14th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP14
Dublin, Ireland, July 9-13, 2023

Could rooftop solar panels and storage have enhanced the electricity resilience during Hurricane Isaias (2020)?

Prateek Arora
Ph.D. Candidate, Dept. of Civil and Urban Engineering, New York University, Brooklyn, NY, USA

Luis Ceferino
Assistant Professor, Dept. of Civil and Urban Engineering & Center for Urban Science and Progress, New York University, Brooklyn, NY, USA

ABSTRACT: Hurricanes damage power systems extensively, causing large power outages, critical service disruptions, and major economic losses. Hurricane Isaias (2020) caused more than two million power outages in the U.S. that, in several cases, lasted more than four days. This large-scale electricity loss demonstrated a lack of grid resilience, especially in New Jersey. This paper evaluates the contribution of solar panels and behind-the-meter batteries in microgrids to the resilience of an electricity distribution network, we present a what-if case study for New Jersey during Hurricane Isaias in 2020. We analyze an extensive power outage dataset at the building level for 9,267 households from a large utility company in Marlboro Township, New Jersey, during Hurricane Isaias to determine unserved power demand. We use historical irradiance in New Jersey for the duration of outages during Hurricane Isaias (2020) to determine the potential of solar electricity for resilience. We observe that solar panels on each rooftop would have improved resilience for electric energy in the aftermath of Hurricane Isaias.

1. INTRODUCTION

Hurricanes damage power systems, leaving millions without power and causing widespread disruptions for critical facilities (AJOT, 2021; Sheppard and DiSavino, 2012). The United States economy suffers 20 to 55 billion dollars in economic losses from unwanted power disruptions (Smith, 2020). Hurricane Isaias (2020) exposed the vulnerability of power systems in the Northeast United States, causing more than 2 million outages across the United States and more than a million outages in New Jersey (Jim Giuliano, 2020; Zaveri and Shanahan, 2020). Extreme weather events caused 53% of the major power blackouts in the United States between 2002-2017 (Ankit et al., 2021). Researchers have worked on predicting hurricane-induced outages (Arora and Ceferino, 2022; Shashaani et al., 2018) so that utilities can coordinate (National Academies of Sciences, Engineering, and Medicine, 2017) and arrange for backup generators. Almost 95% of the residential and critical buildings, e.g., buildings, are backed by fossil fuel fired generators using diesel or natural gas (Phillips et al., 2016). However, these backup sources may not be reliable as hurricanes can damage transportation routes and disrupt the supply chain of fossil fuels (Gibbs and Holloway, 2013). Furthermore, the stored fuel is only suitable for sustaining short-duration outages but not prolonged outages, also caused by hurricanes (Ornstein, 2012). Also, the use of fossil fuels does not align with renewable energy goals of reducing the impact of emissions on our climate (The White House, 2021).

A resilient power system needs to minimize the extent of prolonged disruptions (National Academies of Sciences, Engineering, and

Medicine, 2017). Emergency planners are now considering the value of renewable energy sources in enhancing the resilience of power systems (Laws et al., 2018). Distributed resources such as solar panels with clustered local energy resources capable of running in island mode from the electric grid can bring the tremendous potential for enhancing resilience (Chen et al., 2016). The decreasing cost of solar installation and tax incentives can help achieve grid parity resulting in larger penetration of photovoltaic solar panels as an energy source. Also, modern rooftop solar panels can sustain higher hurricane wind speeds than the old vulnerable distribution poles (Ceferino et al., 2023), as seen in recent extreme weather events (Cortes et al., 2022). Babrock Ranch, a community in Florida located 12 miles away from coastlines, has 700,000 solar panel installations providing power to 2,000 households. The community was unaffected by the massive power outages caused by Hurricane Ian in September 2022 with no damage to solar panels (Ramirez, 2022; Cortes et al., 2022).

Researchers studied the addition of renewables as a resilient and sustainable source of energy in microgrids (Newsom et al., 2019). There is also growing literature on the economic and financial benefits that renewables can bring to reduce the billions of dollars in losses caused by power blackouts (Moslehi and Reddy, 2018). Ong et al. (2012) studied grid parity. i.e., the cost of electricity generated through solar panels equals the purchased electricity from the main grid and found that many consumers in the Northeast United States can achieve grid parity. Laws et al. (2018) demonstrated savings in electricity costs with solar installations. Fox (2023) mentioned the reduction of energy vulnerability with more penetration of residential solar panels in the wake of rising electricity bills. More penetration of renewables in future energy markets can reduce the severity of business interruptions and subsequently reduce the insurance premiums for businesses(Anderson et al., 2018). Most studies on renewables-based resiliency in power systems have focused on commercial customers or conducted at a coarse resolution of transmission level addition of renewables (Watson, 2020). However, old distribution systems are often designed for lower wind speeds than transmission systems and are more vulnerable to strong hurricane winds (Brown, 2002). Patel et al. (2021); Ceferino et al. (2020) studied the effect of different adoption policies for solar panels in enhancing the resilience of power systems at the household level during an earthquake. However, hurricanes are very different from earthquakes as clouds during hurricanes can significantly reduce the incident solar irradiance on solar panels (Ceferino et al., 2022; Ceferino and Lin, 2022). Thus, reducing the solar energy generated during a hurricane.

We formulate and analyze a what-if case study for New Jersey during Hurricane Isaias in 2020 to evaluate the value of solar panels and behind-the-meter batteries in microgrids for resilience to supply uninterrupted power during hurricanes. This study focuses on Marlboro Township, New Jersey, residential buildings, where 9,267 households lost power in the aftermath of Hurricane Isaias (2020). We use the historical solar irradiance data to calculate the available solar potential to meet the unserved energy demand due to outages during Hurricane Isaias (2020) with the assumption of 100% adoption of solar panels at the household level. This study does not consider energy sharing between households, and we assume each household will consume the energy generated by the solar panels on their roof.

2. HURRICANE ISAIAS: POWER OUTAGES AND SOLAR IRRADIANCE

Hurricane Isaias reached New Jersey on August 4, 2020 (Latto et al., 2021). High winds in New Jersey snapped and downed many trees and powerlines. We show in Figure 1 the wind fields for Hurricane Isaias in New Jersey computed using a complete wind profile model for tropical cyclones developed by Chavas et al. (2015) and the location of our study area (Marlboro Township, New Jersey). More than one million people were left without electricity in New Jersey (OE-417 Form, 2020), even though Isaias weakened to a tropical storm as it hit New Jersey with sustained winds of 57 mph. Isaias caused economic losses of about 4.2 billion dollars and caused 15 deaths (Latto et al., 2021).

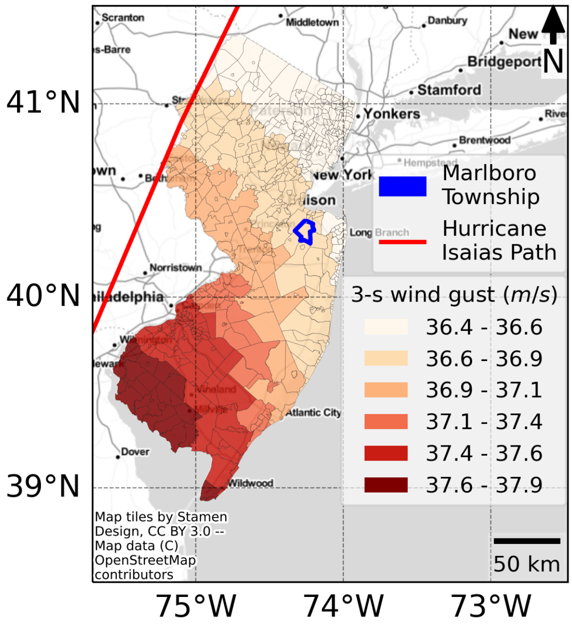

Figure 1: 3-s gust wind speed in New Jersey from Hurricane Isaias (2020) (adapted from Arora and Ceferino (2022)

2.1. *Power Outages*

We obtained the power outage at the building level from Jersey Central Power & Light (JCPL), a major utility company in New Jersey. JCPL serves 1.1 million consumers in New Jersey and recorded 780,000 peak outages in the aftermath of Hurricane Isaias (2020) (Jim Giuliano, 2020). JCPL recorded their first consumer-level outage around 8 am on August 4, 2020, and the JCPL crew restored power for 90% of their consumers after 72 hours (Jim Giuliano, 2020). These prolonged power outages bring a strong need for backup power, motivating this on solar panels and behind-the-meter batteries. Outage data from JCPL includes the city number, the street address of the consumer, zip code, start and end time of power outages, and type of consumer (residential, industrial, or commercial). For the scope of this paper, we limit our study to the outages that happened in residential buildings in Marlboro Township, a municipality in New Jersey (Figure 2).

2.2. *Geocoding Outages, Parcel Data, and Building Footprints*

We geocoded the outages using the New Jersey Office of GIS (NJOGIS) statewide geocoding services (NJ Geographic Information Network | Geocoding, 2022) with an address provided by JCPL in the outage database to get the longitude and latitude of outages in ArcGIS (ESRI, 2019). Next, we matched the geocoded outages with the New Jersey building parcels (complete area covered by a plot).

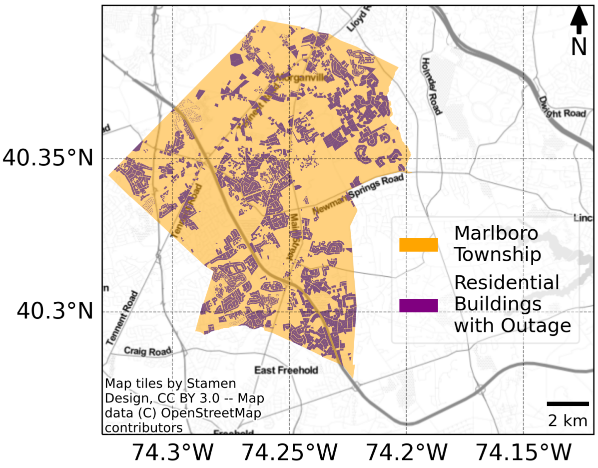

Figure 2: Location of power outages in Marlboro, New Jersey in the aftermath of Hurricane Isaias (2020)

We determined the area available for solar panels for each building. For that, we obtained the building footprints from NJOGIS since footprints of the actual buildings have a smaller area than parcels, as a parcel also includes open areas, e.g., gardens, patios, and garages. Also, a parcel may contain more than one building footprint, as some parcels have separate garages or other open spaces. We took the maximum footprint area in a parcel as the roof area for solar power estimation. Figure 2 shows the residential building with outages in Marlboro Township, New Jersey. We did not match geocoded outages to parcels as the NJOGIS geocoder allocated the latitude and longitude at the center of parcels. We excluded 2.7% outages from our analysis that did not match any parcel as the geocoder did not match some addresses. We further selected outages for 9,267 single-family household residential buildings.

2.3. *Solar Irradiance*

We used global horizontal irradiance (GHI) to calculate the potential solar electricity Patel et al.

(2021). GHI is available from the National Solar Radiation Database from National Renewable Energy Laboratory (NREL) at a spatial resolution of 4km and a temporal resolution of 30 minutes (Sengupta et al., 2018). We obtained the GHI for the duration of outages caused by Hurricane Isaias (2020) in New Jersey. We used nearest neighbor interpolation to get the GHI for a building by assigning the GHI value available at the nearest distance. We averaged GHI values at 30 minutes to get the hourly GHI. Figure 3(c) shows the average GHI across Marlboro township from August 4 to August 13, 2020.

3. MEASURING SOLAR POTENTIAL AND RESILIENCE

The available solar irradiance at the rooftop of a building is often affected by the shadows from the adjacent buildings or trees. Thus, using the entire roof to size a solar panel is not optimal. Lopez et al. (2012) mention about 22% and 27% of the roof area in cold and warm regions, respectively, are often available for solar electricity generation. New Jersey has moderately cold winters and warm summers. Thus, we assume 25% of the rooftop area is available for panel installation.

Also, not all points on a roof are fully exposed to the sky. The sky view factor (SVF) is used to determine the portion of a sky visible from a point on the rooftop (Redweik et al., 2013). SVF varies from zero (for a completely obstructed view of the sky) to one (for a clear view of the sky above the horizon). We use New Jersey Digital Elevation Model from NJOGIS to obtain SVF, with a relief visualization toolbox in Python, for buildings in Marlboro Township. Most of the buildings in the neighborhood of Marlboro are single-family residential buildings with significantly less obstruction on the rooftop to the sky. We obtained a mean SVF of 0.98 across all the residential buildings. The final solar irradiance available at a rooftop is GHI multiplied by 25% of the roof area and SVF. An alternative approach to solar panel sizing (Patel et al., 2021) is based on net zero, where the energy consumed matches the energy produced by a user. In this paper, we use the maximum available area in order to quantify the maximum resilience potential of solar panels.

3.1. Solar Generation, Battery, and Consumption

We assumed standard crystal silicone panels are installed for all the buildings with a solar energy conversion efficiency of 19% (Dobos, 2014). We considered 14% system losses used as default by NREL (Dobos, 2014). The system losses due to soiling, shading, mismatch, wiring, connections, light-induced degradation, nameplate rating, and availability, readers can refer to Dobos (2014) for a detailed explanation of system losses. Finally, we assumed a DC-to-AC conversion efficiency of 96%. So, the total converted solar energy is available solar power multiplied by conversion efficiency, system losses, and DC-to-AC efficiency.

We computed the wind fields for Hurricane Isaias (Figure 1) in Marlboro Township using a complete wind profile model for tropical cyclones (Chavas et al., 2015). We observed a maximum 3-s gust wind speed close to 37 m/s. According to Ceferino et al. (2023), rooftop solar has close to zero probability of failure for 3-s gust winds of less than 40 m/s. So, we assume no panel failure for the Hurricane Isaias scenario, and all panels generate solar energy.

We assumed households have a Tesla Powerwall installed with a usable capacity of 13.5 kWh. The battery will discharge every hour by the amount of energy consumed by the user and will charge if the generated solar power exceeds the consumed power.

Power consumption data at the building level is not publicly available. The U.S. Energy Information Administration (EIA) collects data on monthly sold electricity to residential consumers by utilities as part of the monthly industry report, also known as form EIA-861M (EIA, 2020). Since sales in the year 2020 were affected by Hurricane Isaias, we considered the average sales during August from 2019 to 2021 to get the average energy consumed by the user per hour. Thus, for this study, we considered the power consumption of 1,534 kW for every household. Refinements to this study could adjust consumption depending on the building size, as bigger homes could consume more electricity (Patel et al., 2021).

3.2. *Resilience Metric*

Previously, researchers (Cimellaro et al. 2010; Ouyang and Dueñas-Osorio 2014) have defined a time-dependent resilience metric to quantify the performance and responsiveness of the power systems disruption post extreme weather events. The resilience metric in Eq.1 is the ratio of the area under the actual performance curve and the area under the expected performance curve of power systems.

$$R(T) = \int_0^T P_R(t)dt / \int_0^T P_T(t)dt \qquad (1)$$

Where $P_T(t)$ is the expected percent of consumers with power under normal conditions, ideally 100%. And, $P_R(t)$ is the actual percent of consumers with power disruption post-hurricane.

For this paper, we compare the percent increase in resilience for power systems with solar panels compared to no backup power. To get the percentage of residential consumers with power, we set the total number of consumers equal to the peak number of outages in the aftermath of Hurricane Isaias. We perform the integrals in Eq. (1) from the onset of the first outage ($t = 0$) to the time of restoration of the last outage ($t = T$).

4. RESULTS

Given National Oceanic and Atmospheric Administration provide weather forecast 3-7 days ahead of a storm (Squitieri and Gallus, 2022), we assume in response to pre-disaster planning for outages, households keep their battery charged. We consider two scenarios for the state of the battery, (a) fully charged battery and (b) half-charged battery.

Considering solar panels could provide limited backup power, households may choose to reduce their power consumption post-hurricane. We consider three scenarios for consumption, (a) no reduction in power consumption, (b) 25% reduction in consumption, and (c) 50% reduction in consumption. Thus, we present results for six combinations based on the state of the battery and reduction in consumption in Figure 3.

Rooftop solar panels installed under all scenarios show a resilience gain compared to the base case of actual outages with no backup power. The resiliency gain for the 50% consumption scenario for a battery fully and half charged at the onset of outages is 37.3% compared to no backup power. The resiliency gain for a 75% consumption scenario for battery fully and half charge is close to 35%. And, for 100% consumption, resiliency gain is close to 30%.

From Figure 3, we can observe all the households will have no outage if they curtail their consumption to 50%. For scenarios with 75% and 100% consumption, consumers only depend on battery storage for supply at night, and outages occur once the battery is completely drained. However, battery charges during day time, and households recover from the outage. This cycle continues until the main grid supply is restored.

5. CONCLUSIONS AND DISCUSSION

We presented a what-if scenario of resilience to power outages in the aftermath of Hurricane Isaias (2020) with solar panel adoption by residents of Marlboro Township, New Jersey. We observed that all the houses gain resilience with solar panels compared to no backup. Moreover, by intentionally reducing their consumption, households can sustain themselves throughout power outages with solar panels and energy stored in the battery even more effectively.

This study presented the importance of solar panels for electric grid resilence. However, the study was limited to certain conditions. We did not consider that electricity could be shared between households. Energy sharing in microgrids between households with surplus solar energy production and households with less energy production could enhance the neighborhood's resilience (Patel et al., 2021). Hurricane Isaias (2020) had low winds in New Jersey, and most rooftop panels are likely to survive such winds (Ceferino et al., 2023). However, a high hurricane could likely cause the failure of some panels, and energy sharing under such a scenario might be necessary between buildings with failed and non-failed panels. In addition to economic benefits (Ong et al., 2012; Laws et al., 2018; Fox, 2023), results presented in this study suggest that solar panels can play an essential role

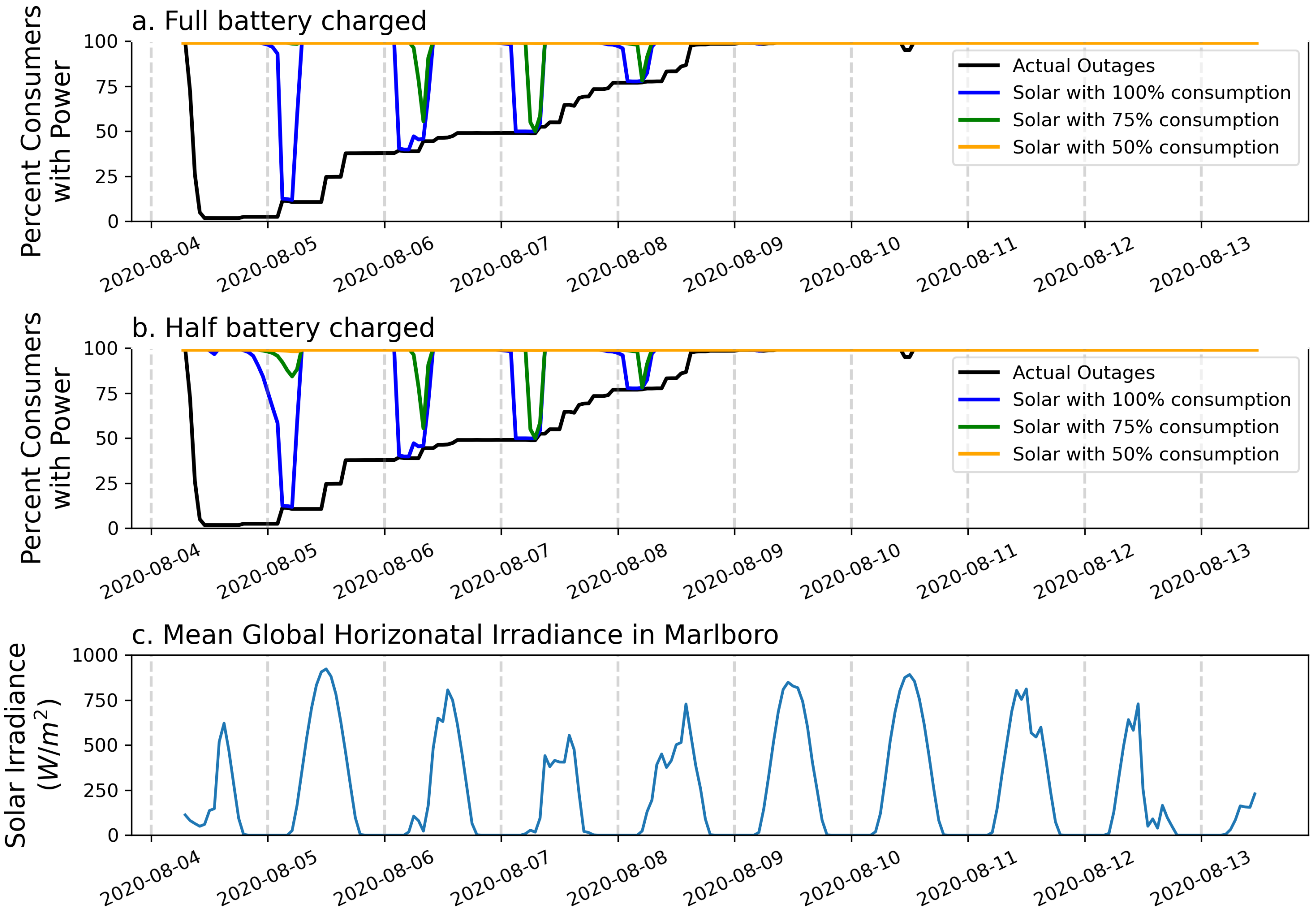

Figure 3: (a) Power Outage scenarios when the battery is fully charged at the onset of power outages. (b) Power Outage scenarios when the is half charged at the onset of power outages. (c) mean solar irradiance in Marlboro Township

in power grid resilience against hurricanes. The methods presented in this study could be extended to a more comprehensive study on resilience with solar panels.

6. ACKNOWLEDGEMENT

We are thankful to Jersey Central Power & Light for sharing the data on power outages for Hurricane Isaias (2020).

We acknowledge the financial support from the NYU Tandon School of Engineering Fellowship. Additionally, this research is supported by Coalition for Disaster Resilient Infrastructure (CDRI) fellowship program.

7. REFERENCES

AJOT (2021). “Hurricane Ida caused at least 1.2 million electricity customers to lose power | AJOT.COM, <https://ajot.com/news/hurricane-ida-caused-at-least-1.2-million-electricity-customers-to-lose-power> (9).

Anderson, K., Laws, N. D., Marr, S., Lisell, L., Jimenez, T., Case, T., Li, X., Lohmann, D., and Cutler, D. (2018). “Quantifying and Monetizing Renewable Energy Resiliency.” *Sustainability 2018, Vol. 10, Page 933*, 10(4), 933.

Ankit, A., Liu, Z., Miles, S. B., and Choe, Y. (2021). “U.S. Power Resilience for 2002–2017.

Arora, P. and Ceferino, L. (2022). “Probabilistic and Machine Learning Methods for Uncertainty Quantification in Power Outage Prediction due to Extreme Events [Preprint].

Brown, R. E. (2002). “Electric Power Distribution Reliability.

Ceferino, L. and Lin, N. (2022). “Hurricane Risk of Solar Generation in the United States.” *Preprint*, 1–17.

Ceferino, L., Lin, N., and Xi, D. (2022). “Stochastic modeling of solar irradiance during hurricanes.” *Stochastic Environmental Research and Risk Assessment*, 36(9), 2681–2693.

Ceferino, L., Lin, N., and Xi, D. (2023). “Bayesian updating of solar panel fragility curves and implications of higher panel strength for solar generation resilience.” *Reliability Engineering & System Safety*, 229, 108896.

Ceferino, L., Liu, C., Alisjahbana, I., Patel, S., Sun, T., Kiremidjian, A., and Rajagopal, R. (2020). “Earthquake resilience of distributed energy resources.” *17th World Conference on Earthquake Engineering*, Tokyo, Japan.

Chavas, D. R., Lin, N., and Emanuel, K. (2015). “A model for the complete radial structure of the tropical cyclone wind field. Part I: Comparison with observed structure.” *Journal of the Atmospheric Sciences*, 72(9), 3647–3662.

Chen, C., Wang, J., Qiu, F., and Zhao, D. (2016). “Resilient Distribution System by Microgrids Formation after Natural Disasters.” *IEEE Transactions on Smart Grid*, 7(2), 958–966.

Cortes, M., Arora, P., Ceferino, L., Ibrahim, H., Istrati, D., Reed, D., Roueche, D., Safiey, A., Tomoczek, T., Zisis, I., Alam, M., Kijewski-Correa, T., Prevatt, D., and Robertson, I. (2022). “StEER - Hurricane Ian | DesignSafe-CI.

Dobos, A. P. (2014). “PVWatts Version 5 Manual.

EIA (2020). “Form EIA-861M (formerly EIA-826) detailed data, <https://www.eia.gov/electricity/data/eia861m/>.

ESRI (2019). “ArcGIS Desktop: Release 10.8.” *Report no.*, Environmental Systems Research Institute, Relands,CA.

Fox, N. (2023). “Increasing solar entitlement and decreasing energy vulnerability in a low-income community by adopting the Prosuming Project.” *Nature Energy 2023 8:1*, 8(1), 74–83.

Gibbs, L. and Holloway, C. (2013). “Hurricane Sandy After Action Report and Recommendations to Mayor Michael R. Bloomberg.

Jim Giuliano (2020). “Review and Assessment of Electric Utility Performance August.” (1135), 1406489.

Latto, A., Hagen, A., and Berg, R. (2021). “National Hurricane Center Tropical Cyclone Report. Hurricane Isaias.” (June), 1–32.

Laws, N. D., Anderson, K., DiOrio, N. A., Li, X., and McLaren, J. (2018). “Impacts of valuing resilience on cost-optimal PV and storage systems for commercial buildings.” *Renewable Energy*, 127, 896–909.

Lopez, A., Roberts, B., Heimiller, D., Blair, N., and Porro, G. (2012). “U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis.

Moslehi, S. and Reddy, T. A. (2018). “Sustainability of integrated energy systems: A performance-based resilience assessment methodology.” *Applied Energy*, 228, 487–498.

National Academies of Sciences, Engineering, and Medicine (2017). “Enhancing the Resilience of the Nation’s Electricity System.” *Enhancing the Resilience of the Nation’s Electricity System.*

Newsom, G., Carter, D., Saucedo, D., Zoellick, J., Chamberlin, C., Marshall, M., Shoemaker, S., Chapman, G., Ganion, J., Lehman, P., Singh, P., Patterson, J., Piña, F., and Bohan, D. (2019). “Demonstrating a Secure, Reliable, Low-Carbon Community Microgrid at the Blue Lake Rancheria California Energy Commission Month Year.

NJ Geographic Information Network | Geocoding (2022). “NJ Geographic Information Network | Geocoding, <njgin.nj.gov/njgin/edata/geocoding/index.html>.

OE-417 Form (2020). “OE-417 Form, <www.oe.netl.doe.gov/OE417/Form/Home.aspx>.

Ong, S., Denholm, P., and Clark, N. (2012). “Grid Parity for Residential Photovoltaics in the United States: Key Drivers and Sensitivities Preprint WREF 2012: GRID PARITY FOR RESIDENTIAL PHOTOVOLTAICS IN THE UNITED STATES: KEY DRIVERS AND SENSITIVITIES.

Ornstein, C. (2012). “Why Do Hospital Generators Keep Failing? — ProPublica, <https://www.propublica.org/article/why-do-hospitals-generators-keep-failing>.

Patel, S., Ceferino, L., Liu, C., Kiremidjian, A., and Rajagopal, R. (2021). “The disaster resilience value of shared rooftop solar systems in residential communities.” *Earthquake Spectra*, 37(4), 2638–2661.

Phillips, J. A., Wallace, K. E., Kudo, T. Y., and Eto, J. H. (2016). “Onsite and Electric Backup Capabilities at Critical Infrastructure Facilities in the United States.

Ramirez, R. (2022). “This 100% solar community endured Hurricane Ian with no loss of power and minimal damage | CNN, <https://www.cnn.com/2022/10/02/us/solar-babcock-ranch-florida-hurricane-ian-climate/index.html>.

Redweik, P., Catita, C., and Brito, M. (2013). “Solar energy potential on roofs and facades in an urban landscape.” *Solar Energy*, 97, 332–341.

Sengupta, M., Xie, Y., Lopez, A., Habte, A., Maclaurin, G., and Shelby, J. (2018). “The National Solar Radiation Data Base (NSRDB).” *Renewable and Sustainable Energy Reviews*, 89, 51–60.

Shashaani, S., Guikema, S. D., Zhai, C., Pino, J. V., and Quiring, S. M. (2018). “Multi-Stage Prediction for Zero-Inflated Hurricane Induced Power Outages.” *IEEE Access*, 6, 62432–62449.

Sheppard, D. and DiSavino, S. (2012). “Superstorm Sandy cuts power to 8.1 million homes | Reuters, <https://www.reuters.com/article/us-storm-sandy-powercuts/superstorm-sandy-cuts-power-to-8-1-million-homes-idUSBRE89T10G20121030> (10).

Smith, A. B. (2020). “2010-2019: A landmark decade of U.S. billion-dollar weather and climate disasters.

Squitieri, B. J. and Gallus, W. A. (2022). “On the Changes in Convection-Allowing WRF Forecasts of MCS Evolution due to Decreases in Model Horizontal and Vertical Grid Spacing. Part I: Changes in Cold Pool Evolution.

The White House (2021). “Federal Sustainability Plan Catalyzing America’s Clean Energy Industries and Jobs.

Watson, E. B. (2020). “Wind Conditions With Increased Solar and Wind Power Generation.” *Ieee Transactions on Power Systems*, 35(2), 929–937.

Zaveri, M. and Shanahan, E. (2020). “2.5 Million Lose Power and One Is Killed as Isaias Batters N.Y. Area, <https://www.nytimes.com/2020/08/04/nyregion/isaias-ny.html>.