are specific times and places in which the cost impact of weather, climate, or environmental conditions is above a historical threshold. Analysis of a database maintained by the NCEI, indicates that both the count and average cost of extreme weather events in Iowa has generally increased between 1980 and 2022. These events include severe storms, droughts, floods, and freezes, but the most common extreme event in Iowa is a severe storm, where severe is defined as having an impact exceeding $1B. In Iowa, the number of severe storms per decade has increased for the past four decades and the state is projected to experience 30 of them in the current decade. These observations are consistent with simulations of future weather events using global climate models (GCM's), which project increased storm activity over the U.S. Midwest, especially during the March-April-May timeframe. However, it must be pointed out that the study of future weather using global climate models contains a great deal of uncertainty, and the prevalence of certain effects such as tornadic activity are difficult to determine.

Finally, we identified a few ideas for future work. First, we would like to refine our analysis by using an actual load projection instead of temperature as an indication of load. Such projections may be difficult to obtain but would be quite useful. Secondly, for long term expansion planning, we will need to identify other sites in the state of Iowa that have high potential for economic energy production. We can identify the sites using the NREL reV software, and then incorporate them into future simulations. Finally, we would like to use other weather datasets to repeat the analysis presented in this report. Other historic weather datasets could be used to confirm the validity of the Sup3rCC data and datasets that use a different GCM (when they become available) could be used to quantify the magnitude of uncertainty associated with climate change modelling.