

# Weather-Grid Impact Model: Gas-Fired Generators Under Extreme Winter Weather

**Presenter: Anamika Dubey**  
**Huie-Rogers Endowed Chair**  
**Associate Professor of Electrical Engineering**  
**Washington State University (WSU), Pullman**  
**Co-director WSU-PNNL Advanced Grid Institute (AGI)**  
**Research Scientist, Pacific Northwest National Lab (PNNL)**

Email: [anamika.dubey@wsu.edu](mailto:anamika.dubey@wsu.edu)  
Website: [anamika-dubey.github.io](https://anamika-dubey.github.io)



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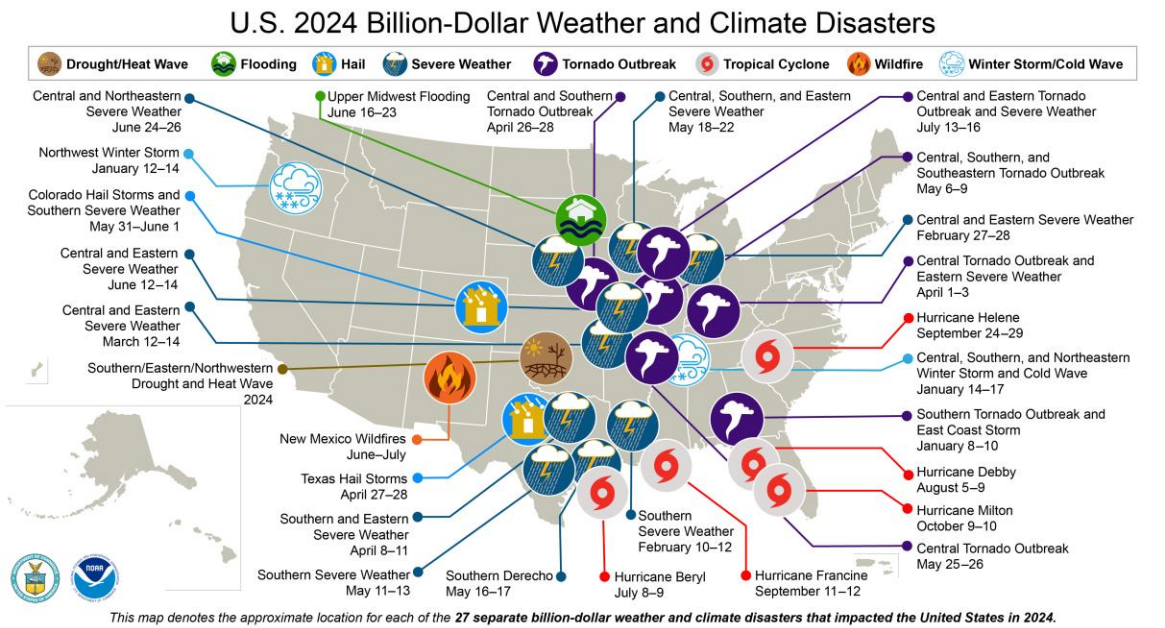


*NSF SAI Award ## 2324544*

# Billion-Dollar Disasters in the U.S.

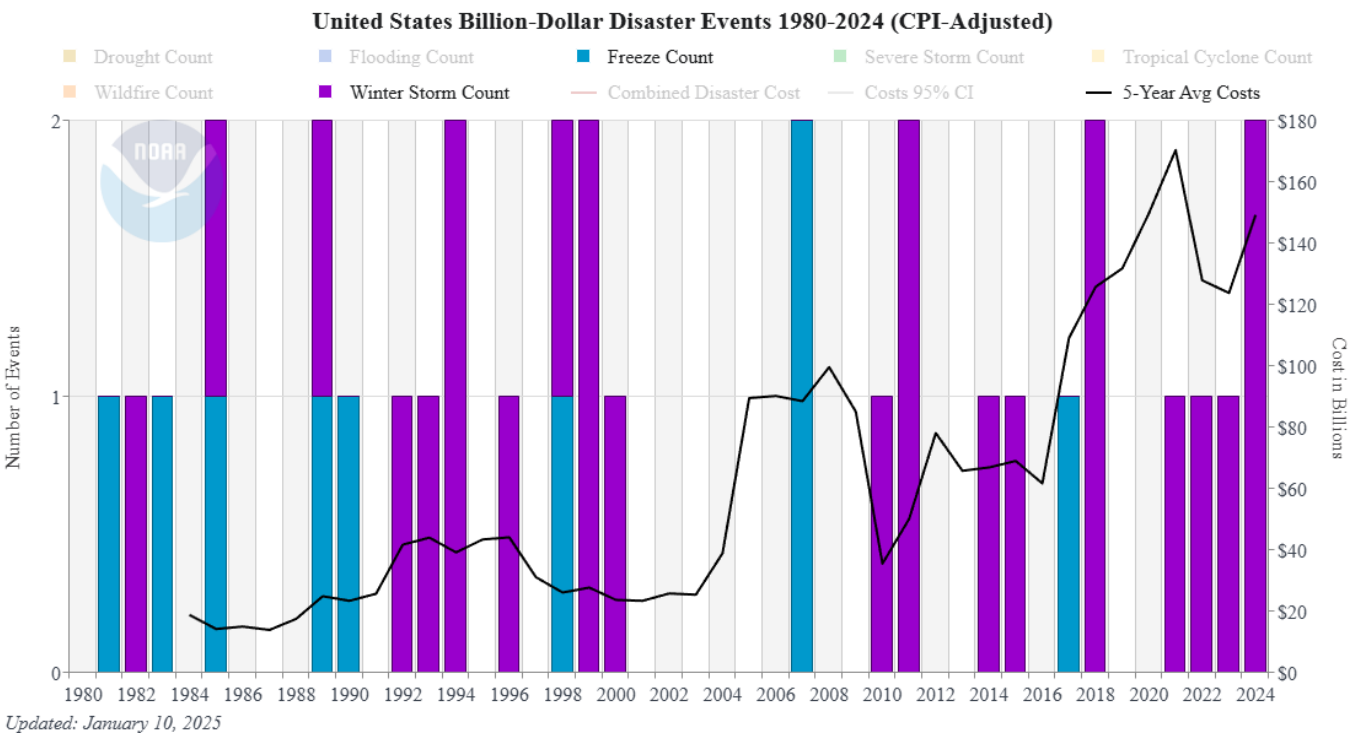
More than \$1.4 trillion economic loss due to weather-related events in the past decade<sup>1</sup>

27 separate billion-dollar weather-related disasters in 2022



| Disaster Type | Events | Events/Year | Percent Frequency | Total Costs | Percent of Total Costs | Cost/Event | Cost/Year | Deaths | Deaths/Year |
|---------------|--------|-------------|-------------------|-------------|------------------------|------------|-----------|--------|-------------|
| Freeze        | 9      | 0.2         | 2.2%              | \$37.4B     | 1.3%                   | \$4.2B     | \$0.8B    | 162    | 4           |
| Winter Storm  | 24     | 0.5         | 6.0%              | \$104.2B    | 3.6%                   | \$4.3B     | \$2.3B    | 1,463  | 33          |

Winter storms and freeze event alone cost \$141.6B since 1980

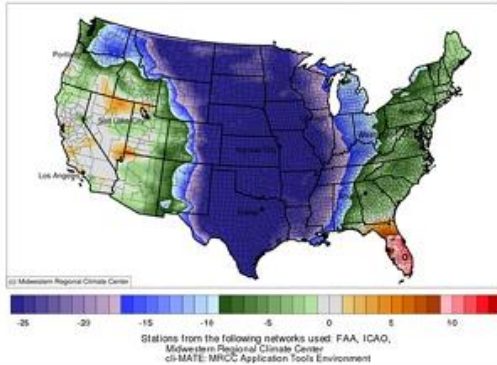


1. Billion-Dollar Weather and Climate Disasters, Jan 19, 2024 [Online]. Available at: <https://www.ncdc.noaa.gov/billions/>

# Past Winter Storms: Temperature Deviation and Impacts

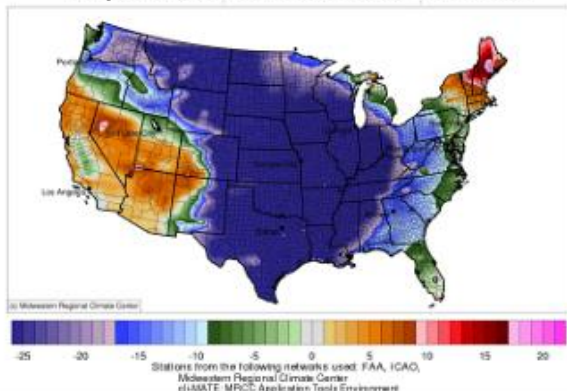
## WINTER STORM URI FEBRUARY 12-18, 2021

Average Temperature:  
Departure from 30-Year Normal

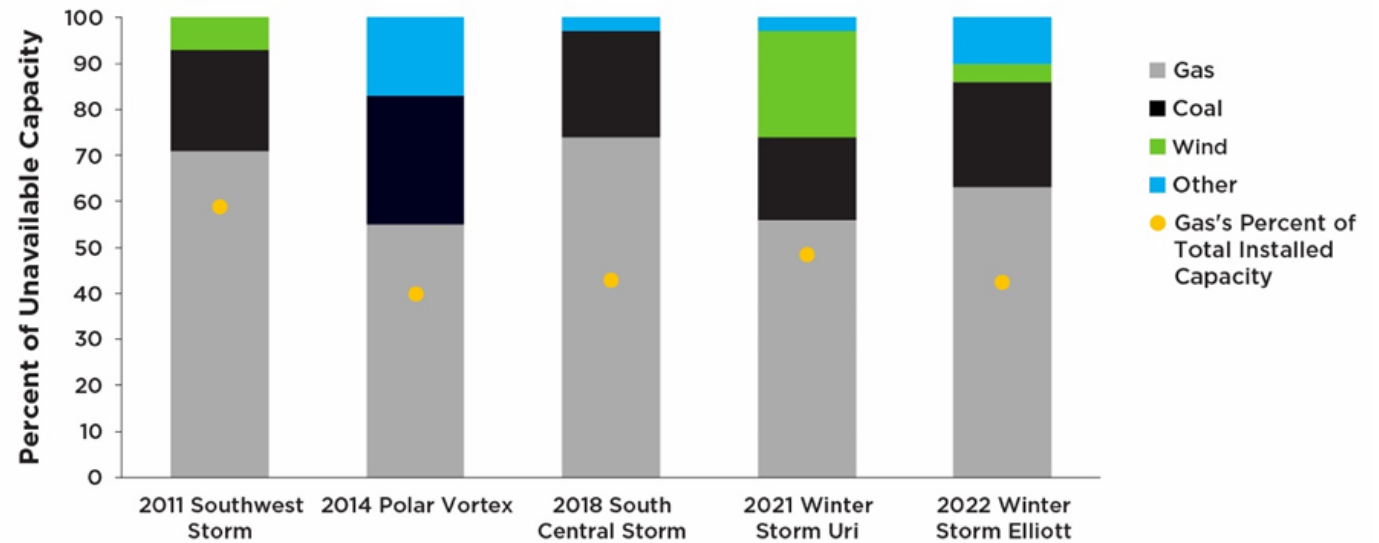


## WINTER STORM ELLIOTT DECEMBER 23, 2022

Average Temperature:  
Departure from 30-Year Normal



## Generation Failures by Fuel Type During Five Extreme Winter Storms<sup>3</sup>



Both winter storms Uri and Elliott imposed exceptionally low temperatures to a broad area of the country, resulting several power plant failures.<sup>1,2</sup>

1. "Overview of Winter Storm Elliott December 23, Maximum Generation Event" [Online]. Available: <https://cdn.misoenergy.org/20230117%20RSC%20Item%2005%20Winter%20Storm%20Elliott%20Preliminary%20Report627535.pdf>
2. A. Paul, "How Transmission—Not Gas—Will Bolster Winter Grid Reliability: A Look at MISO South" (2025). [Online]. Available: <https://blog.ucsusa.org/paul-arbaje/how-transmission-not-gas-will-bolster-winter-grid-reliability-a-look-at-miso-south/>
3. "Gas Malfunction". [Online] Available: [https://www.ucsusa.org/sites/default/files/2024-01/Gas%20Malfunction\\_brief\\_1.8.pdf](https://www.ucsusa.org/sites/default/files/2024-01/Gas%20Malfunction_brief_1.8.pdf)

# Past Winter Storms: Temperature Deviation and Impacts

| Event Name                       | Period                      | Event Area                                                                                                                   | Deviation from Average Daily Temperature | Unavailable Generation Due to Cold Weather, at Worst Point (MW) | Peak Magnitude of Rolling Blackout (MW) |
|----------------------------------|-----------------------------|------------------------------------------------------------------------------------------------------------------------------|------------------------------------------|-----------------------------------------------------------------|-----------------------------------------|
| Groundhog's Day Blizzard of 2011 | First week of February 2011 | Texas and Southwest U.S. (ERCOT, SPP, WECC)                                                                                  | 17° to 36° below average                 | 14,702                                                          | 5,412                                   |
| Polar Vortex 2014                | Early January of 2014       | Midwest, South-Central, East Coast regions (MISO, PJM, NYISO, ISO-NE, TVA, VACS RC, Southeastern RC, SPP, ERCOT, FRCC)       | 20° to 30° below average                 | 9,800                                                           | 300                                     |
| 2018 Cold Snap                   | Jan 15-19, 2018             | South-Central U.S. (MISO, TVA, SPP, Southeastern RC)                                                                         | 12° to 28° below average                 | 15,600                                                          | 0                                       |
| 2021 Winter Storm Uri            | Feb 8-13, 2021              | Texas and South-Central U.S. (ERCOT, MISO, SPP)                                                                              | 40° to 50° below average                 | 65,622                                                          | 23,418                                  |
| 2022 Winter Storm Elliot         | Dec 21- 26, 2022            | Central, Midwest, and large parts of Southeast and Northeast U.S. (PJM, MISO, SPP, and grid operators in the Southeast U.S.) | 20° to 30° below average                 | 90,500                                                          | 5,459                                   |

Percentage of total outage or derates (by MW loss) during past major events for different fuel type

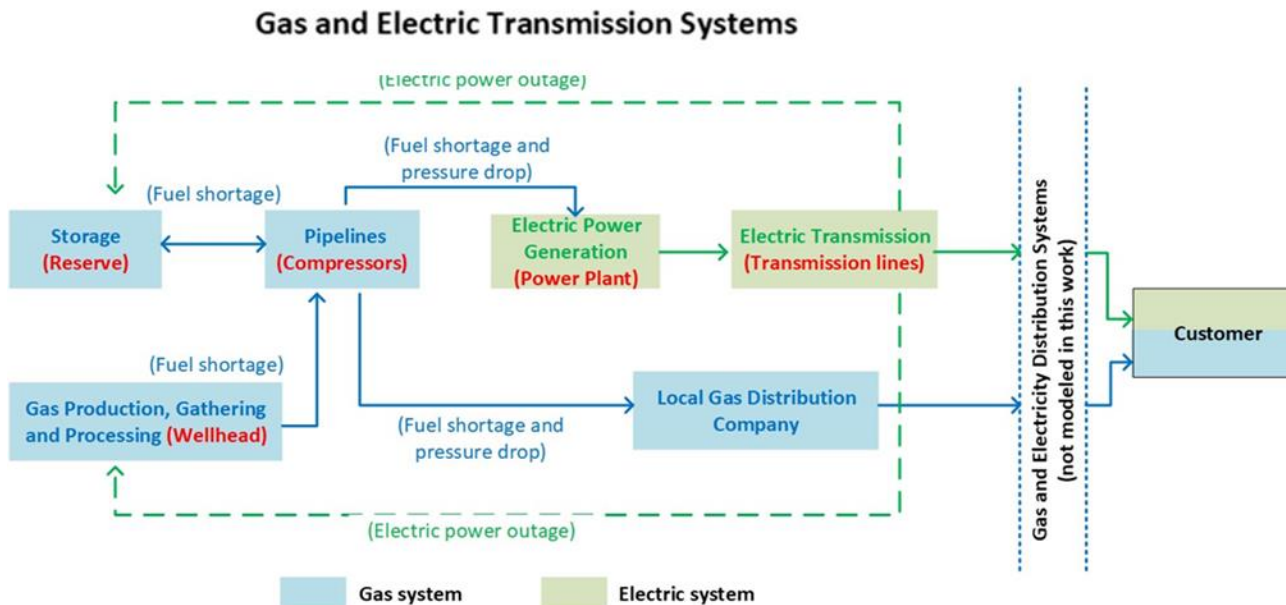
| Plant Type \ Year | 2014 | 2021 | 2022 |
|-------------------|------|------|------|
| Gas               | 55%  | 56%  | 63%  |
| Coal              | 28%  | 18%  | 23%  |
| Oil               | 6%   | -    | 4%   |
| Nuclear           | 5%   | 1%   | 1%   |
| Solar             | -    | 1%   | 1%   |
| Wind              |      | 23%  | 1%   |
| Other             | 6%   | 1%   | 1%   |

- FERC, NERC and regional entity staff report October 2023: Inquiry into bulk-power system operations during December 2022 winter storm Elliott. [Online]. Available: <https://www.ferc.gov/news-events/news/ferc-nerc-release-final-report-lessons-winter-storm-elliott>
- Winter storm Elliott event analysis and recommendation report. [On-line]. Available: <https://pjm.com/-/media/library/reports-notices/special-reports/2023/20230717-winter-storm-elliott-event-analysis-and-recommendation-report.ashx>
- FERC-NERC-regional entity staff report: The February 2021 cold weather outages in Texas and the south-central united states. [Online]. Available: <https://www.ferc.gov/media/february-2021-cold-weather-outages-texas-and-south-central-united-states-ferc-nerc-and>
- Report on outages and curtailments during the southwest cold weather event of February 1-5, 2011. [Online]. Available: <https://www.ferc.gov/sites/default/files/2020-04/08-16-11-report.pdf>
- 2019 FERC and NERC staff report: The south-central united states cold weather bulk electric system event of January 17, 2018. [Online]. Available: [https://www.nerc.com/pa/rmm/ea/Documents/South\\_Central\\_Cold\\_Weather\\_Event\\_FERC-NERC-Report\\_20190718.pdf](https://www.nerc.com/pa/rmm/ea/Documents/South_Central_Cold_Weather_Event_FERC-NERC-Report_20190718.pdf)
- “Gas Malfunction”. [Online] Available: [https://www.ucsusa.org/sites/default/files/2024-01/Gas%20Malfunction\\_brief\\_1.8.pdf](https://www.ucsusa.org/sites/default/files/2024-01/Gas%20Malfunction_brief_1.8.pdf)
- The timeline and events of the February 2021 Texas electric grid blackouts [Online]. Available: <https://energy.utexas.edu/sites/default/files/UTAustin%20%282021%29%20EventsFebruary2021TexasBlackout%2020210714.pdf>

# Interdependencies between Gas & Electric Grid

- The United States has significantly increased its dependence on the natural gas for electricity generation in past 40 years.
- Decarbonization - More electricity usage for space heating instead of gas.

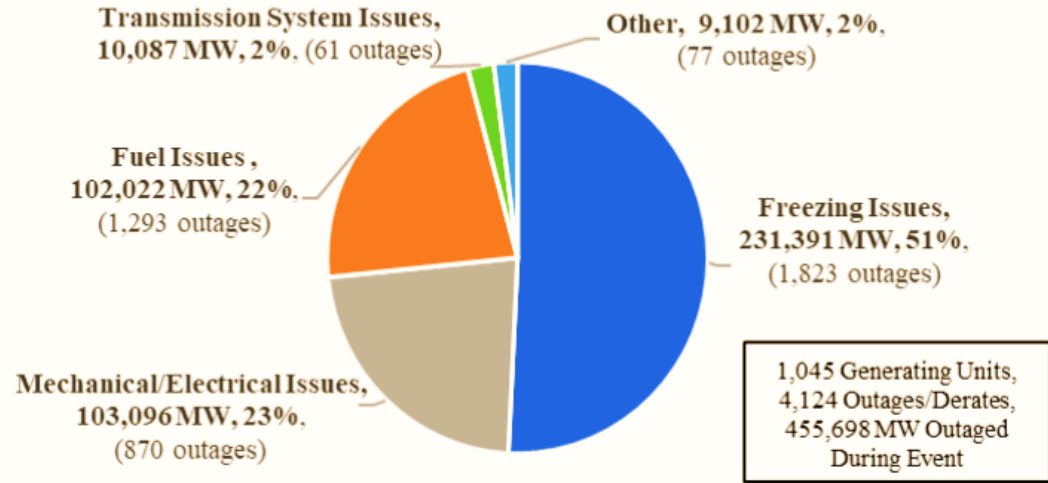
Gas-electric systems, vulnerable components, and interdependencies;  
blue and green arrows indicate flow of natural gas and electricity



| Grid     | Components   | Issues                                                                                                           |
|----------|--------------|------------------------------------------------------------------------------------------------------------------|
| Electric | Generation   | Freezing issue (Frozen equipment, pipeline, low temperature limit, etc.), Fuel issue (Reduced supply, high wind) |
|          | Transmission | Freezing issue                                                                                                   |
| Gas      | Production   | Freezing issue (Wellhead freeze, equipment freezing )                                                            |
|          | Processing   | Freezing issue (Producer freeze and pressure issues)<br>Fuel issue (Reduction in receipt)<br>Power outage        |
|          | Distribution | Freezing issue (Pipeline freeze and pressure issues)<br>Fuel issue (Reduction in receipt)                        |

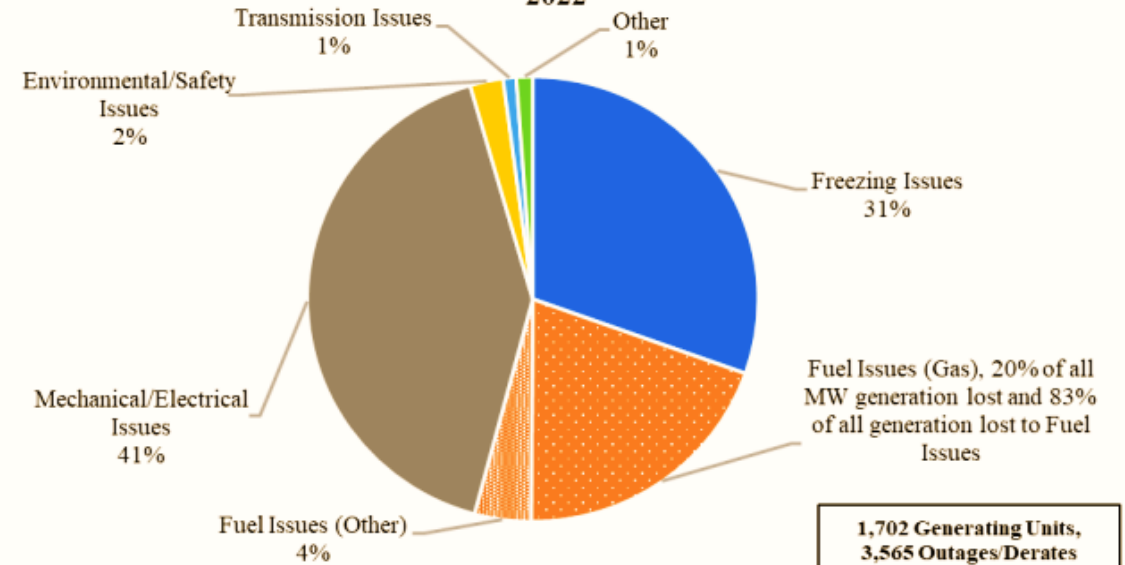
# Major Causes behind Generation Failure during Extreme Winter Conditions

**Total MW Loss of Incremental Unplanned Generator Outages, Derates, and Start-Up Failures by Cause, Total Event Area**



Winter Storm Uri

**Total MW Loss of Incremental Unplanned Generator Outages, Derates, and Start-Up Failures by Cause, Total Event Area, December 21-26, 2022**



Winter Storm Elliott

- FERC, NERC and regional entity staff report October 2023: Inquiry into bulk-power system operations during December 2022 winter storm Elliott. [Online]. Available: <https://www.ferc.gov/news-events/news/ferc-nerc-release-final-report-lessons-winter-storm-elliott>
- FERC-NERC-regional entity staff report: The February 2021 cold weather outages in Texas and the south-central United States. [Online]. Available: <https://www.ferc.gov/media/february-2021-cold-weather-outages-texas-and-south-central-united-states-ferc-nerc-and>

# Key Research Questions

Understanding and modeling of component-level damage within the gas-grid infrastructure due to extreme cold weather events:

1. How do extreme winter weather conditions affect the operational capacity and reliability of gas-fired generators? What are the vulnerable components and critical interdependencies between gas-grid infrastructure during an extreme winter event?
2. What are the key factors (e.g., temperature, demand, generator type) influencing generator performance and outage probabilities during extreme cold events?
3. Which modeling approach best captures the relationship between weather conditions and generator performance, ensuring accurate and reliable predictions?
4. How do different modeling cases perform in terms of accuracy, predictive uncertainty, and resilience insights? Which case provides the most balanced and reliable results?
5. How can the findings of this study inform grid operators, planners, and policymakers to enhance grid preparedness and mitigate risks during extreme winter weather?

# Existing Literature

- Sequential Monte Carlo Simulation for Weather-Dependent Failures<sup>1</sup>
  - Only considers wind-based fragility model and its impact on the infrastructure resilience.
- Two-stage Stochastic Programming Models for Generator Winterization<sup>2,3</sup>
  - Winter storms severity is based on the outage magnitudes, does not incorporate weather parameters.
- Outage Prediction Models for Snow and Ice Storms on distribution grid<sup>4</sup>
  - Weather model is based on snow density and freezing rain, does not focus on individual generator failure.
- Quantifying Temperature Dependence of Generator Failures<sup>5</sup>
  - Examines generator failures broadly across different weather conditions but does not focus exclusively on extreme winter events.

1. M. Panteli and P. Mancarella, "Modeling and Evaluating the Resilience of Critical Electrical Power Infrastructure to Extreme Weather Events," in IEEE Systems Journal, vol. 11, no. 3, pp. 1733-1742, Sept. 2017.

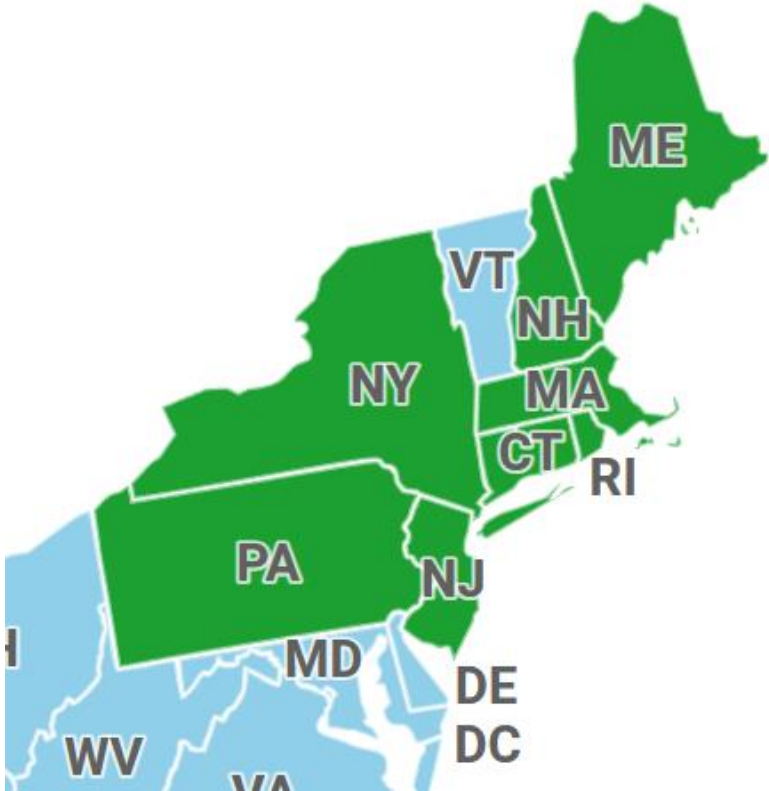
2. Bilir, Banş, et al. "Enhancing power grid resilience to winter storms via generator winterization with equity considerations." Sustainable Cities and Society 114 (2024): 105736.

3. B. Austgen, M. Garcia, B. Pierre, J. Hasenbein and E. Kutanoglu, "Winter Storm Scenario Generation for Power Grids Based on Historical Generator Outages," 2022 IEEE/PES Transmission and Distribution Conference and Exposition (T&D), New Orleans, LA, USA, 2022, pp. 1-5.

4. Cerrai, Diego, et al. "Outage prediction models for snow and ice storms." Sustainable Energy, Grids and Networks 21 (2020): 100294.

5. Murphy, S., Sowell, F., & Apt, J. (2019). A time-dependent model of generator failures and recoveries captures correlated events and quantifies temperature dependence. *Applied energy*, 253, 113513.

# Study Region



**Study Region (Green)**

- The Northeastern U.S. will serve as a case study in our analysis.
- The region experienced several extreme cold weather events that placed coincident stress on gas and electric power infrastructures.
- It contains 8 states:

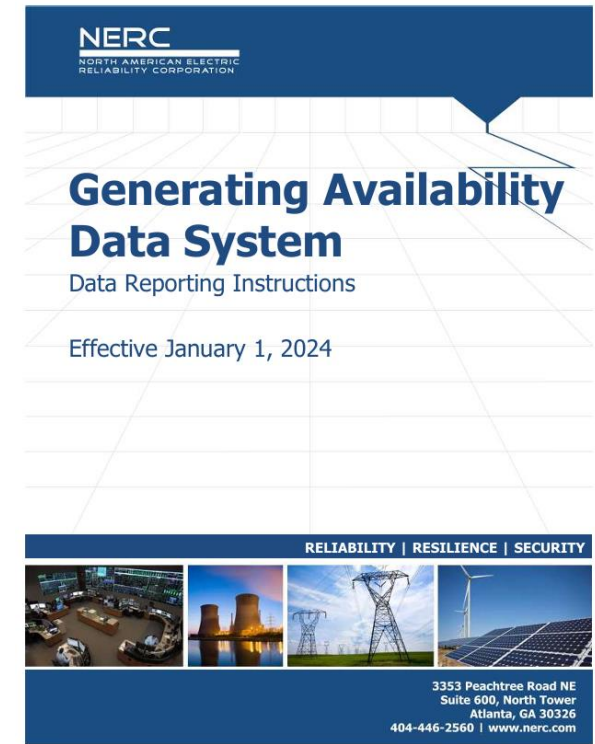
$$S = \{CT, MA, ME, NH, NJ, NY, PA, RI\}$$

# Data Collection: GADS Data

## Generator Outage/Derating Dataset:

Generating Availability Data System (GADS)<sup>1</sup> by NERC

- GADS maintains complete operating histories on more than 8,000 generating units, representing over 90% of the installed generating capacity of the United States and Canada.<sup>2</sup>
- As of January 1, 2013, GADS became a mandatory industry program for conventional generating units 20 MW and larger.<sup>2</sup>
- GADS data various information including:
  - Generator's location in terms of state and NERC region
  - Type of prime mover and fuel
  - Outage / derating event information: generator unit number, start-end datetime, event cause, type of outage (planned/unplanned/etc.), the percentage of the Net Available Capacity ( $NAC_{perc}$ ) during event period.
- Outage and derating scenarios are classified based on GADS provided data,  $NAC_{perc}$ :
  - **Outage:**  $NAC_{perc} = 0$
  - **Derating (Reduced output) :**  $0 < NAC_{perc} < 1$
- For each outage/derating event, GADS data provide a cause code of that event



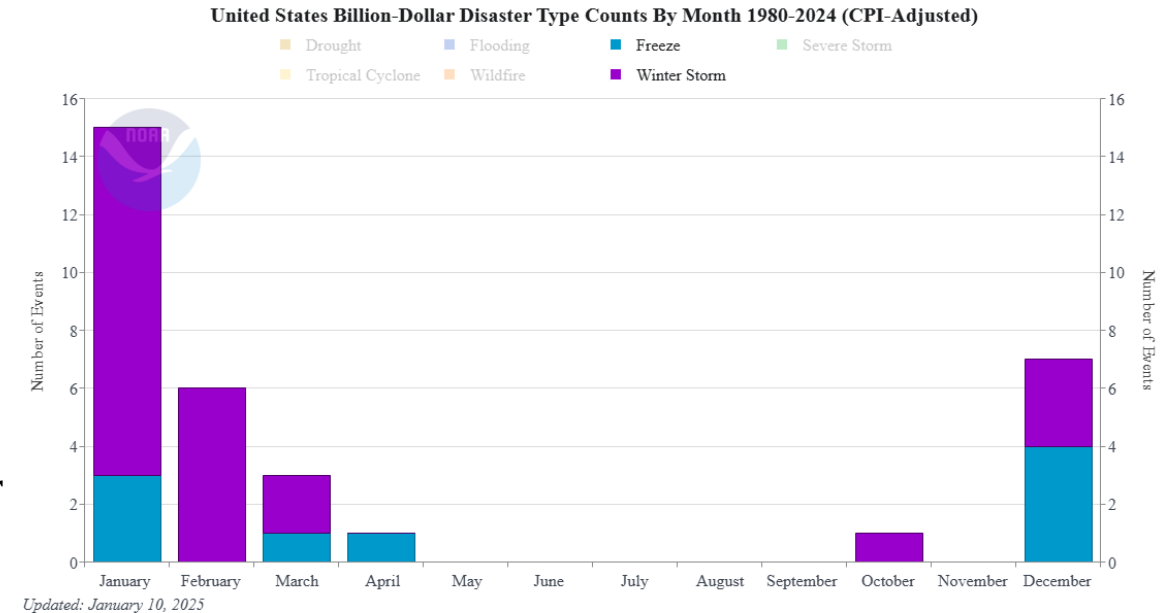
| Units                                                                                                                                                                                                                                                                                 |           | Event Classifications |          |                  |                |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------|-----------------------|----------|------------------|----------------|
| Types                                                                                                                                                                                                                                                                                 | Size (MW) | Outage                | Derates  | Reserve Shutdown | Non-Curtailing |
| Fossil (Steam)                                                                                                                                                                                                                                                                        | 20+       | Required              | Required | Required         | Voluntary      |
| Nuclear                                                                                                                                                                                                                                                                               | 20+       | Required              | Required | Required         | Voluntary      |
| Hydro & Pumped Storage (with automatic data recording equipment)                                                                                                                                                                                                                      | 20+       | Required              | Required | Required         | Voluntary      |
| Hydro & Pumped Storage (without automatic data recording equipment)                                                                                                                                                                                                                   | 20+       | Required              | Required | Voluntary        | Voluntary      |
| Gas Turbines/Jet Engines                                                                                                                                                                                                                                                              | 20+       | Required              | Required | Required         | Voluntary      |
| Combined Cycle/Co-generators                                                                                                                                                                                                                                                          | 20+       | Required              | Required | Required         | Voluntary      |
| Internal Combustion/Reciprocating Engines                                                                                                                                                                                                                                             | 20+       | Required              | Required | Required         | Voluntary      |
| Fluidized Bed Combustion                                                                                                                                                                                                                                                              | 20+       | Required              | Required | Required         | Voluntary      |
| Miscellaneous – including multi-boiler/multi-turbine, geothermal, other miscellaneous conventional generating units (such as variable fuel – biomass, landfill gases, etc.) used to generate electric power for the grid and similar in design and operation as the units shown above | 20+       | Required              | Required | Required         | Voluntary      |

1. “Generating Availability Data System (GADS).” [Online]. Available: [https://www.nerc.com/pa/RAPA/gads/Pages/GeneratingAvailabilityDataSystem-\(GADS\).aspx](https://www.nerc.com/pa/RAPA/gads/Pages/GeneratingAvailabilityDataSystem-(GADS).aspx)

2. “Generating Availability Data System: Data Reporting Instructions”. [Online]. Available: <https://www.nerc.com/pa/RAPA/gads/pages/data%20reporting%20instructions.aspx>

# Data Collection: GADS Data

- The study focuses on the Northeastern U.S. hence we extract the GADS data for the following 8 states only:  
Study states:  $S = \{CT, MA, ME, NH, NJ, NY, PA, RI\}$
- GADS became mandatory since 2013; in this study we utilize the GADS data from 2013 to 2022.
- Winter months (Dec, Jan, Feb) are selected to capture only winter weather related extreme weather events.\*
- For each event data, GADS provides an event type. For this study only unplanned / forced outage or derating events and startup failure events are considered. Planned outages, maintenance outage, reserve shutdown are not considered.
- We only select the gas-fired power plants for this study.



\*From NOAA, it is observed that major extreme winter events observed during December, January and February months.

# Data Collection: GADS Data

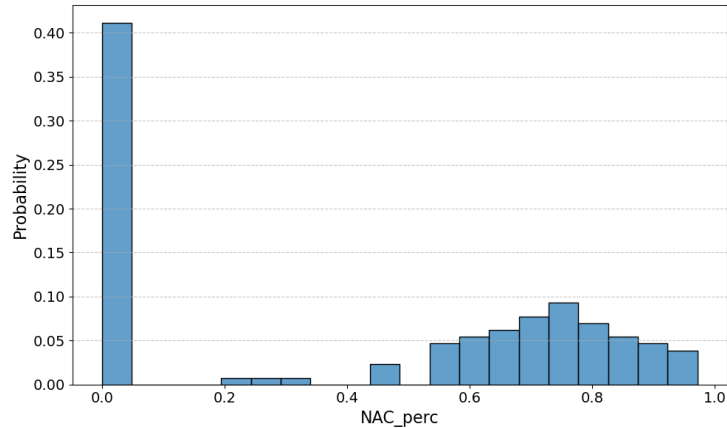
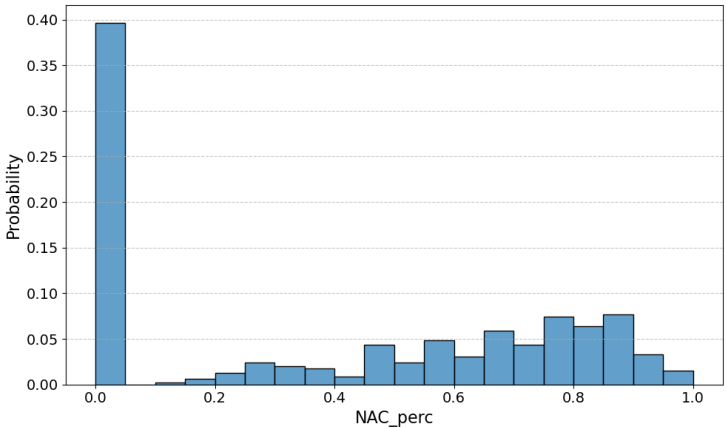
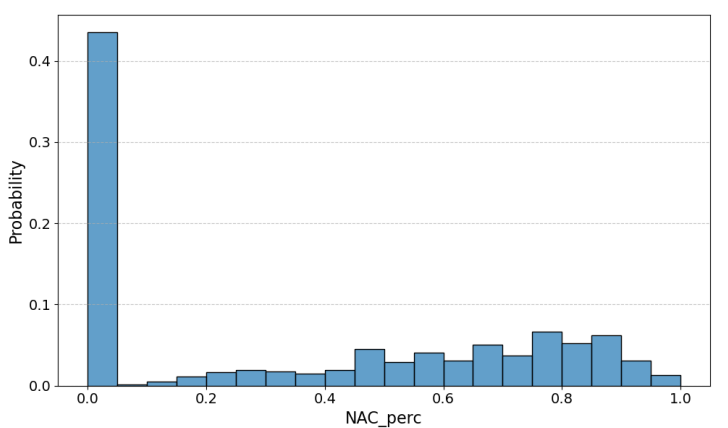
- Each of the GADS event data is associated with a cause code
- Three variation of dataset are filtered based on event cause code<sup>1</sup> selection:
  - ***C<sub>Storm</sub>*** : Events tagged with external cause code 9036: “Storms (ice, snow, etc)”
  - ***C<sub>Storm+Fuel</sub>***: Events tagged with external cause code 9036: “Storms (ice, snow, etc)”, and 9130: “Lack of fuel: Physical failures of fuel supply or delivery/transportation of fuel”
  - ***C<sub>Storm+Fuel+Equip</sub>***: Some equipment related internal cause codes are selected along with previously selected external cause codes. These equipment are prone to be affected by extreme low temperature as observed in previous official reports and GADS data analysis during past winter storms period.

1. “Generating Availability Data System: Data Reporting Instructions”. [Online]. Available: <https://www.nerc.com/pa/RAPA/gads/pages/data%20reporting%20instructions.aspx>  
2. Billion-Dollar Weather and Climate Disasters, Jan 19, 2024 [Online]. Available at: <https://www.ncdc.noaa.gov/billions/>

| Dataset                             | Selected Cause Code <sup>1</sup>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|-------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>C<sub>Storm</sub></i>            | <ul style="list-style-type: none"><li>• 9036: Storms (ice, snow, etc)</li></ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| <i>C<sub>Storm+Fuel</sub></i>       | <ul style="list-style-type: none"><li>• 9036: Storms (ice, snow, etc)</li><li>• 9130: Lack of fuel: Physical failures of fuel supply or delivery/transportation of fuel</li></ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
| <i>C<sub>Storm+Fuel+Equip</sub></i> | <ul style="list-style-type: none"><li>• 9036: Storms (ice, snow, etc)</li><li>• 9130: Lack of fuel: Physical failures of fuel supply or delivery/transportation of fuel</li><li>• 5041: Fuel piping and valves</li><li>• 3410: Feedwater pump</li><li>• 680: Feedwater valves (not feedwater regulating valve)</li><li>• 670: Feedwater piping downstream of feedwater regulating valve</li><li>• 9137: Ground water or other water supply problems</li><li>• 3416: Other feedwater pump problems</li><li>• 3499: Other feedwater system problems</li><li>• 3431: Other feedwater valves</li><li>• 9320: Other miscellaneous external problems</li><li>• 1700: Feedwater controls (report local controls - feedwater pump, feedwater regulator valve, etc., - with component or system)</li><li>• 3250: Circulating water system instruments and controls</li><li>• 3230: Circulating water valves</li><li>• 3220: Circulating water piping</li></ul> |

# Data Collection: GADS Data

## Histogram of the GADS dataset used in the study

| $C_{Storm}$                                                                                                                                                                      | $C_{Storm+Fuel}$                                                                                                                                                 | $C_{Storm+Fuel+Equip}$                                                                                                                                           |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                                                                                                  |                                                                                |                                                                               |
| <p>Total Event : 131</p> <p>Outage (Zero) Event : 54</p> <p>Derating (Non-Zero) Event : 77</p> <p>Outage Event Percentage : 41.22%</p> <p>Derating Event Percentage : 58.78%</p> | <p>Total Event : 457</p> <p>Outage Event : 181</p> <p>Derating Event : 276</p> <p>Outage Event Percentage : 39.61%</p> <p>Derating Event Percentage : 60.39%</p> | <p>Total Event : 614</p> <p>Outage Event : 267</p> <p>Derating Event : 347</p> <p>Outage Event Percentage : 43.49%</p> <p>Derating Event Percentage : 56.51%</p> |

- “Generating Availability Data System (GADS).” [Online]. Available: [https://www.nerc.com/pa/RAPA/gads/Pages/GeneratingAvailabilityDataSystem-\(GADS\).aspx](https://www.nerc.com/pa/RAPA/gads/Pages/GeneratingAvailabilityDataSystem-(GADS).aspx)
- “Generating Availability Data System: Data Reporting Instructions”. [Online]. Available: <https://www.nerc.com/pa/RAPA/gads/pages/data%20reporting%20instructions.aspx>

# Data Collection: Weather Data

## Temperature Dataset:

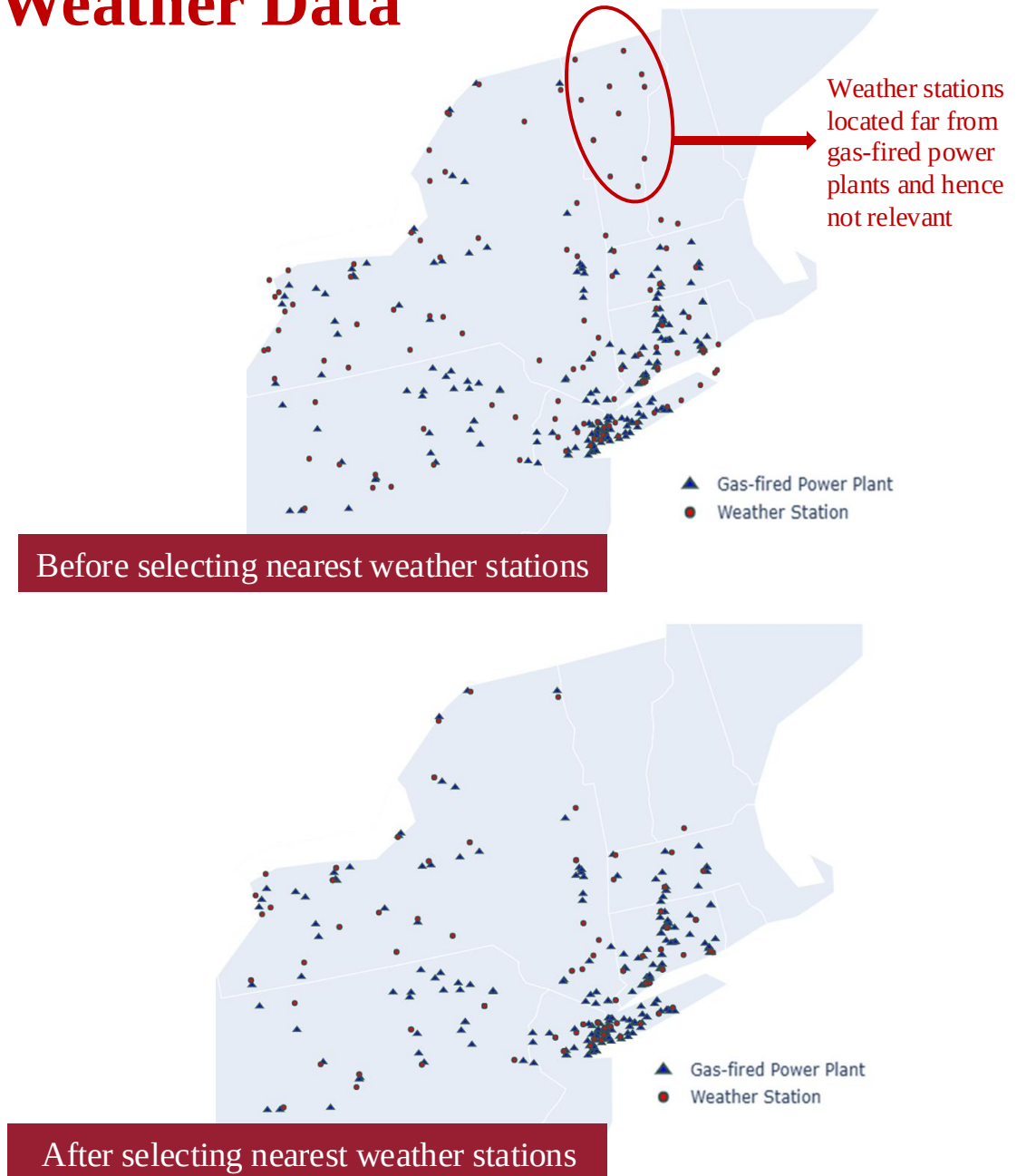
Hourly temperature data from NOAA's Integrated Surface Database (ISD)<sup>1</sup>

- GADS data does not disclose the exact location of power plants. It only provides the US state in which each plant is located
- To resolve this:
  - We match power plants (from eGRID<sup>2</sup>) to nearby weather stations (from ISD).
  - Then we filter weather stations to retain only those relevant to gas-fired plants in each state.
- This allows to consider only the relevant weather stations for temperature readings.

**For an event with duration  $E_{\Delta t}$  associated with a generator  $G$  located in a specific state  $S$ , we obtain the minimum temperature as follows:**

$$T = T_{min}^{G,S}(E_{\Delta t}) = \min(T(t) | t \in E_{\Delta t})$$

1. "Integrated Surface Dataset (Global)." [Online]. Available: <https://www.ncdc.noaa.gov/access/search/data-search/global-hourly>  
2. "Emissions & Generation Resource Integrated Database (eGRID) 2022." [Online]. Available: <https://www.epa.gov/egrid/download-data>



# Data Collection: Demand Data

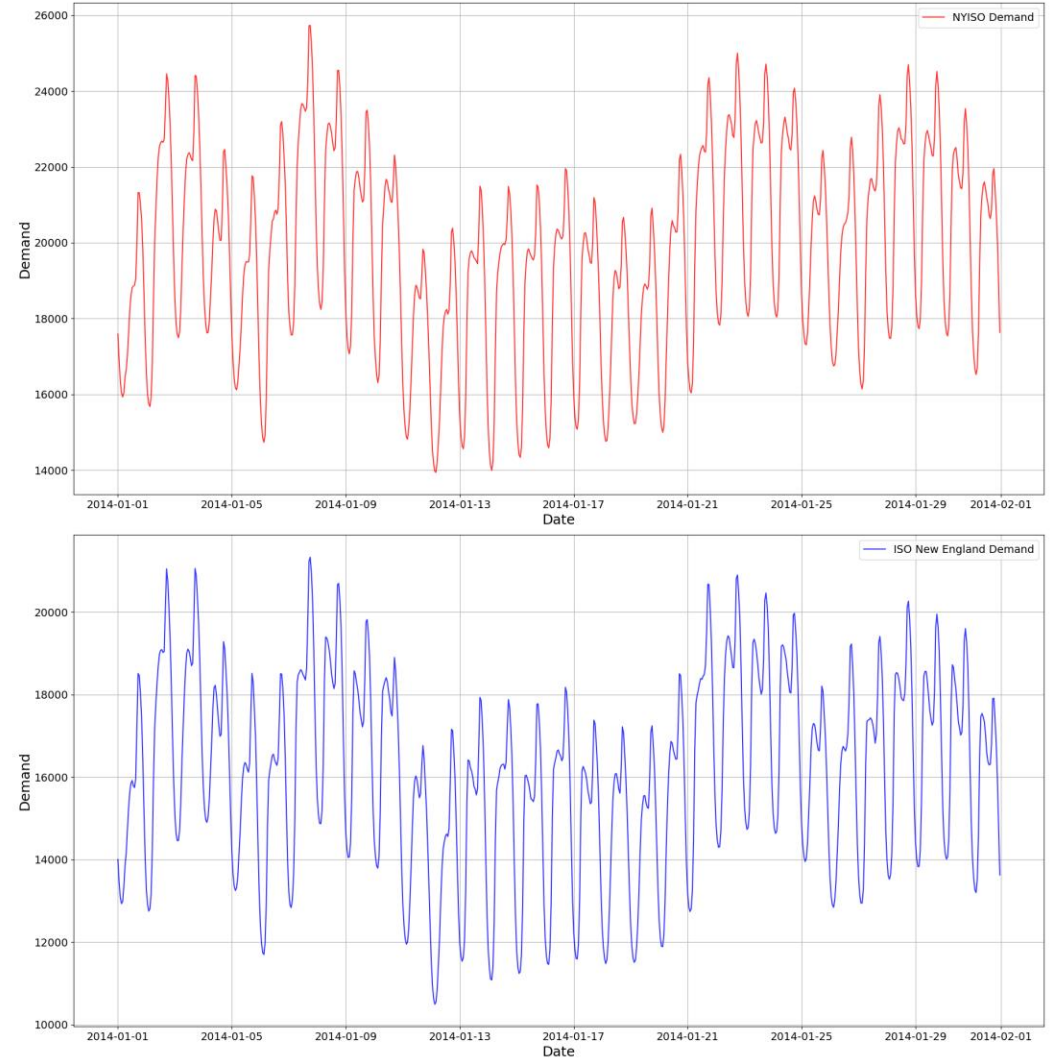
## Demand Dataset:

Hourly demand data from ISO New England<sup>1</sup> and NYISO<sup>2</sup>

- For NY,  $D(t)$  is from NYISO and for the rest of the state,  $D(t)$  is from ISO New England.
- We use normalized demand by dividing each demand with the max(demand).

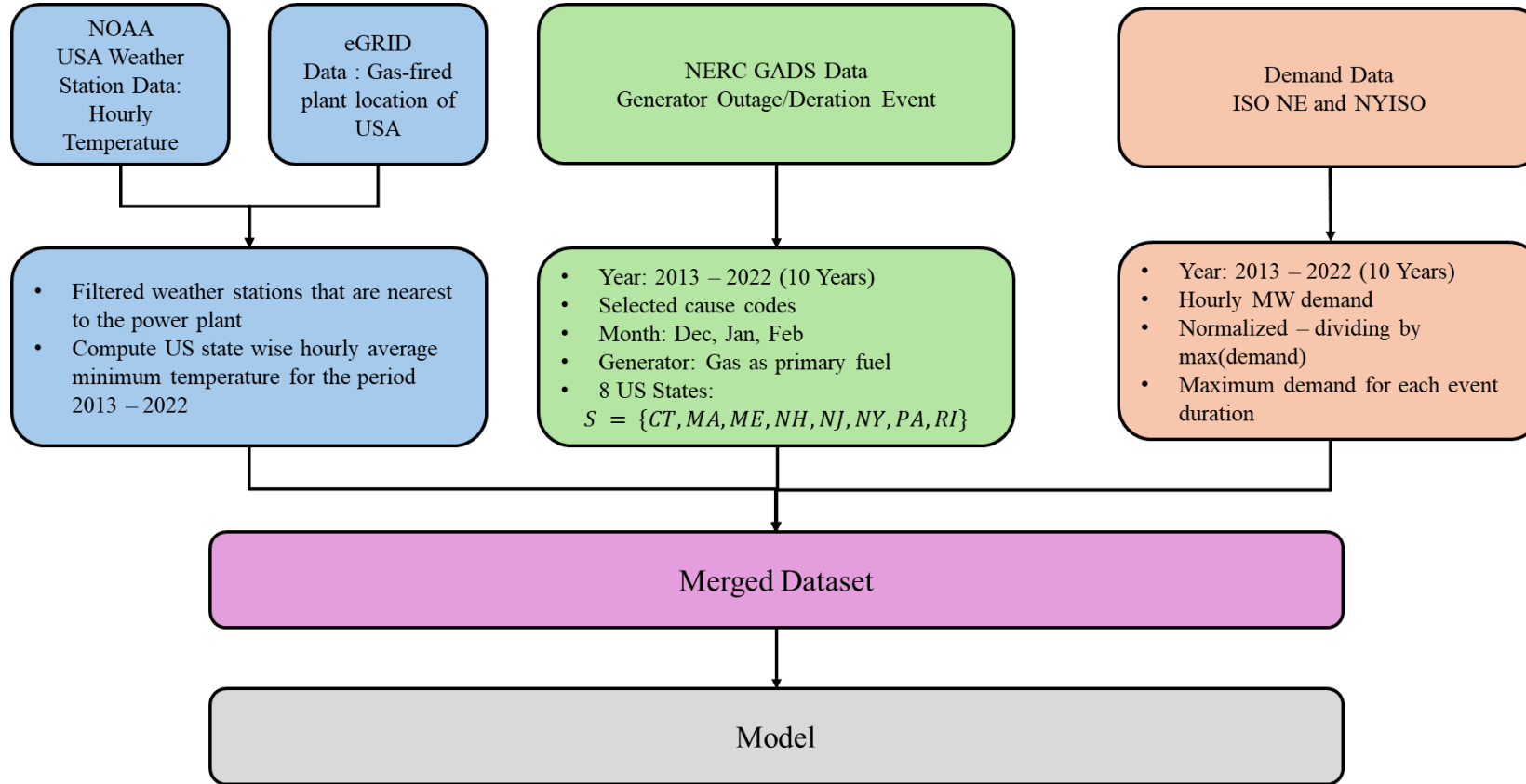
**For an event with duration  $E_{\Delta t}$  associated with a generator  $G$  located in a specific state  $S$ , we obtain the max demand as follows:**

$$D = D_{max}^{G,S}(E_{\Delta t}) = \max(D(t) | t \in E_{\Delta t})$$



1. “Energy, Load, and Demand Reports”, ISO New England. [Online]. Available: <https://www.iso-ne.com/isoexpress/web/reports/load-and-demand>  
2. “Load Data”, NYISO. [Online]. Available: <https://www.nyiso.com/load-data>

# Data Preprocessing

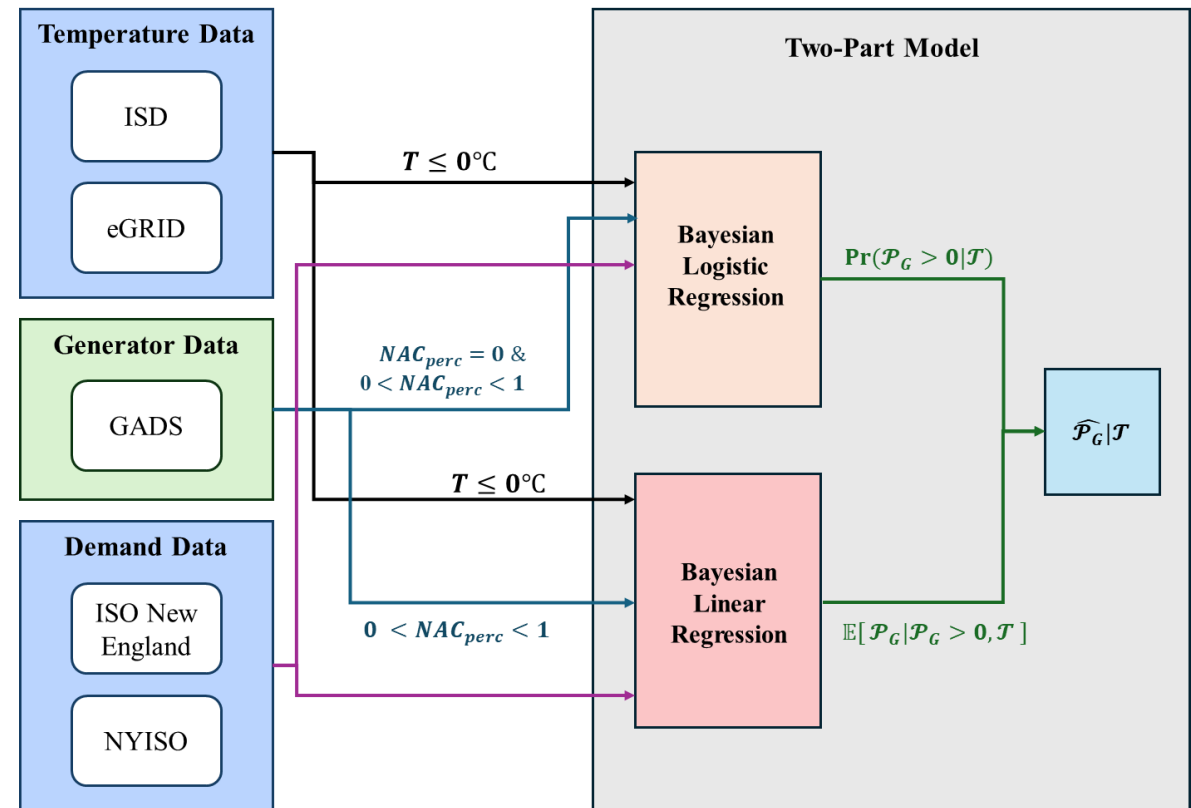


- This model predicts the gas-generator derated output given that an extreme winter event is observed as function of selected covariates.
- We selected the extreme winter events by selecting those events only that are happened during winter months, the temperature is 0°C or below during the event period and tagged under the previously mentioned cause code sets.

- “Generating Availability Data System (GADS).” [Online]. Available: [https://www.nerc.com/pa/RAPA/gads/Pages/GeneratingAvailabilityDataSystem-\(GADS\).aspx](https://www.nerc.com/pa/RAPA/gads/Pages/GeneratingAvailabilityDataSystem-(GADS).aspx)
- “Integrated Surface Dataset (Global).” [Online]. Available: <https://www.ncei.noaa.gov/access/search/data-search/global-hourly>
- “Emissions & Generation Resource Integrated Database (eGRID) 2022.” [Online]. Available: <https://www.epa.gov/egrid/download-data>
- “Energy, Load, and Demand Reports”, ISO New England. [Online]. Available: <https://www.iso-ne.com/isoexpress/web/reports/load-and-demand>
- “Load Data”, NYISO. [Online]. Available: <https://www.nyiso.com/load-data>

# Weather-Grid Impact Model: A Two-Part Bayesian Regression Model

- A two-part model to estimate the generator's net available capacity
- A two-part model is suitable for semi-continuous data.
- The model divides data into two parts: with and without zero observations
- Response variable is the generator's net available capacity, and predictors are Temperature,  $\mathcal{T}$ , and Demand,  $\mathcal{D}$
- Based on the predictor selection, we have three model choices:
  - $\mathcal{M}_{Temp}$  :  $\mathcal{T}$  as the only regressor
  - $\mathcal{M}_{Demand}$  :  $\mathcal{D}$  as the only regressor
  - $\mathcal{M}_{Temp+Demand}$  : Both  $\mathcal{T}$  and  $\mathcal{D}$  as the regressors
- **First part:** Bayesian Logistic regression - predicts the probability of outage or derating given that an extreme winter condition is observed
- **Second part:** Bayesian Linear regression – estimates the generator's derated net available capacity in case of non-outage (derating) scenarios only
- **Final output:** combined both regression model



# Weather-Grid Impact Model: A Two-Part Bayesian Regression Model

## Part 1: Bayesian Logistic Regression for Zero Inflation

$$\varphi(y) = \Pr(\mathcal{P}_G > 0|x) = F(x \cdot \delta)$$

- $\mathcal{P}_G$  = generator's output
- $x = [\mathcal{T}, \mathcal{D}]$  = regressor vector
- $\Pr(\mathcal{P}_G > 0|x)$  = probability of a non-zero output (i.e. derating event)
- $\delta = [\delta_0, \delta_{\mathcal{T}}, \delta_{\mathcal{D}}]$  = parameter vector;  $\delta_0$  is the intercept and  $\delta_{\mathcal{T}}, \delta_{\mathcal{D}}$  are the corresponding vector parameters for temperature and demand, respectively
- $F(x \cdot \delta) = \frac{1}{1+e^{-(\delta_0+\delta_{\mathcal{T}} \cdot \mathcal{T}+\delta_{\mathcal{D}} \cdot \mathcal{D})}}$  = logit function

## Part 2: Bayesian Linear Regression for Positive Derating

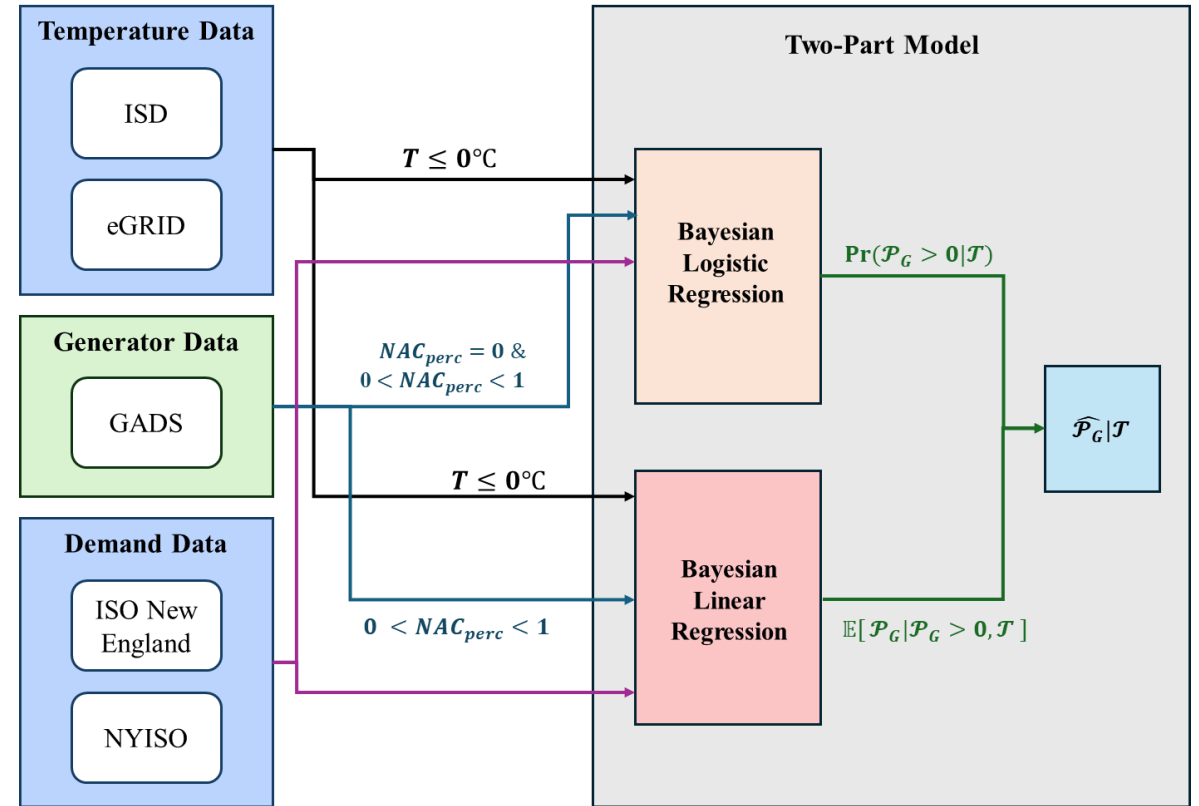
For the events where  $0 < \mathcal{P}_G < 1$  (indicating a derating event)

$$\mathbb{E}[\mathcal{P}_G | \mathcal{P}_G > 0, x] = x \cdot \gamma + \epsilon$$

- $\gamma = [\gamma_0, \gamma_{\mathcal{T}}, \gamma_{\mathcal{D}}]^T$  = parameter vector,  $\gamma_0$  is the intercept and  $\gamma_{\mathcal{T}}, \gamma_{\mathcal{D}}$  are the corresponding vector parameters for temperature and demand, respectively
- $\epsilon \sim \mathcal{N}(0, \sigma^2)$  = normally distributed error term

## Final Outcome (Law of Total Expectation)<sup>1</sup>:

$$\widehat{\mathcal{P}}_G|x = \Pr(\mathcal{P}_G > 0|x) \cdot \mathbb{E}[\mathcal{P}_G | \mathcal{P}_G > 0, x]$$



# Weather-Grid Impact Models

9 models based on the regressor and cause-code selection:

- Two-part Bayesian regression models
- Three cause codes for dataset selection
  - *Storm*
  - *Storm + Fuel*
  - *Storm + Fuel + Equip*
- Three regressors:
  - *Ambient Temp*
  - *Total load Demand*
  - *Temp + Demand*

| Model Configuration         |                                  | Model   |
|-----------------------------|----------------------------------|---------|
| Regressor                   | Cause Code Set                   |         |
| $\mathcal{M}_{Temp}$        | $\mathcal{C}_{Storm}$            | Model 1 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 2 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 3 |
| $\mathcal{M}_{Demand}$      | $\mathcal{C}_{Storm}$            | Model 4 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 5 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 6 |
| $\mathcal{M}_{Temp+Demand}$ | $\mathcal{C}_{Storm}$            | Model 7 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 8 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 9 |

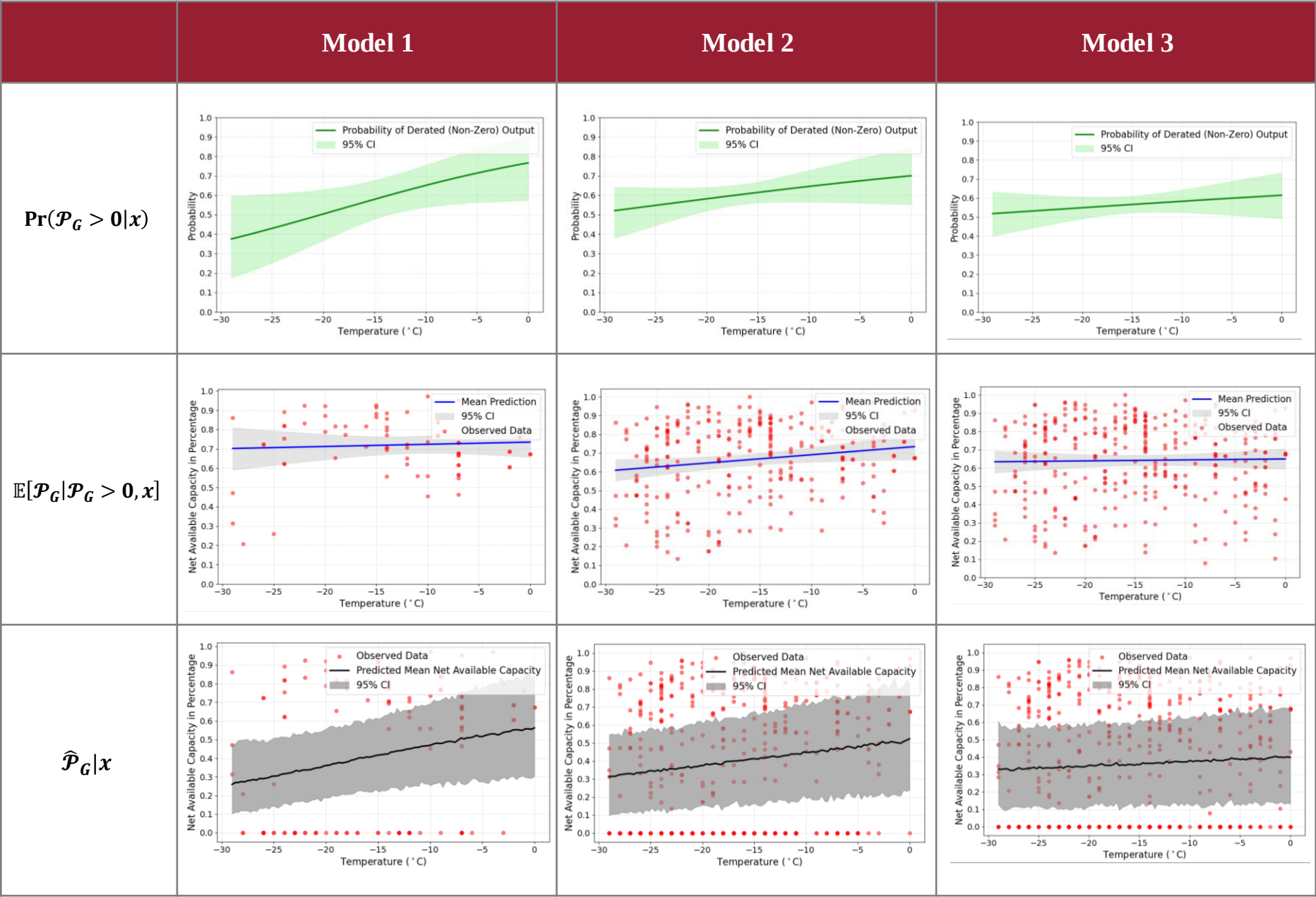
# Weather-Grid Impact Model: Results

9 models based on the regressor and cause-code selection

| Model Configuration         |                                  | Model   |
|-----------------------------|----------------------------------|---------|
| Regressor                   | Cause Code Set                   |         |
| $\mathcal{M}_{Temp}$        | $\mathcal{C}_{Storm}$            | Model 1 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 2 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 3 |
| $\mathcal{M}_{Demand}$      | $\mathcal{C}_{Storm}$            | Model 4 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 5 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 6 |
| $\mathcal{M}_{Temp+Demand}$ | $\mathcal{C}_{Storm}$            | Model 7 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 8 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 9 |

When temperature decreases significantly, the probability of generator operating at a derated capacity becomes lower indicating that generator is more likely to go into an outage.

However, at near freezing temperature, the generator is likely to operate but at a derated capacity.



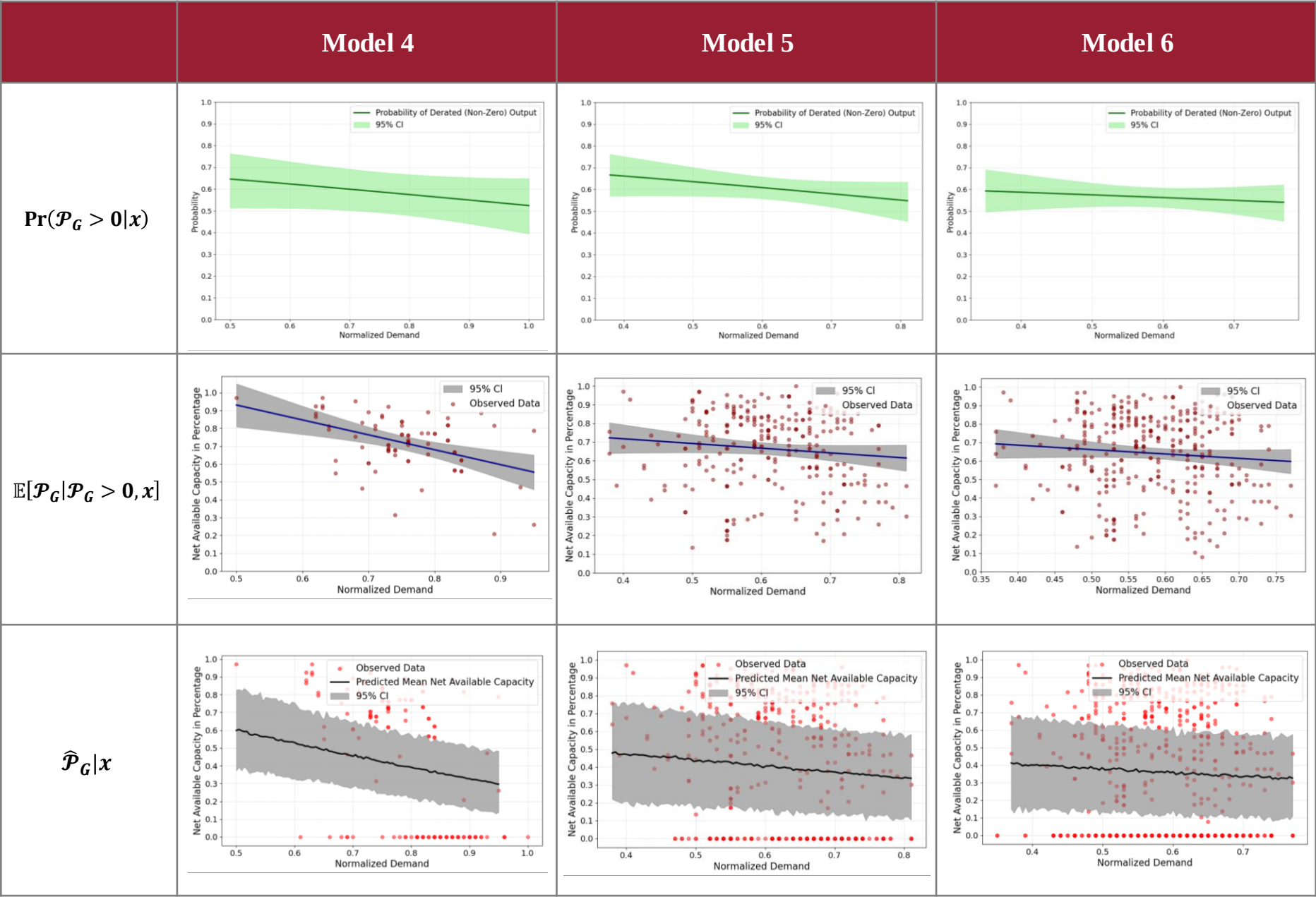
# Weather-Grid Impact Model: Results

9 models based on the regressor and cause-code selection

| Model Configuration         |                                  | Model   |
|-----------------------------|----------------------------------|---------|
| Regressor                   | Cause Code Set                   |         |
| $\mathcal{M}_{Temp}$        | $\mathcal{C}_{Storm}$            | Model 1 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 2 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 3 |
| $\mathcal{M}_{Demand}$      | $\mathcal{C}_{Storm}$            | Model 4 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 5 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 6 |
| $\mathcal{M}_{Temp+Demand}$ | $\mathcal{C}_{Storm}$            | Model 7 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 8 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 9 |

When demand is low during extreme winter conditions, generator is likely to operate at derated capacity.

However, as the demand gets higher, stress on the generator increases and hence the probability of a generator operating at a derated capacity becomes lower and it is prone to having an outage.



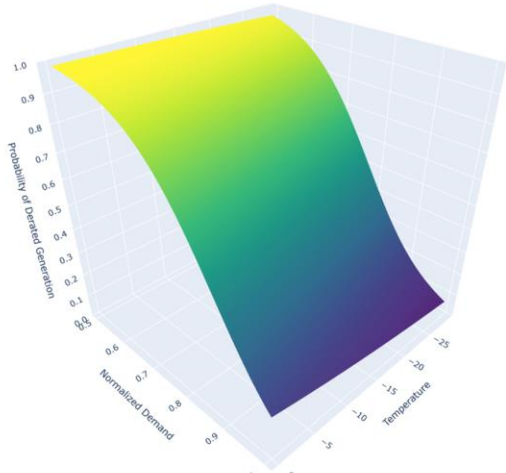
# Weather-Grid Impact Model: Results

9 models based on the regressor and cause-code selection

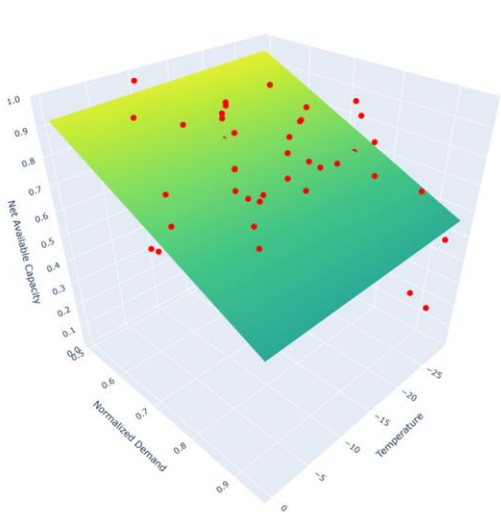
| Model Configuration         |                                  | Model   |
|-----------------------------|----------------------------------|---------|
| Regressor                   | Cause Code Set                   |         |
| $\mathcal{M}_{Temp}$        | $\mathcal{C}_{Storm}$            | Model 1 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 2 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 3 |
| $\mathcal{M}_{Demand}$      | $\mathcal{C}_{Storm}$            | Model 4 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 5 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 6 |
| $\mathcal{M}_{Temp+Demand}$ | $\mathcal{C}_{Storm}$            | Model 7 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 8 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 9 |

At near freezing temperature and low demand, the generator is predicted to run at a derated capacity.

With further decrease of temperature and increase in demand, the generator's ability to operated at derated capacity becomes lower and it is likely to experience a complete outage.

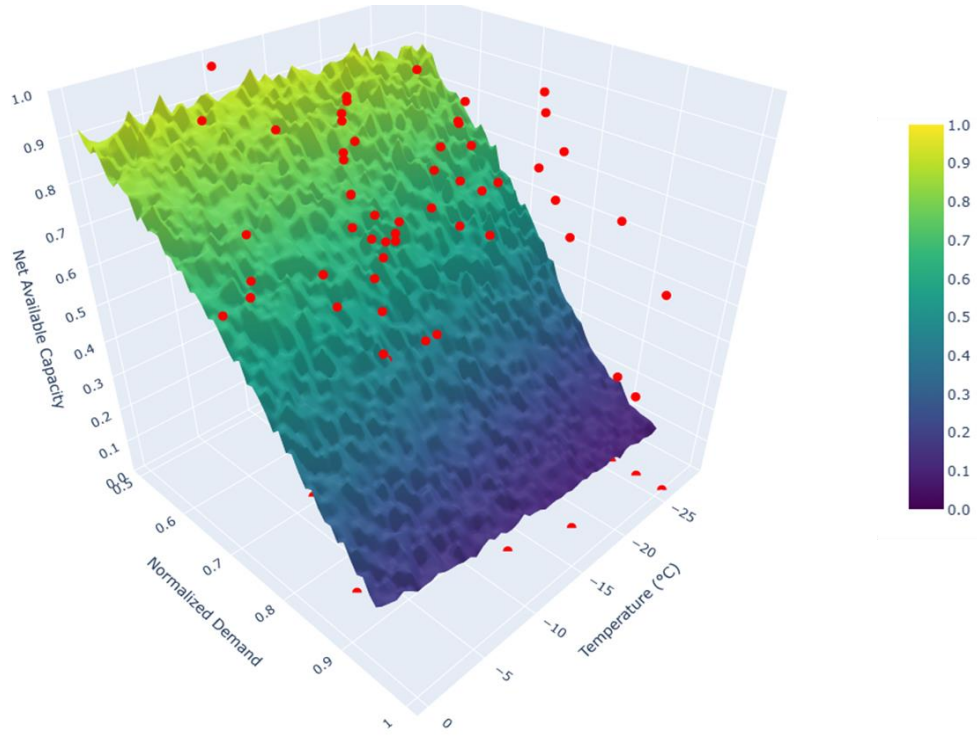


$$\Pr(\mathcal{P}_G > 0|x)$$



$$\mathbb{E}[\mathcal{P}_G | \mathcal{P}_G > 0, x]$$

Model 7



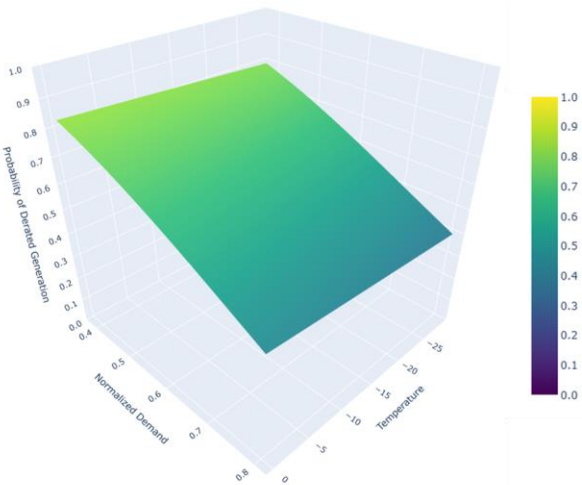
$$\hat{\mathcal{P}}_G|x$$

# Weather-Grid Impact Model: Results

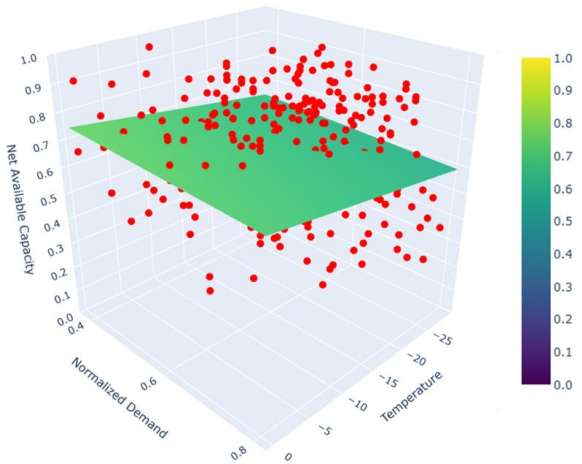
9 models based on the regressor and cause-code selection

| Model Configuration         |                                  | Model   |
|-----------------------------|----------------------------------|---------|
| Regressor                   | Cause Code Set                   |         |
| $\mathcal{M}_{Temp}$        | $\mathcal{C}_{Storm}$            | Model 1 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 2 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 3 |
| $\mathcal{M}_{Demand}$      | $\mathcal{C}_{Storm}$            | Model 4 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 5 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 6 |
| $\mathcal{M}_{Temp+Demand}$ | $\mathcal{C}_{Storm}$            | Model 7 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 8 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 9 |

Model 8 uses more data than Model 7, but less relevant labeling for extreme winter events leads to slightly overestimated capacity predictions.

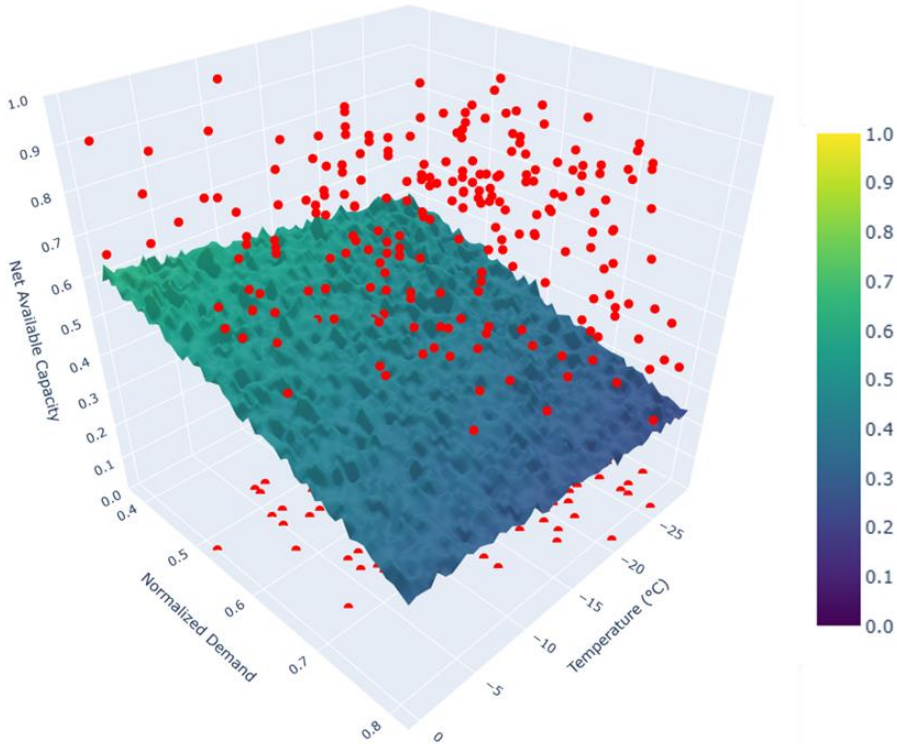


$$\Pr(\mathcal{P}_G > 0 | x)$$



$$\mathbb{E}[\mathcal{P}_G | \mathcal{P}_G > 0, x]$$

Model 8



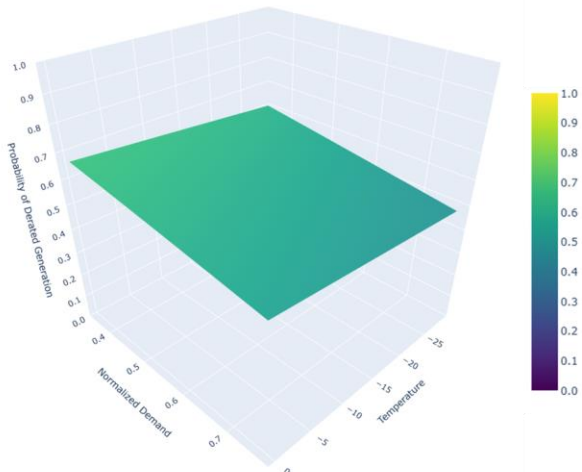
$$\hat{\mathcal{P}}_G | x$$

# Weather-Grid Impact Model: Results

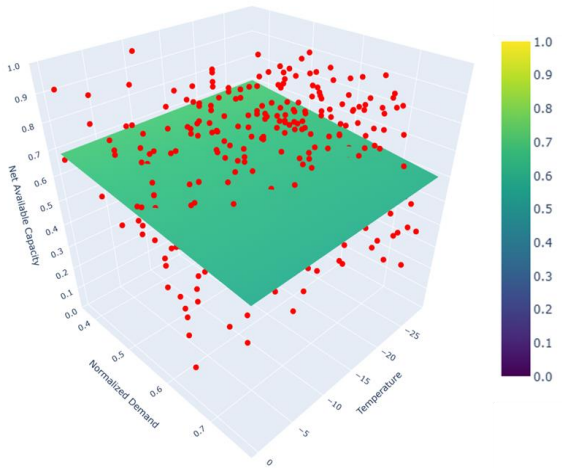
9 models based on the regressor and cause-code selection

| Model Configuration         |                                  | Model   |
|-----------------------------|----------------------------------|---------|
| Regressor                   | Cause Code Set                   |         |
| $\mathcal{M}_{Temp}$        | $\mathcal{C}_{Storm}$            | Model 1 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 2 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 3 |
| $\mathcal{M}_{Demand}$      | $\mathcal{C}_{Storm}$            | Model 4 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 5 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 6 |
| $\mathcal{M}_{Temp+Demand}$ | $\mathcal{C}_{Storm}$            | Model 7 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 8 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 9 |

Despite incorporating the largest dataset, Model 9 suffers from improper labeling in data, resulting in a conservative model with lower predicted capacity but less reliable output identified through validation.

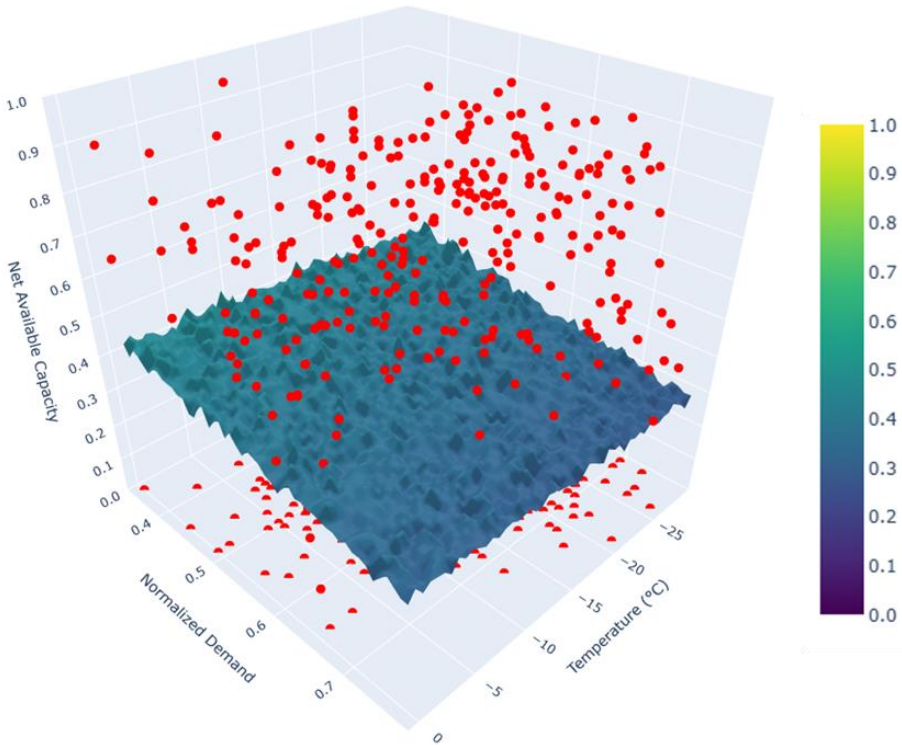


$$\Pr(\mathcal{P}_G > 0|x)$$



$$\mathbb{E}[\mathcal{P}_G | \mathcal{P}_G > 0, x]$$

Model 9

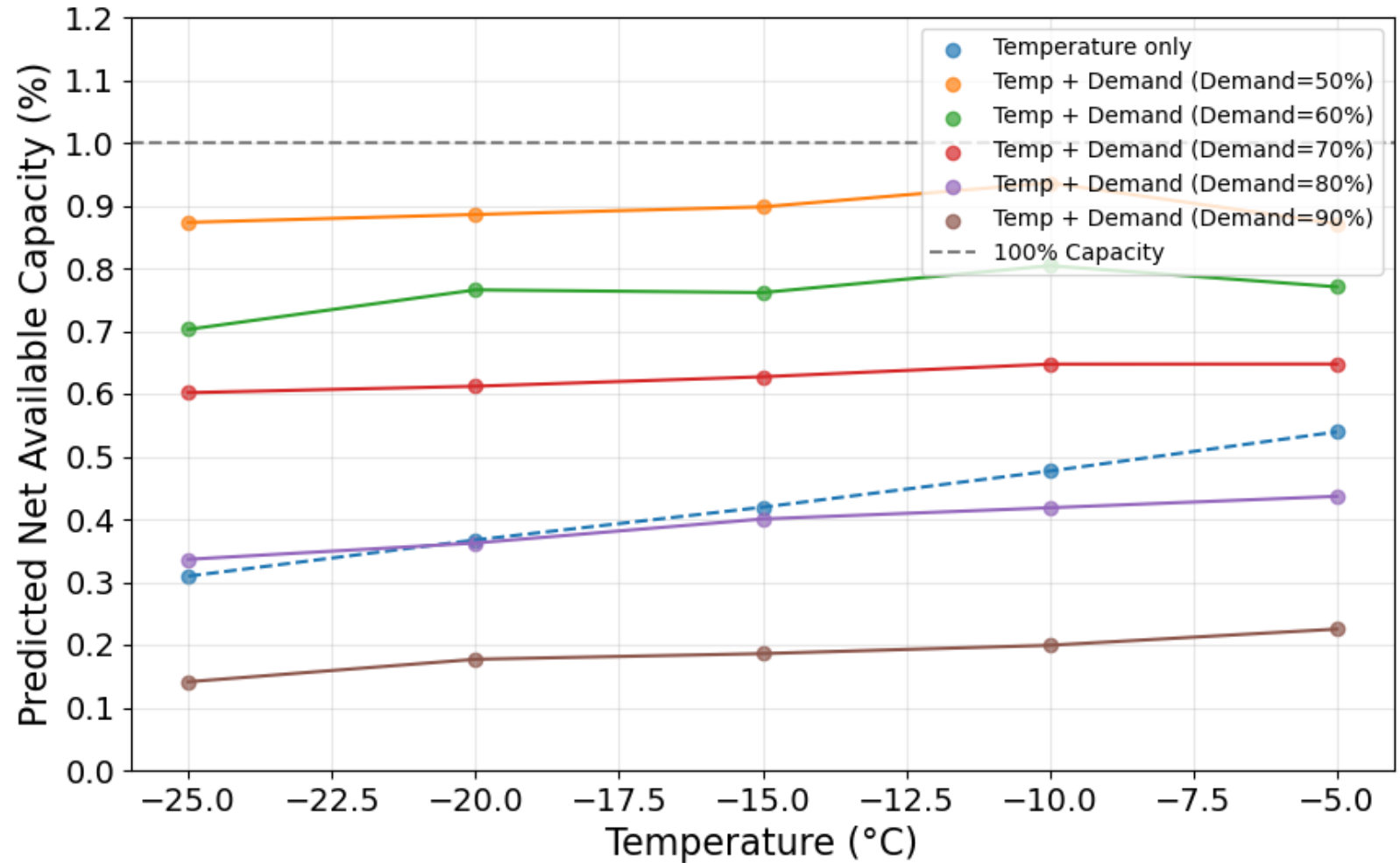


$$\hat{\mathcal{P}}_G|x$$

# Effect of Adding Regressors

Impact of adding demand as a regressor with temperature on predicted capacity for various demand scenarios

Cause Code Set:  $C_{Storm}$

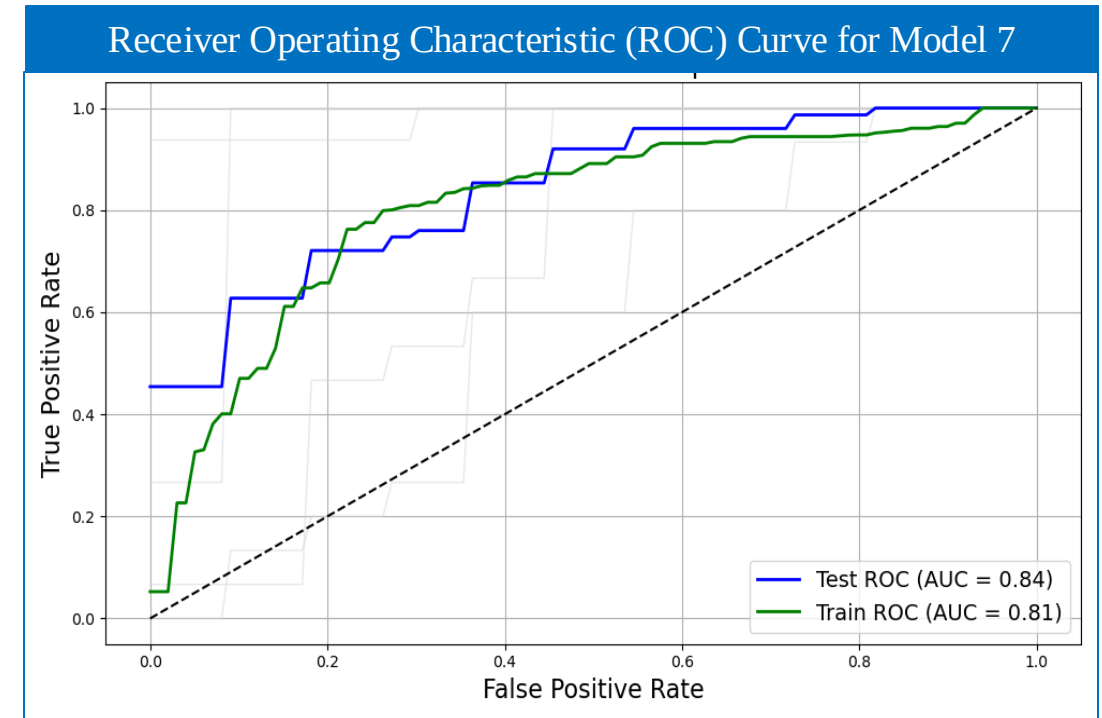


# Weather-Grid Impact Model: Validation

## Bayesian Logistic Regression Model Validation

### Classification Metrics

- We use the classification metrics - accuracy, precision, recall, F1 score, and area under the ROC curve (AUC)
- However, we focus more on AUC-ROC as it evaluates model performance across different thresholds whereas other metrics is dependent on a single threshold
- ROC curve plots the True Positive Rate (Sensitivity) against the False Positive Rate at various threshold settings. Each point on the ROC curve represents a different threshold.
- AUC (Area Under the Curve) is a single number summary that represents the classifier's ability to distinguish between classes. AUC = 1 indicates perfect classifier (ideal performance)



Stratified k-fold cross validation is used

# Weather-Grid Impact Model: Validation

## Bayesian Logistic Regression Model Validation

### Classification Metrics

- Accuracy : Proportion of correct classifications but can be misleading with class imbalance.
- Precision : Correctly predicted positives out of all predicted positives; crucial when false positives are costly.
- Recall : Correctly identified positives out of all actual positives; important when false negatives are costly.
- F1 Score : Balances precision and recall into a single metric but depends on specific threshold
- AUC-ROC : Evaluates model performance across all thresholds, independent of a specific threshold.

|         | Accuracy | Precision | Recall | F1-Score | AUC-ROC |
|---------|----------|-----------|--------|----------|---------|
| Model 1 | 0.620    | 0.661     | 0.747  | 0.687    | 0.672   |
| Model 2 | 0.591    | 0.600     | 0.960  | 0.738    | 0.565   |
| Model 3 | 0.546    | 0.556     | 0.945  | 0.699    | 0.462   |
| Model 4 | 0.589    | 0.589     | 1.000  | 0.741    | 0.844   |
| Model 5 | 0.604    | 0.604     | 1.000  | 0.753    | 0.621   |
| Model 6 | 0.565    | 0.565     | 1.000  | 0.720    | 0.552   |
| Model 7 | 0.590    | 0.735     | 0.787  | 0.729    | 0.840   |
| Model 8 | 0.573    | 0.597     | 0.869  | 0.702    | 0.591   |
| Model 9 | 0.536    | 0.551     | 0.904  | 0.681    | 0.511   |

- Model 4 has the highest AUC-ROC, followed by Model 7 and Model 1.
- However, Model 4 achieves perfect recall (1.000) but low precision (0.589), indicating many false positives.
- Therefore, Model 7 demonstrates better balanced performance across all metrics.**

# Weather-Grid Impact Model: Validation

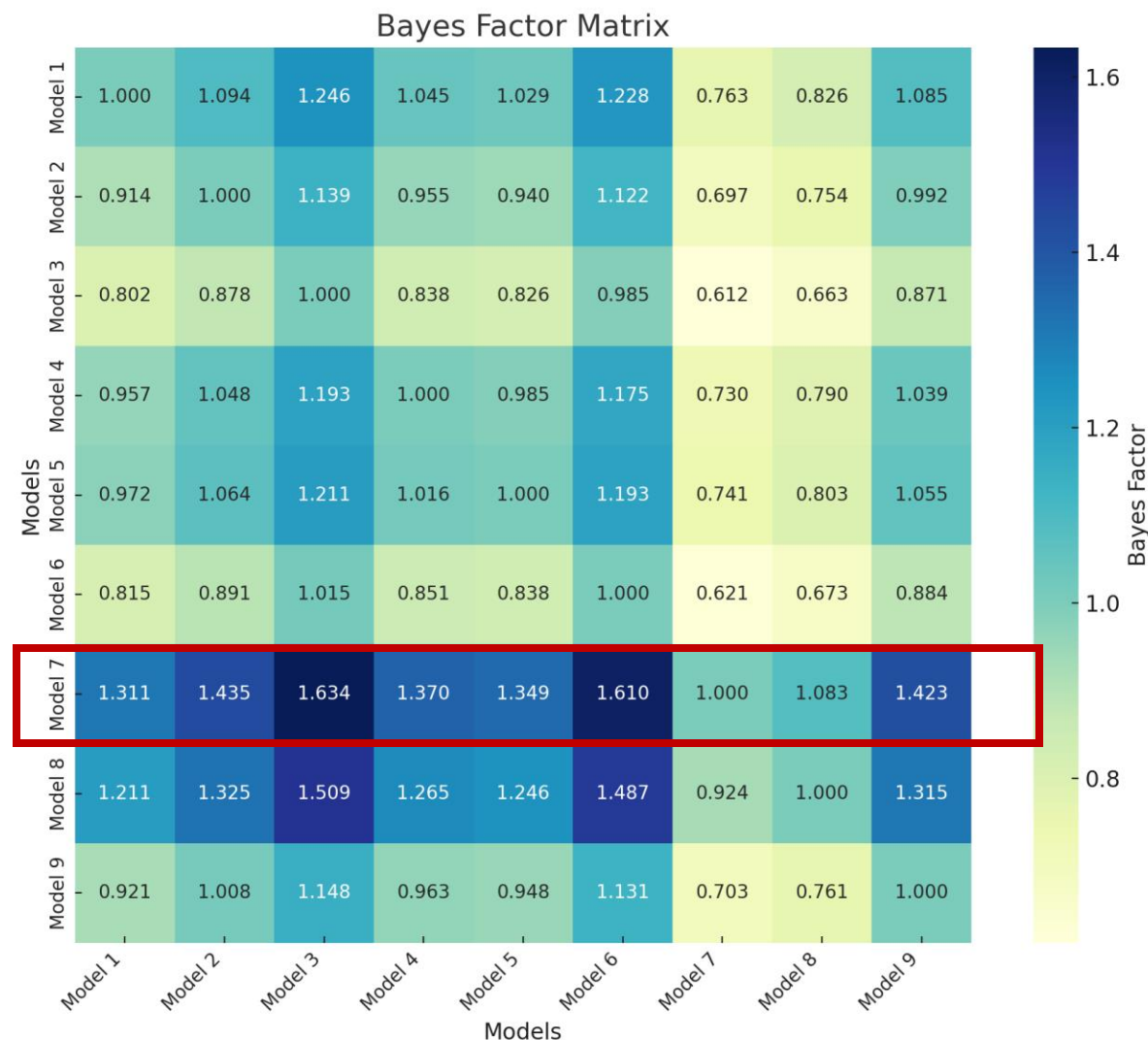
## Bayesian Logistic Regression Model Validation

### Bayes Factor

- Bayes Factor is a statistical measure used in Bayesian analysis to quantify the strength of evidence provided by the data in favor of one statistical model over another. Specifically, it compares the likelihood of the data under two competing hypotheses or models.
- Bayes factor can be derived from the difference in Bayesian Information Criterion (BIC) values. BIC is a statistical metric used to evaluate the goodness of fit of a model while penalizing for model complexity to avoid overfitting.
- If the BIC values for model A and B are  $BIC_A$  and  $BIC_B$  respectively, then the Bayes Factor can be approximated as follows:

$$BF_{AB} = e^{-\frac{1}{2}(BIC_A - BIC_B)}$$

- $BF_{AB} > 1$ : Indicates that the data provide more support for Model A compared to Model B.
- $BF_{AB} < 1$ : Indicates that the data provide more support for Model B compared to Model A.
- $BF_{AB} = 1$ : Indicates that the data equally support both models.



Model 7 outperforms ( Bayes Factor > 1.00) all other cases.

# Weather-Grid Impact Model: Validation

## Bayesian Linear Regression Model Validation

| Model Configuration         |                                  | Model   |
|-----------------------------|----------------------------------|---------|
| Regressor                   | Cause Code Set                   |         |
| $\mathcal{M}_{Temp}$        | $\mathcal{C}_{Storm}$            | Model 1 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 2 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 3 |
| $\mathcal{M}_{Demand}$      | $\mathcal{C}_{Storm}$            | Model 4 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 5 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 6 |
| $\mathcal{M}_{Temp+Demand}$ | $\mathcal{C}_{Storm}$            | Model 7 |
|                             | $\mathcal{C}_{Storm+Fuel}$       | Model 8 |
|                             | $\mathcal{C}_{Storm+Fuel+Equip}$ | Model 9 |

Mean Absolute Error, Root Mean Squared Error and Mean Log Predictive Density are used to validate the linear regression model.

|         | MAE    | RMSE   | MLPD   |
|---------|--------|--------|--------|
| Model 1 | 0.1212 | 0.1589 | 0.4202 |
| Model 2 | 0.1698 | 0.2018 | 0.1814 |
| Model 3 | 0.1809 | 0.2154 | 0.1162 |
| Model 4 | 0.1062 | 0.1382 | 0.5597 |
| Model 5 | 0.1684 | 0.2033 | 0.1742 |
| Model 6 | 0.1797 | 0.2143 | 0.1216 |
| Model 7 | 0.1065 | 0.1398 | 0.5485 |
| Model 8 | 0.1694 | 0.2019 | 0.1811 |
| Model 9 | 0.1803 | 0.2153 | 0.1167 |

- Model 7 uses the generator's outage/derating output data ( $\mathcal{C}_{Storm}$ ) from GADS that are explicitly tagged with external cause code 9036: Storms (ice, snow, etc).
- Hence, this  $\mathcal{C}_{Storm}$  is properly labeled with the winter storms in the GADS data and even though the dataset is limited, it performs better than the other dataset.
- Although the other two dataset ( $\mathcal{C}_{Storm+Fuel}$ ,  $\mathcal{C}_{Storm+Fuel+Equip}$ ) has more data, those are not only explicitly tagged with winter storms in the GADS data.
- Hence the performance is poor (high MAE, high RMSE, Low MPLD) in all the models (2,3,5,6,8,9) which utilize these two dataset:  $\mathcal{C}_{Storm+Fuel}$ ,  $\mathcal{C}_{Storm+Fuel+Equip}$

# Weather-Grid Impact Model: Validation

## Bayesian Linear Regression Model Validation

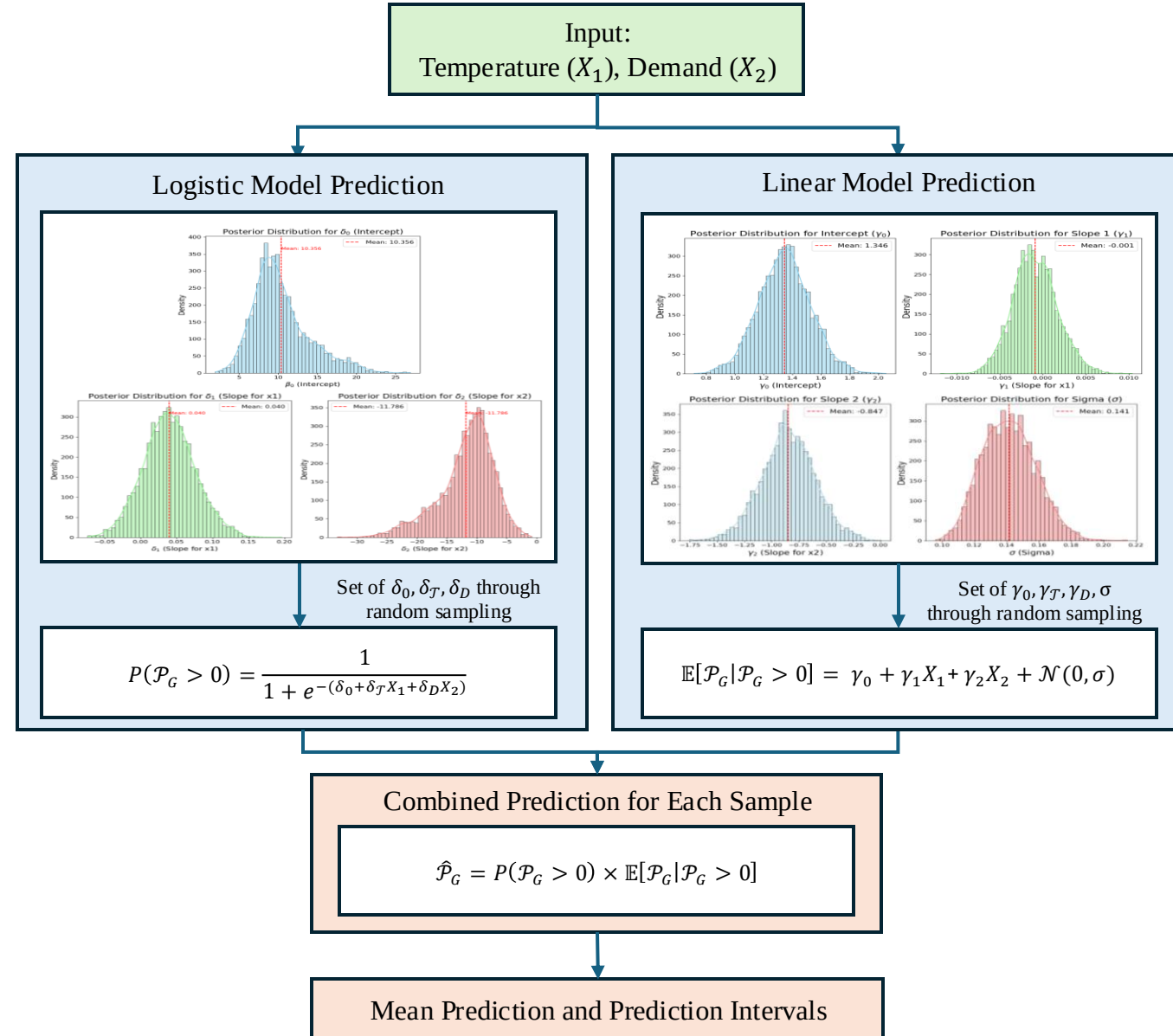
### Predictive Metrics

|         | MAE    | RMSE   | MLPD   |
|---------|--------|--------|--------|
| Model 1 | 0.1212 | 0.1589 | 0.4202 |
| Model 2 | 0.1698 | 0.2018 | 0.1814 |
| Model 3 | 0.1809 | 0.2154 | 0.1162 |
| Model 4 | 0.1062 | 0.1382 | 0.5597 |
| Model 5 | 0.1684 | 0.2033 | 0.1742 |
| Model 6 | 0.1797 | 0.2143 | 0.1216 |
| Model 7 | 0.1065 | 0.1398 | 0.5485 |
| Model 8 | 0.1694 | 0.2019 | 0.1811 |
| Model 9 | 0.1803 | 0.2153 | 0.1167 |

- Model 4 (demand as the only regressor) and Model 7 (both temperature and demand as regressor) exhibit the lowest Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE), along with the highest Mean Log Predictive Density (MLPD).
- Given that our model integrates two parts and Model 7 performed better in the logistic regression analysis, we identify Model 7 as the overall best choice.

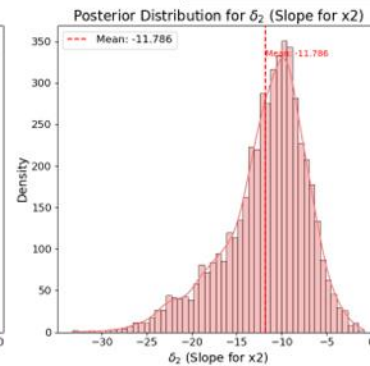
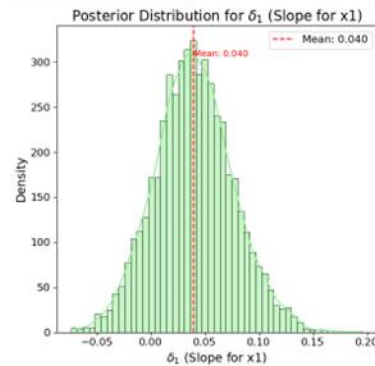
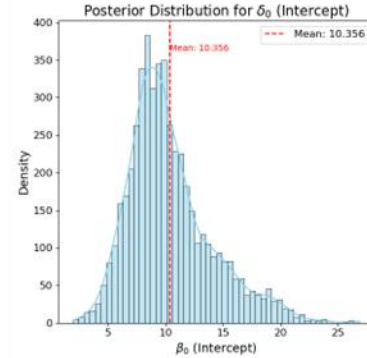
# How the Model Works for a Given Input

- Input Data:
  - Temperature ( $X_1$ ): The observed or forecasted temperature value (e.g.,  $-15^{\circ}\text{C}$ )
  - Demand ( $X_2$ ): The normalized demand value (e.g., 0.7)
- Parameter Distributions:
  - Pre-trained parameter distributions for both the logistic and linear models
- Monte Carlo Sampling:
  - For each input, random samples are drawn from these parameter distributions to account for uncertainty in the learned model
    - Logistic model parameters:  $\delta_0, \delta_T, \delta_D$
    - Linear model parameters:  $\gamma_0, \gamma_T, \gamma_D, \sigma$
- Logistic Model Prediction:
  - Compute the probability of a derated state using each sample (i.e., reduced generator capacity).
- Linear Model Prediction:
  - Predict the derated capacity of the generator if operational using each sample.
- Combined Model Prediction:
  - Multiply the probability from the logistic model and the capacity from the linear model
  - Mean Prediction: Average of all combined outputs.
  - Prediction Intervals: 95% credible interval (e.g., between 2.5th and 97.5th percentiles).

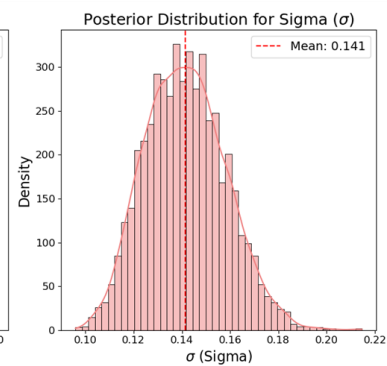
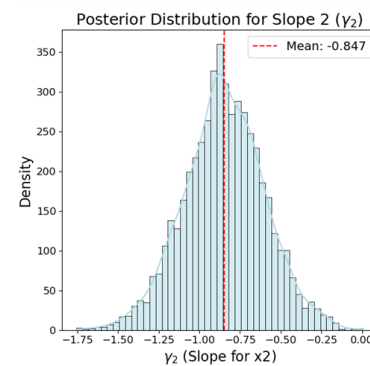
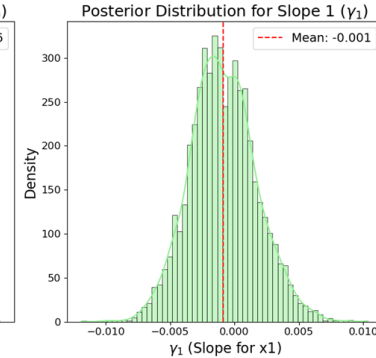
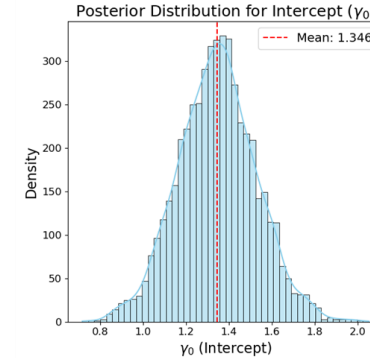


# How the Model Works for a Given Input: Model 7

Parameter Learned from Logistic Regression



Parameter Learned from Linear Regression



Regressor:  $\mathcal{M}_{Temp+Demand}$   
Cause Code:  $\mathcal{C}_{storm}$

| Temperature in °C | Normalized Demand | Mean Net Available Capacity | 95% CI         |
|-------------------|-------------------|-----------------------------|----------------|
| -5                | 0.6               | .0.797                      | [0.495, 1.000] |
| -10               | 0.7               | 0.626                       | [0.389, 0.896] |
| -15               | 0.8               | 0.386                       | [0.211, 0.570] |
| -20               | 0.9               | 0.166                       | [0.046, 0.324] |

# Concluding Remarks

## Model Limitations:

- Despite access to exact weather station locations, the current model uses aggregated temperature data for each state due to the unavailability of generator-specific location information.
- Cause codes related to equipment freeze-off outages are not properly labeled in the GADS dataset, limiting accurate event classification.
- The model operates on a small dataset, which impacts prediction accuracy and generalizability.

## Requirements for Model Improvement:

- Access to generator-specific locations will allow for direct integration of localized weather data.
- Getting more clarity on specific freeze-related issues (e.g., equipment freeze-off, fuel supply constraints) for a generator outage or derating will refine the model's ability to predict generator available capacity under extreme winter conditions.
- Collaboration to acquire generator-specific outage and weather data will address the data limitation, reduce model uncertainty and increase predictive reliability.

# Concluding Remarks

## Key Takeaways:

- Extreme winter weather significantly reduces the operational capacity and reliability of gas-fired generators due to freezing temperatures and high demand.
- The two-part weather-grid impact model predicts generator available capacity well under extreme winter conditions by integrating temperature and demand.
- However, the analysis highlights the critical need for more accurate and well-labeled data to model generator behavior better under extreme winter weathers.

## Submitted Works:

- S. U. Mahmud, A. Dubey, “Weather-Dependent Modeling of Gas-Fired Generator Output in Extreme Winter Condition” in 2025 IEEE Power & Energy Society General Meeting (PESGM). IEEE, 2025. (Submitted)

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- Project collaborators:
  - Chiara Lo Prete: Associate Professor of Energy Economics, John and Willie Leone Family Department of Energy and Mineral Engineering at Penn State University
  - Burcin Unel: Research and Policy Director at the Institute for Policy Integrity at New York University School of Law.



# Thank You



Contact : Anamika Dubey – [anamika.dubey@wsu.edu](mailto:anamika.dubey@wsu.edu)

Website : <https://anamika-dubey.github.io/>