



Presenter: Jake P. Gentle

Senior Relationship  
Manager

Energy, Environment,  
Science and Technology

INL: S M Shafiu Alam

NOAA: Ken Fenton

June 25, 2025



# Wind Forecasting for Dynamic Line Ratings

## ESIG Forecasting & Marketing Workshop

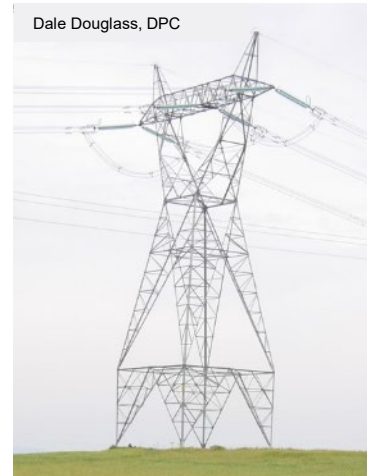


Battelle Energy Alliance manages INL for the  
U.S. Department of Energy's Office of Nuclear Energy



INL/MIS-25-85709

# Options for Increasing Line Capacity



## Change the Methodology

- Adjust Static Rating Parameters
- Apply Other Ratings
  - Seasonal
  - Ambient Adjusted
  - Dynamic Line Ratings (Real-time and Forecasted)

## Change the Physical Rating

- Use Clearance Margin (if available)
- Allow Higher Temperature

## Fix Clearance Limits

- Remove Obstacle
- Adjust Tension
- Modify Insulators
- Modify Structures
- Inset Structures

## Reconductor

- TW Conductor
- Larger Conductor
- HTLS conductors

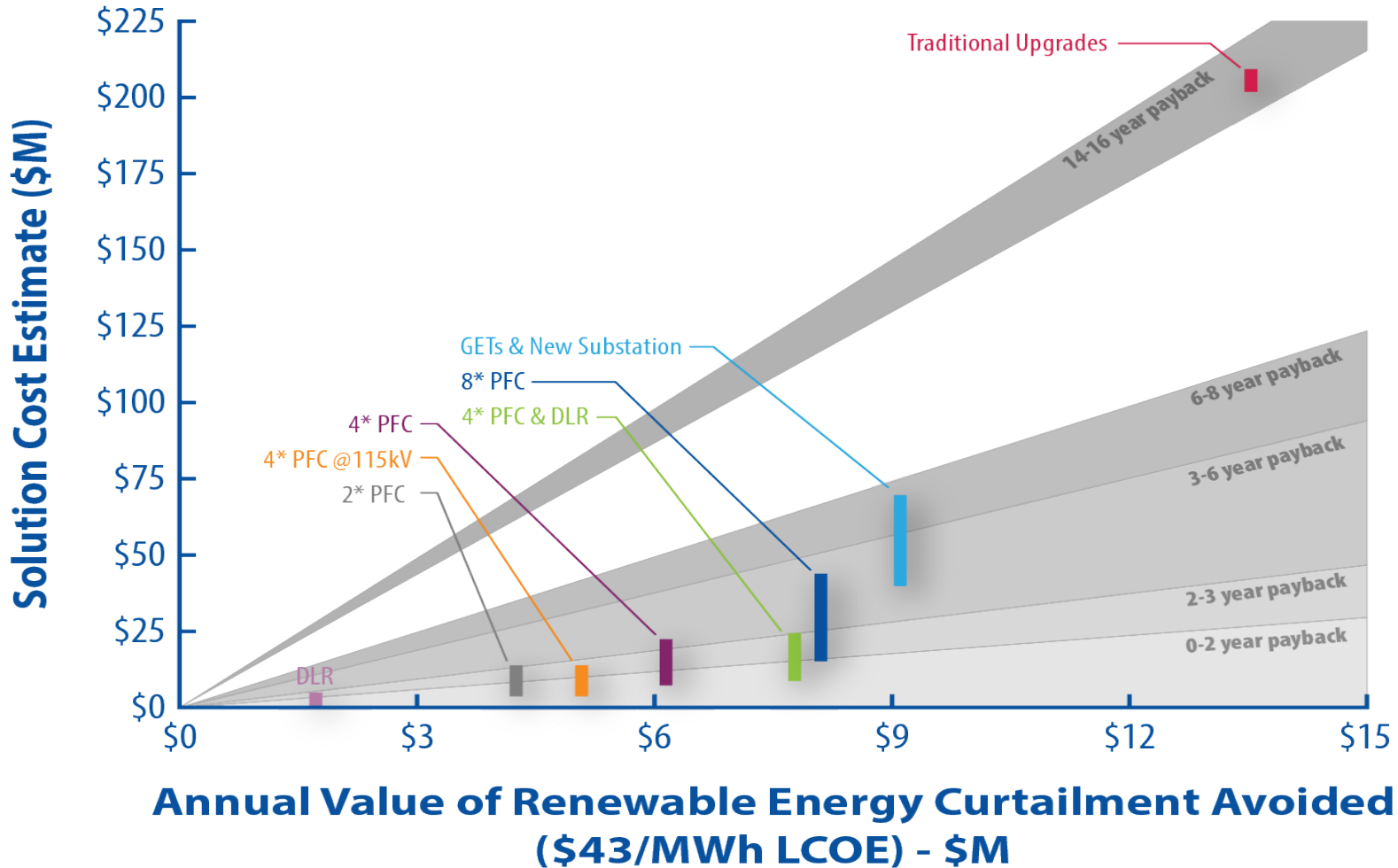
## Increase the Voltage

- Structure/insulator modification

## Rebuild the Line

- New conductor
- More circuits
- Larger voltage

# GETs: Relieving Grid Congestion



- GETs cases provide optionality in addressing curtailment at a fraction of the cost
- Similar story across other system economic metrics
- Payback period appears to be faster for GETs
  - GETs lifecycle shorter than traditional upgrades
- Range of costs identified for each of the GETs cases

INL: 21-50332\_CurtailAvoidanceCost\_r4

# Ratings Come Down to Only a Few Things

## Clearances

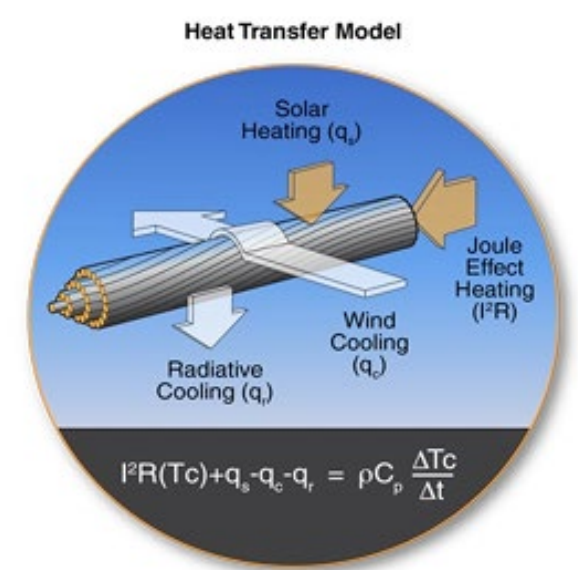
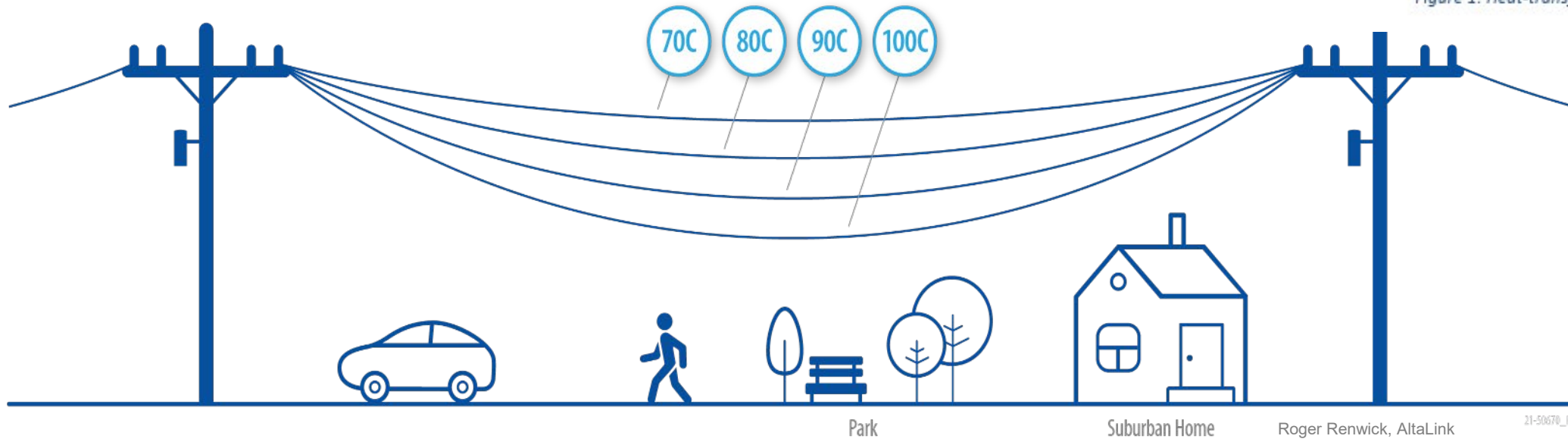


Figure 1: Heat-transfer model for a conductor.

# IEEE 738 Equations

 Where conductor properties enters the equations directly

 Where weather enters the equations directly

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_C)}}$$

$$T_{film} = \frac{T_s + T_a}{2}$$

$$q_{c1} = K_{angle} \cdot [1.01 + 1.35 \cdot N_{Re}^{0.52}] \cdot k_f \cdot (T_s - T_a) \cdot N_{Re} \cdot \frac{D_0 \cdot \rho_f \cdot V_w}{\mu_f}$$

$$q_{c2} = K_{angle} \cdot 0.754 \cdot N_{Re}^{0.6} \cdot k_f \cdot (T_s - T_a)$$

$$q_{cn} = 3.645 \cdot \rho_f^{0.5} \cdot D_0^{0.75} \cdot (T_s - T_a)^{1.25}$$

$$k_f = 2.424 \cdot 10^{-2} + 7.477 \cdot 10^{-5} \cdot T_{film} - 4.407 \cdot 10^{-9} \cdot T_{film}^2$$

$$K_{angle} = 1.194 - \cos(\phi) - 0.194 \cdot \cos(2\phi) - 0.368 \cdot \sin(2\phi)$$

$$\rho_f = \frac{1.293 - 1.525 \cdot 10^{-4} \cdot H_e + 6.379 \cdot 10^{-9} \cdot H_e^2}{1 + 0.00367 \cdot T_{film}}$$

$$\mu_f = \frac{1.458 \cdot 10^{-6} \cdot (T_{film} + 273)^{1.5}}{T_{film} + 383.4}$$

$$q_r = 17.8 \cdot D_0 \cdot \epsilon \cdot \left[ \left( \frac{T_s + 273}{100} \right)^4 - \left( \frac{T_a + 273}{100} \right)^4 \right]$$

$$\theta = \arccos [\cos(H_c) \cdot \cos(Z_c - Z_1)]$$

$$\delta = 23.46 \cdot \sin \left[ \frac{284 + N}{365} \cdot 360 \right]$$

$$q_s = \alpha \cdot \rho_{sc} \cdot \sin(\theta) \cdot A'$$

$$H_c = \arcsin [\cos(Lat) \cdot \cos(\delta) \cdot \cos(\omega) + \sin(Lat) \cdot \sin(\delta)]$$

$$Z_c = C + \arctan(\chi)$$

$$R(T_{avg}) = \left[ \frac{R(T_{high}) - R(T_{low})}{T_{high} - T_{low}} \right] \cdot (T_{avg} - T_{low}) + R(T_{low})$$

$$\chi = \frac{\sin(\omega)}{\sin(Lat) \cdot \cos(\omega) - \cos(Lat) \cdot \tan(\delta)}$$

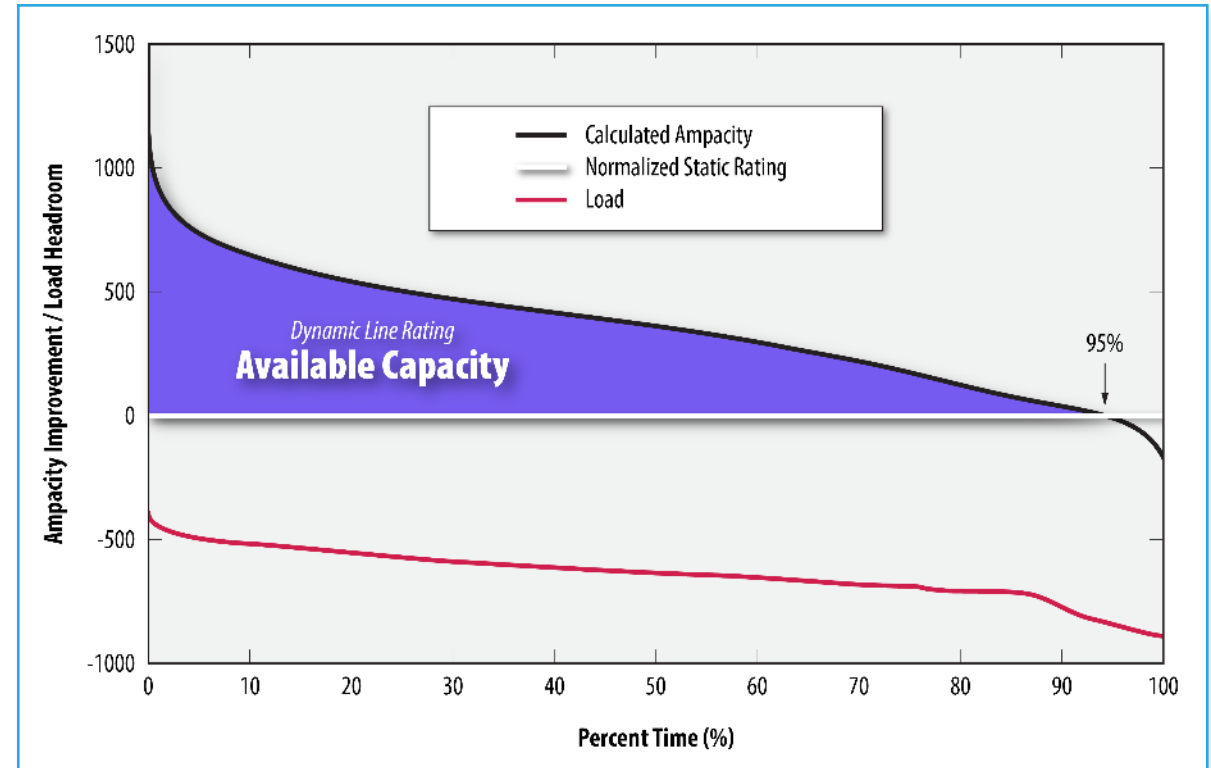
# Why Should We Increase Our Ratings?

## *To safely increase line utilization*

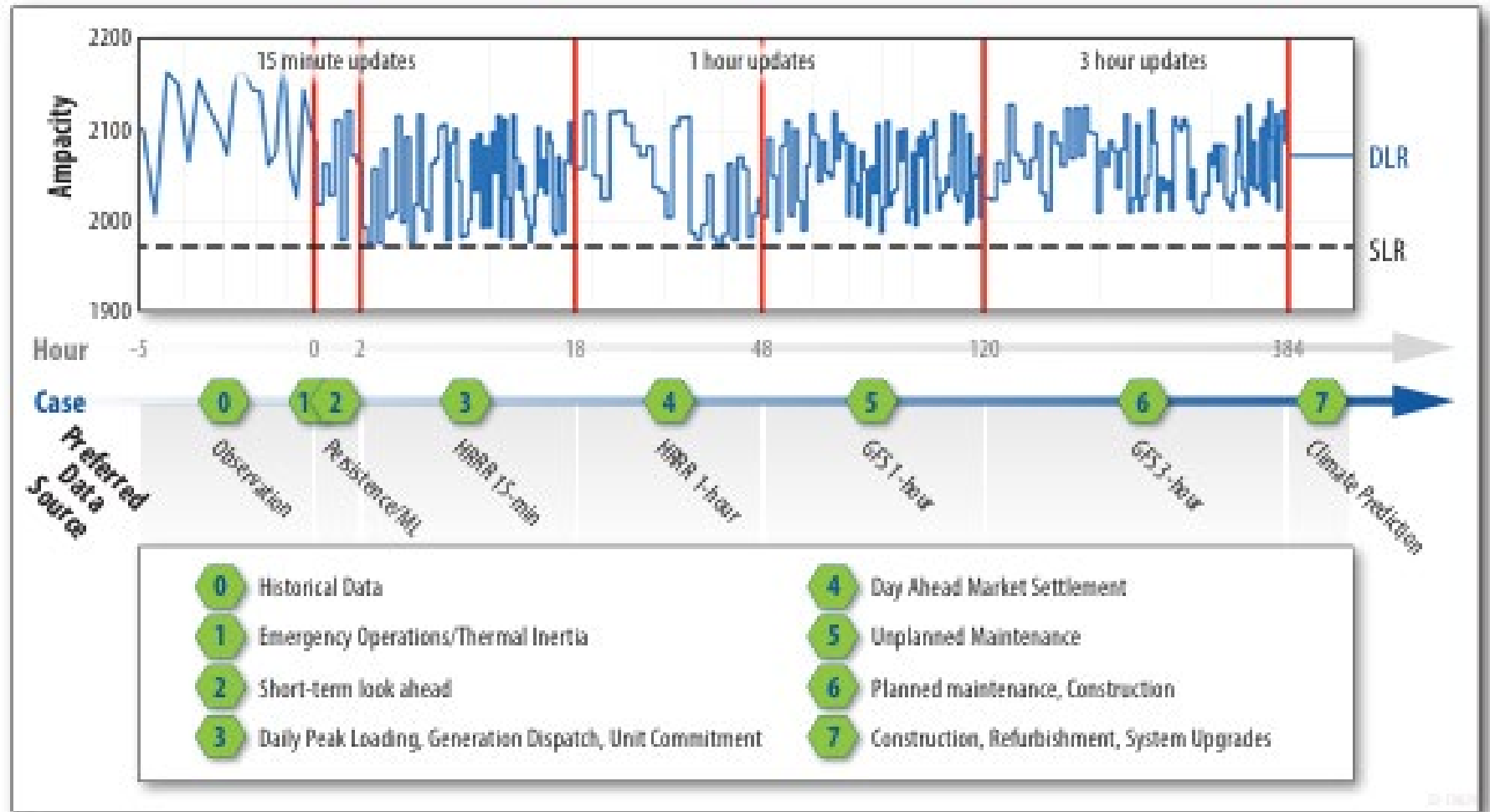
- Power Flow Optimizations
- More access to lower priced generators
- Contingency analysis

## *DLR accurately reflects the real-world*

- Risk mitigations (equipment failure/fatigue)
- Safety & reliability



# DLR Forecasting Timelines: circa 2015-2023



*A Timeline of Forecasting Use Cases. The plot compares DLR at different time horizons to the constant static line rating (SLR).*

[https://inldigitalibrary.inl.gov/sites/sti/sti/Sort\\_53432.pdf](https://inldigitalibrary.inl.gov/sites/sti/sti/Sort_53432.pdf)

<https://www.ferc.gov/sites/default/files/2020-09/Gentle-INL.pdf>

# NOAA Weather Forecast Models: 2025



Model	Horizontal Resolution	Time Step	Refresh Rate	Maximum Forecast Lead Time	Ensemble?
<b>NBM</b>	2.5 km	1-hr (1-36 hours) 3-hr (39-195 hours)	1-hr	240 hours (10 days)	Yes
<b>HREF</b>	2.5 km	1-hr	6-hr	48 hours (2 days)	Yes
<b>HRRR (RRFS update FY26)</b>	3 km	15-min (0-18 hours) 1-hr (18-48 hours)	1-hr	48 hours (2 days)	REFS ensemble available in Spring 2026
<b>GFS</b>	13 km	1-hr (1-120 hours) 3-hr (93-144 hours) 6-hr (150-384 hours)	6-hr	384 hours (16 days)	GEFS is an ensemble.

NBM: National Blend of Models

HREF: High Resolution Ensemble Forecast

HRRR: High Resolution Rapid Refresh

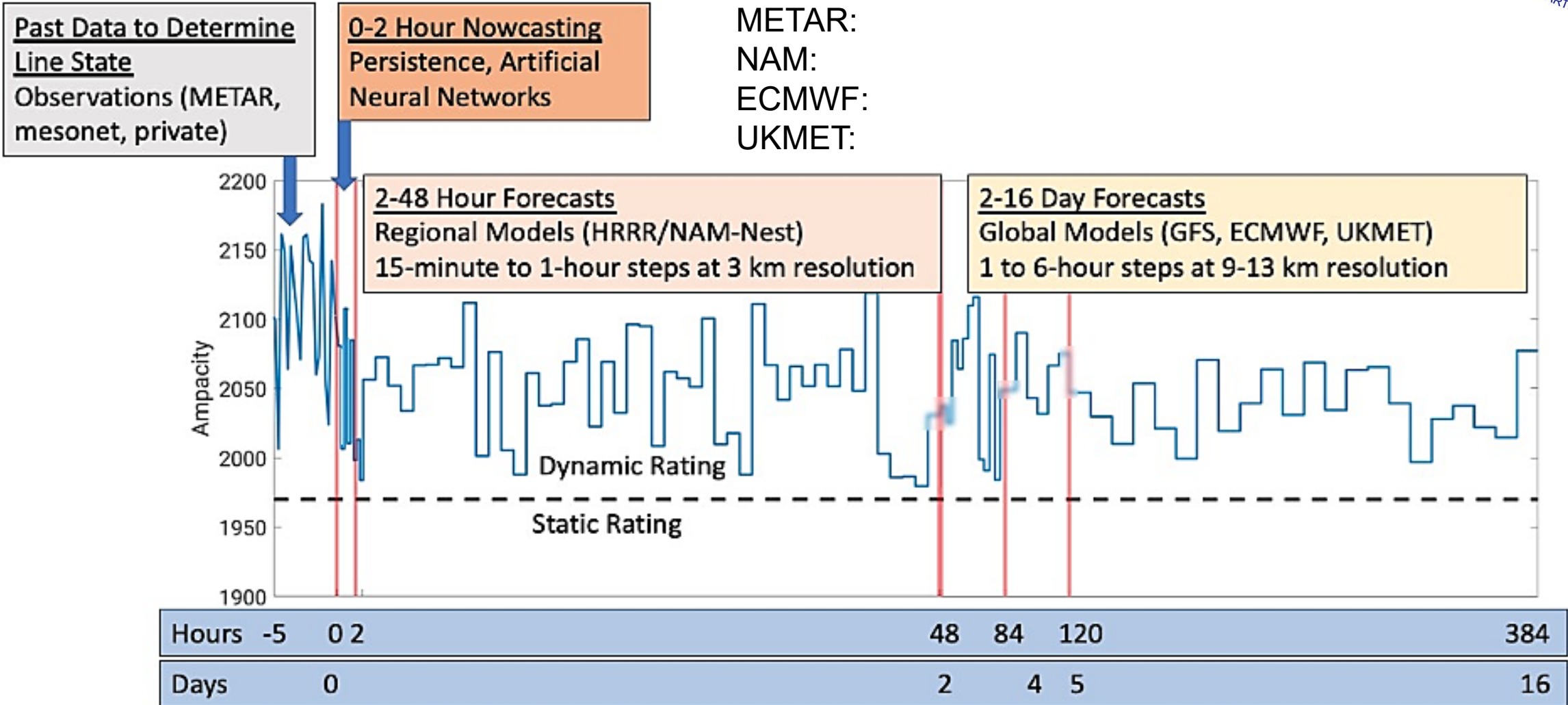
RRFS: Rapid Refresh Forecast System

REFS: Rapid Ensemble Forecast System

GFS: Global Forecast System

GEFS: Global Ensemble Forecast System

# Timeline of Weather Data Integration into DLRs

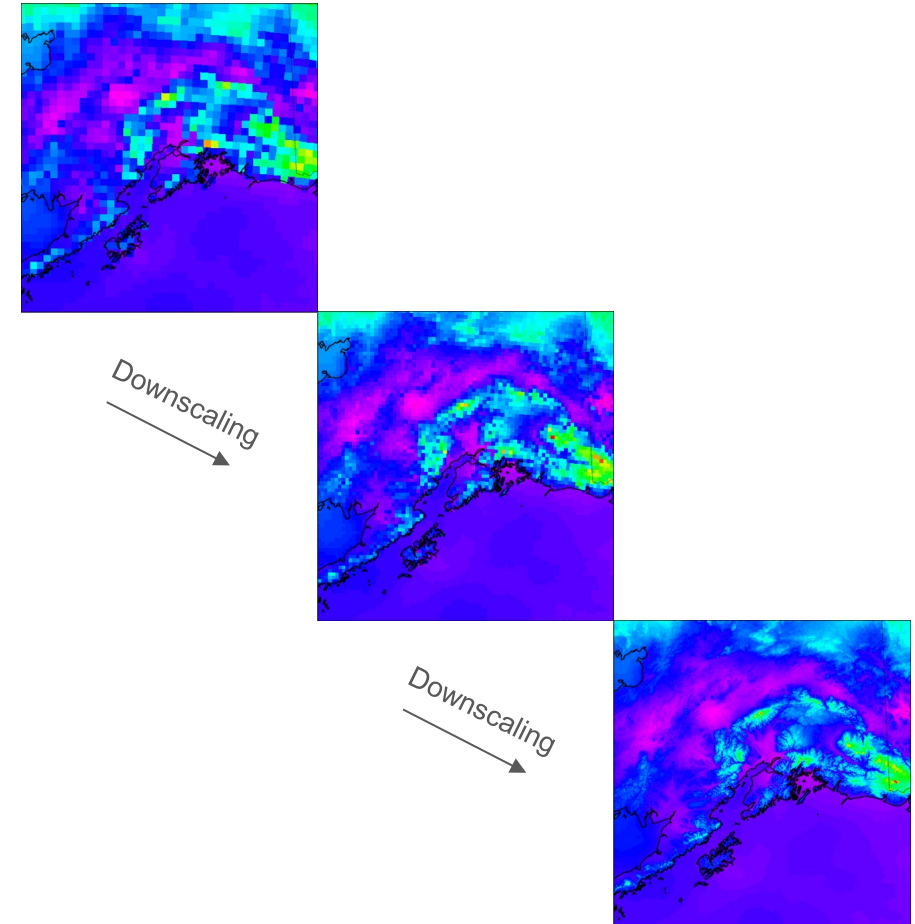


# AI for Superscaling (or Super Resolution)

Use AI for super resolution both for downscaling temporally and spatially

## Impacts:

- Improved forecasts in complicated terrain (scaling to higher spatial resolution)
- Improved forecasts where time matters (like aviation) (scale to 5 or 15 minute forecasts) Nowcasting



**Downscaling Data for Alaska (Bergstrom)**

# Wind Observations

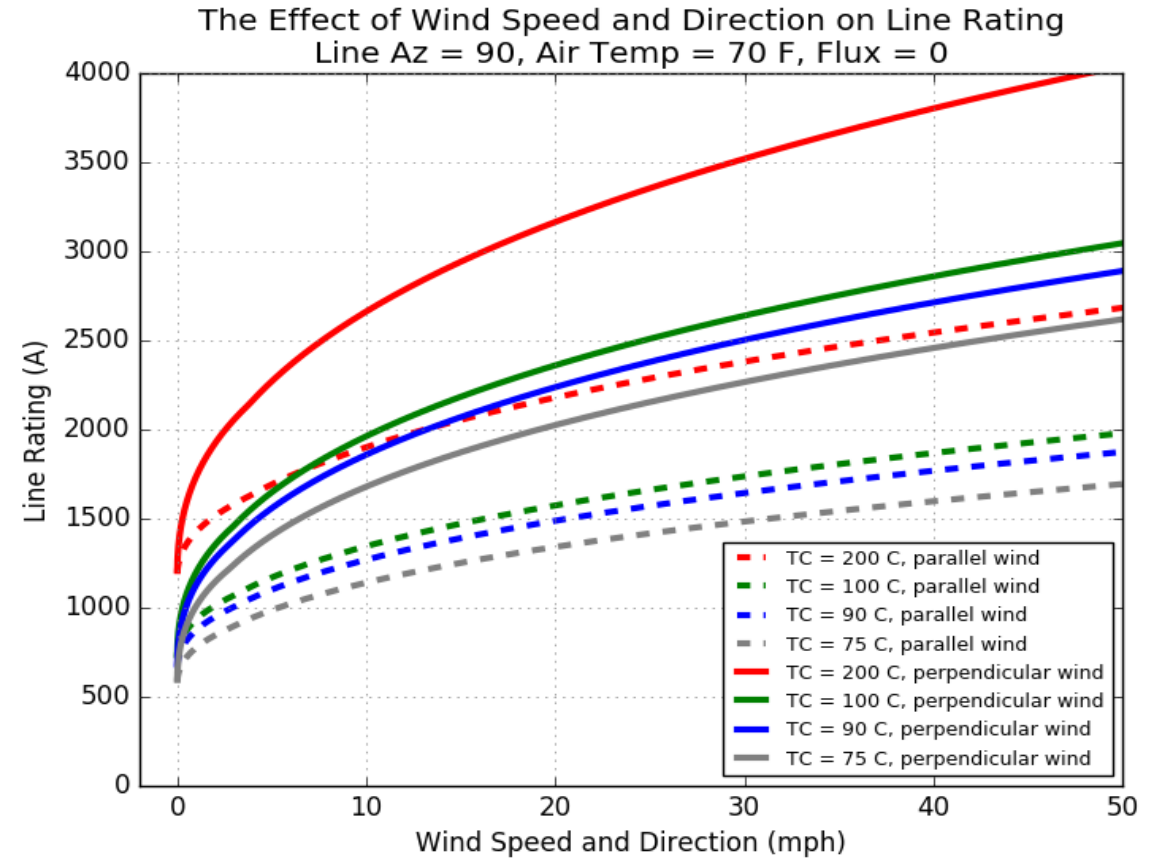
- Sensor type
- Cost
- Terrain
- Vegetation
- Verification with weather models



	Speed Accuracy ( $\pm$ m/s)	Direction Accuracy ( $\pm$ degrees)	Cost (\$)
<b>Low-cost cup anemometers</b>	0.5	10	10s
<b>High-accuracy cup anemometers</b>	0.1	1	10s - 100s
<b>Ultrasonic anemometers</b>	0.01	1	100s - 1000s

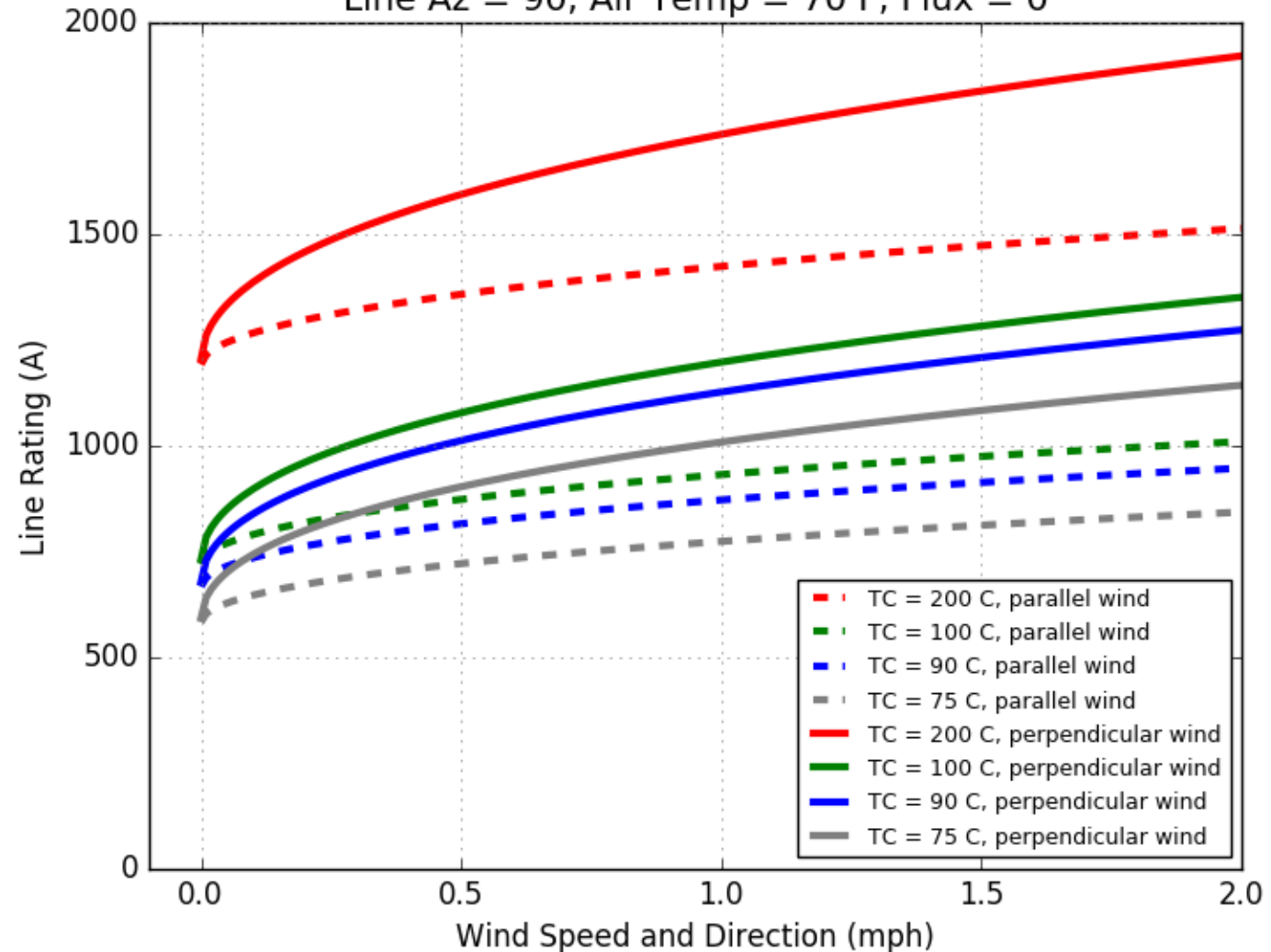
# Parallel vs Perpendicular Winds and TC

Perpendicular winds have a larger affect than parallel winds on line cooling at **higher conductor temperatures.**



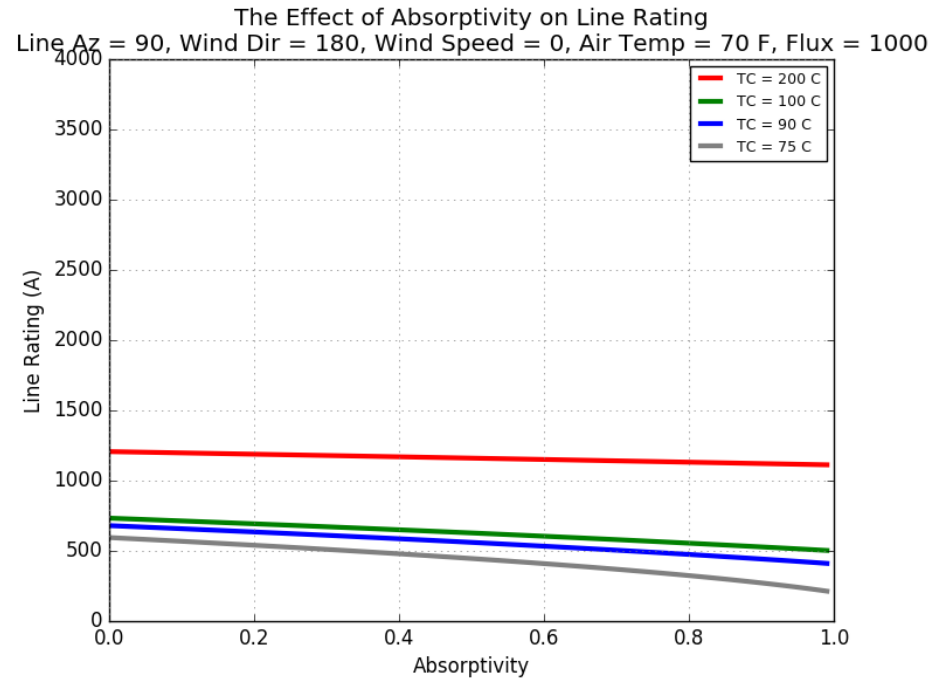
# Low Wind Speed, Parallel vs Perpendicular and TC

The Effect of Wind Speed and Direction on Line Rating  
Line Az = 90, Air Temp = 70 F, Flux = 0

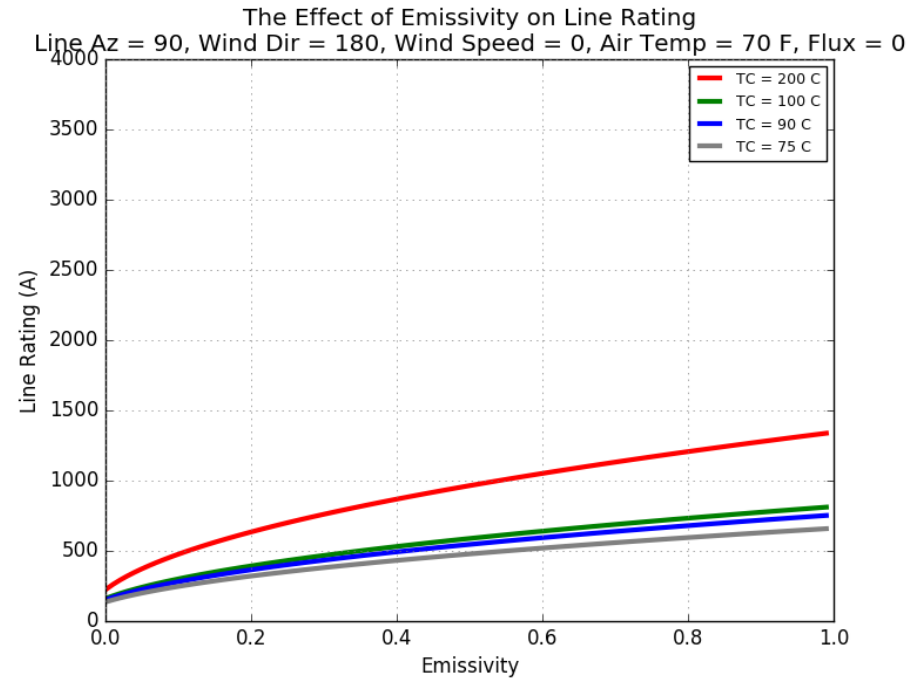


More line rating is gained for the same increase in wind speed at **higher conductor temperatures**.

# Absorptivity, Emissivity, and Conductor Temperature



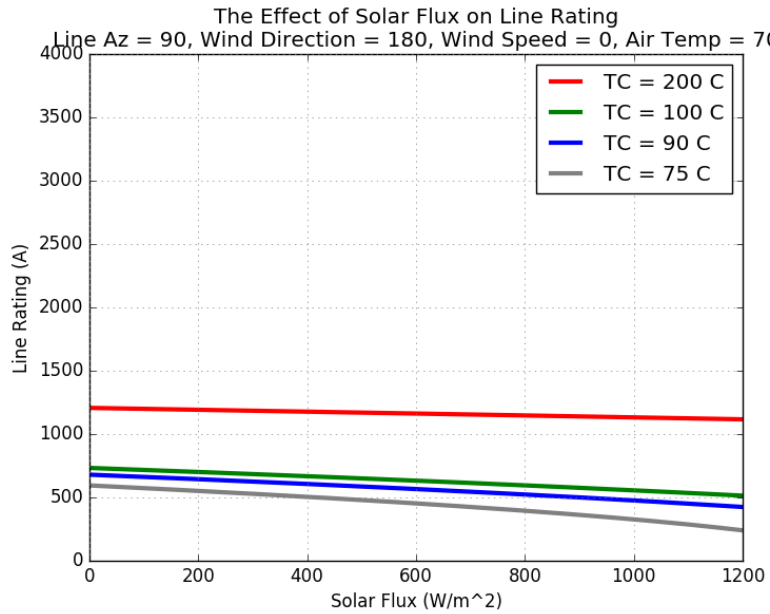
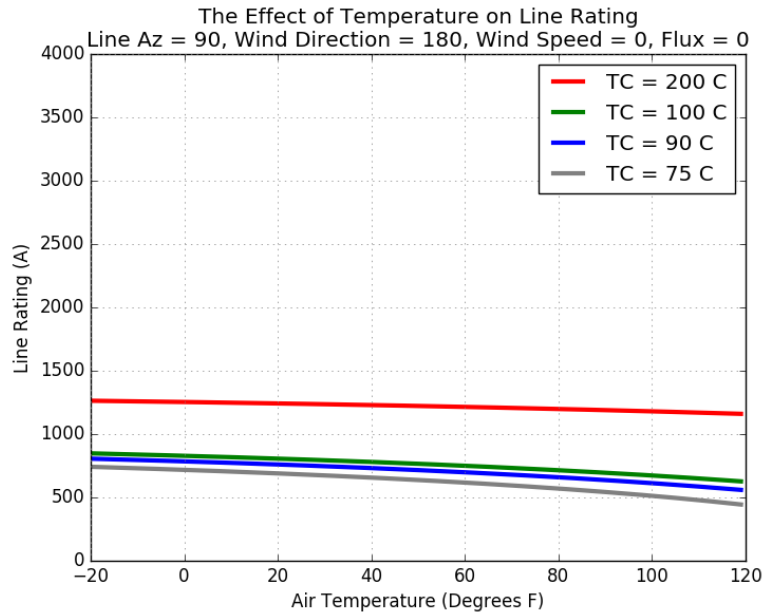
Absorptivity only makes a difference when there is solar flux on the line. The absorptivity of the line changes the rating more at **lower conductor temperatures**.



The emissivity of the line changes the rating more at **higher conductor temperatures**.

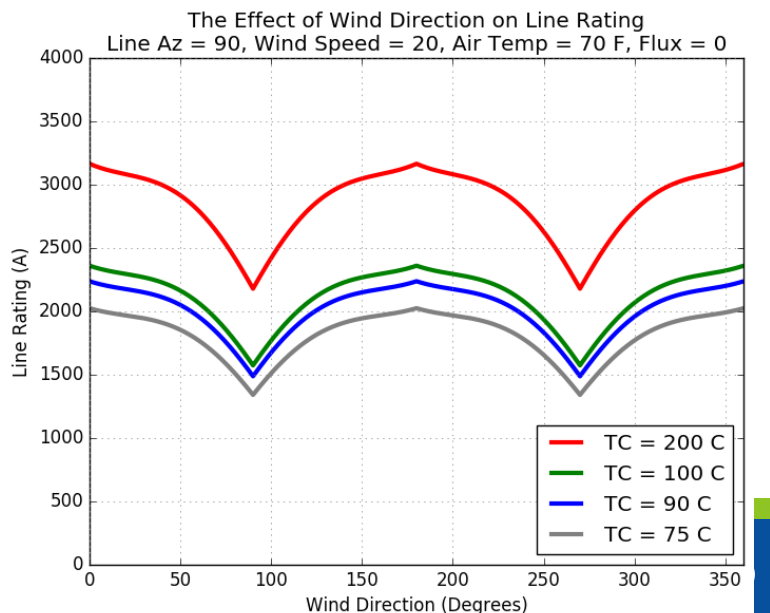
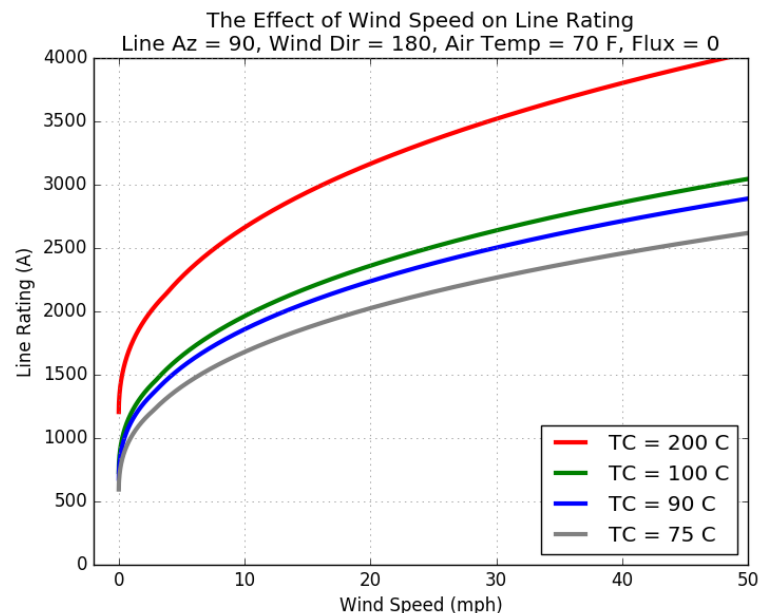
# Impact of Conductor Temperatures

The impact of temperature increases at lower conductor temperatures.



The impact of solar flux increases at lower conductor temperatures.

The impact of wind speed increases at higher conductor temperatures.



The impact of wind direction increases at higher conductor temperatures.

# Summary on DLR Sensitivity

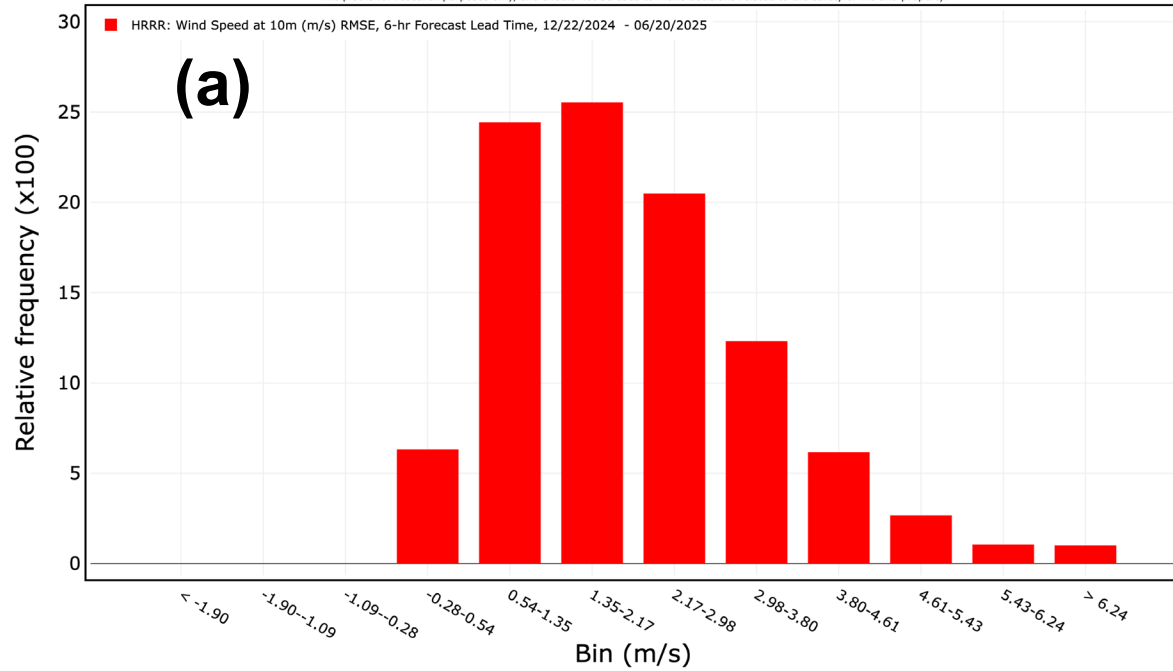


<b>Variable</b>	<b>Greater Impact at:</b>
Emissivity	Higher conductor temperature
Wind Direction	Higher conductor temperature
Wind Speed	Higher conductor temperature
Absorptivity	Lower conductor temperature
Solar Flux	Lower conductor temperature
Temperature	Lower conductor temperature

# 2020 Wind Speed Forecast Error Distribution

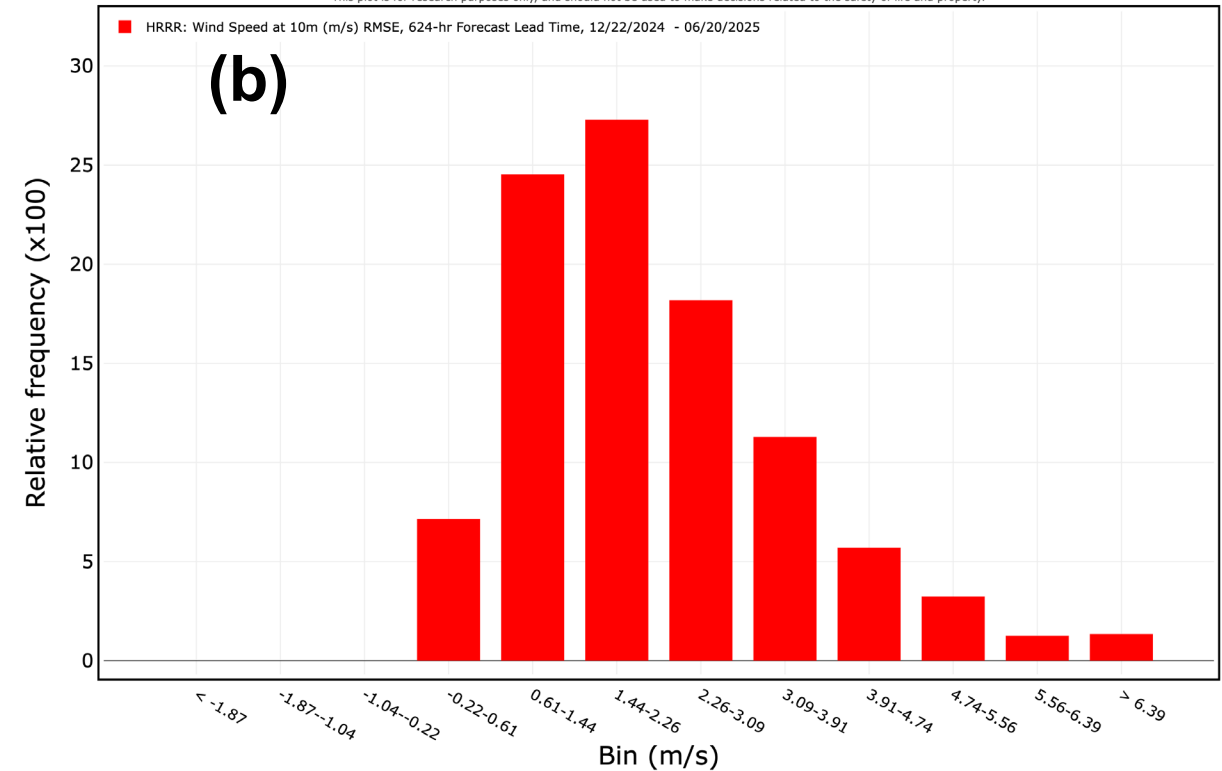
Surface : Histogram: no diffs UNMATCHED

This plot is for research purposes only, and should not be used to make decisions related to the safety of life and property.



Surface : Histogram: no diffs UNMATCHED

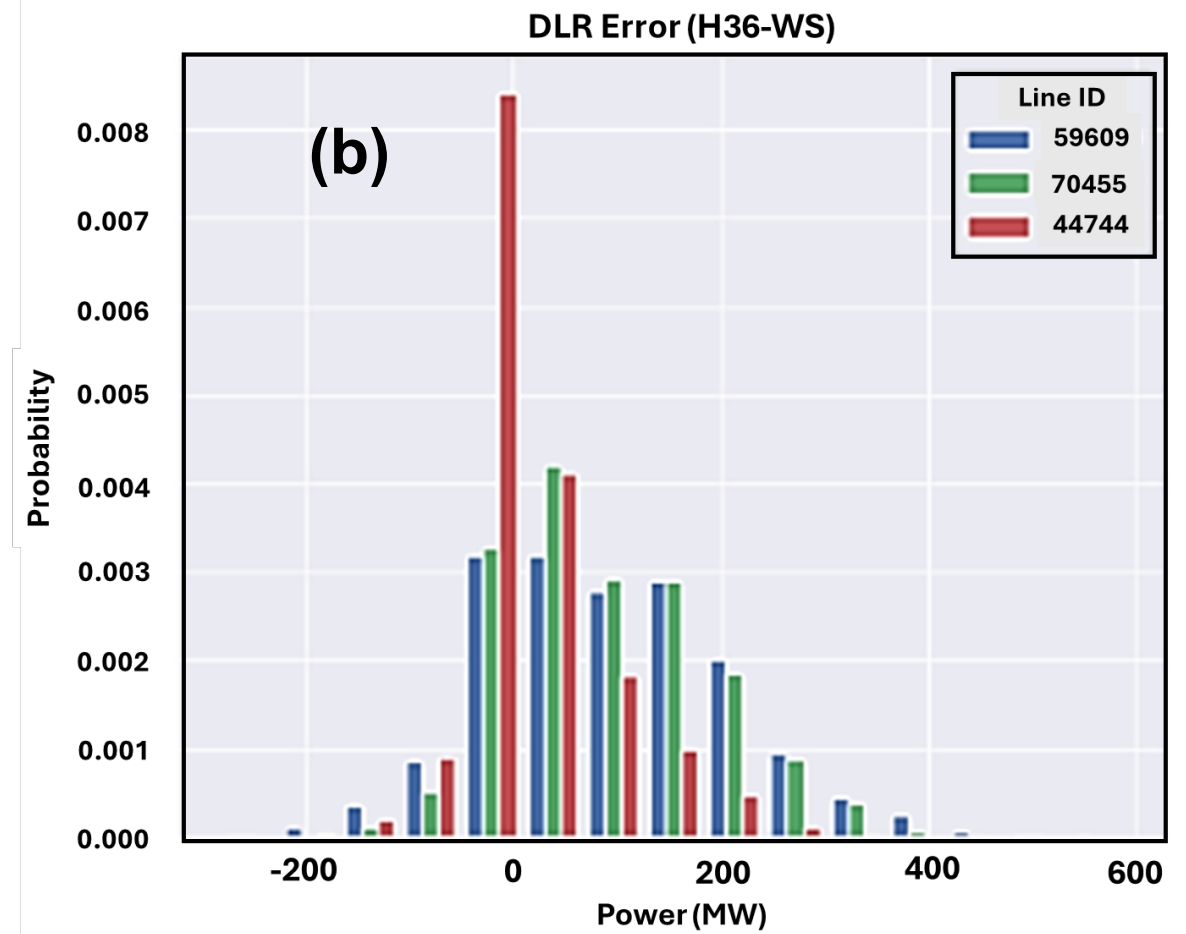
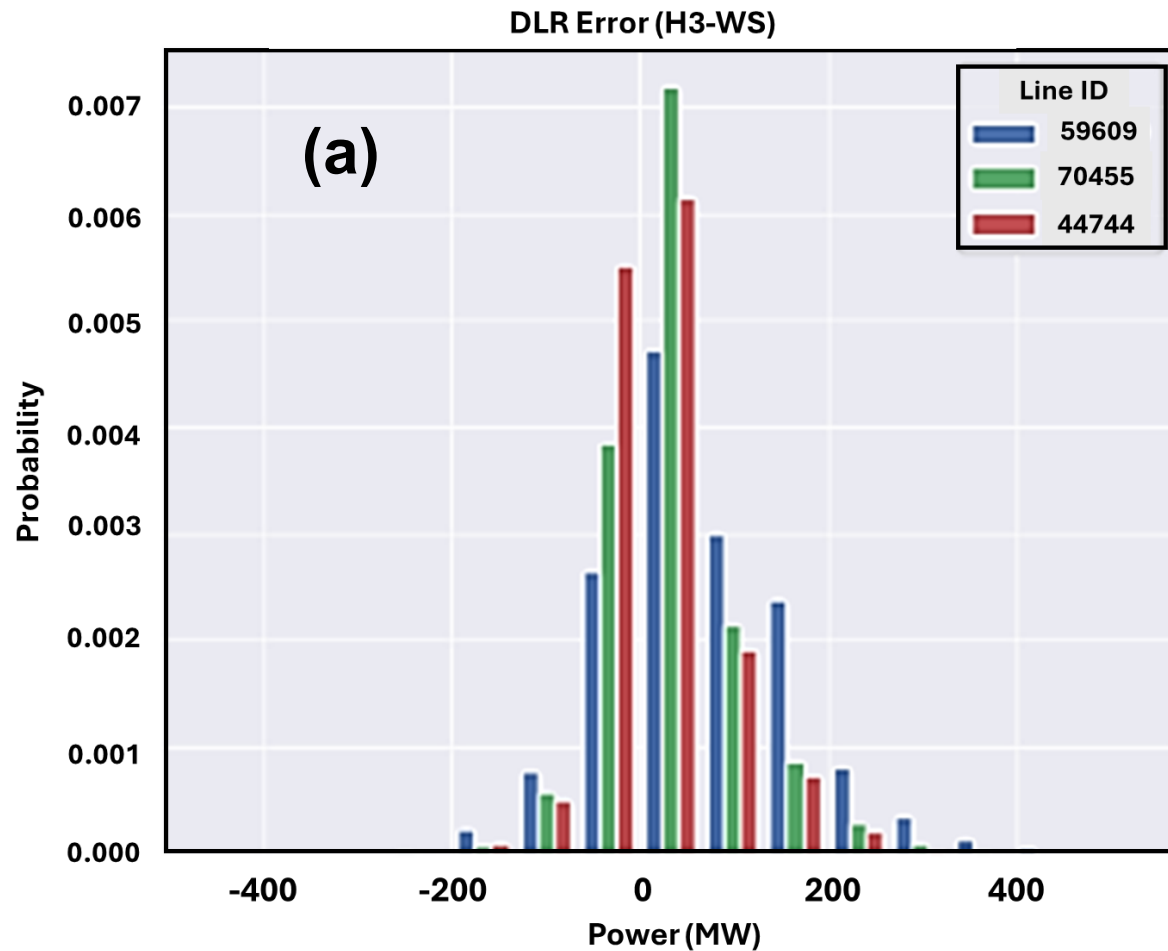
This plot is for research purposes only, and should not be used to make decisions related to the safety of life and property.



**(a) 6-hour, and (b) 24-hour.**

- 24-hour forecast error distribution is more positively skewed.

# 2020 DLR Error Distribution from Weather Forecast



Three 230 kV lines in NYISO: (a) Short-term, and (b) Long-term forecast error distribution.

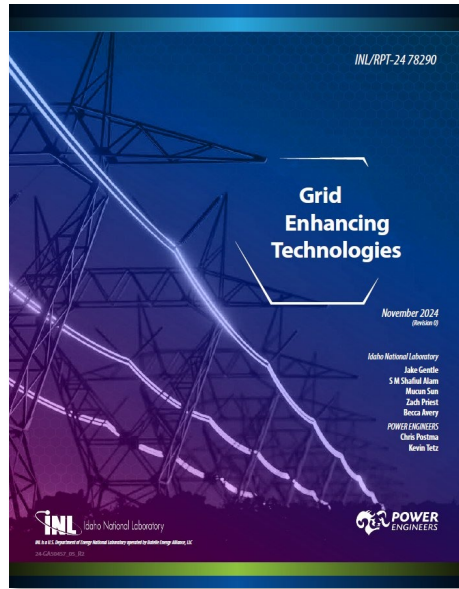
- Long-term forecast error distribution is more positively skewed. Similar pattern for the 115 kV Lines.

## Relevant Resources

- Sensitivity Effects of High Temperature Overhead Conductors to Line Rating Variables, <https://www.osti.gov/biblio/1678691>
- Dynamic Line Rating Forecast Time Frames, <https://www.osti.gov/biblio/1999389>
- Grid-Enhancing Technologies: A Case Study on Ratepayer Impact, <https://www.energy.gov/oe/articles/doe-study-shows-maximizing-capabilities-existing-transmission-lines-through-grid>

# Industry Driven Literature on GETs Integration and Control

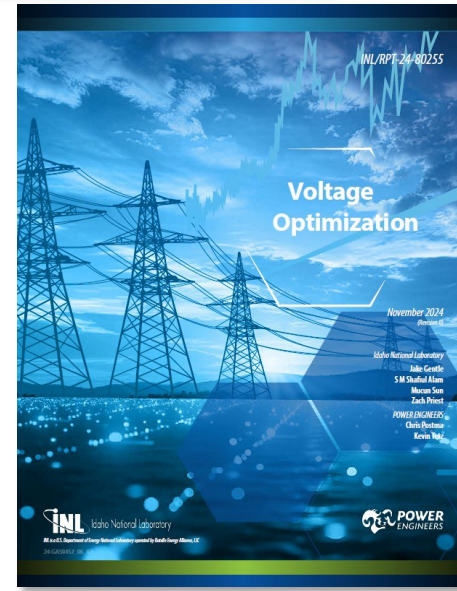
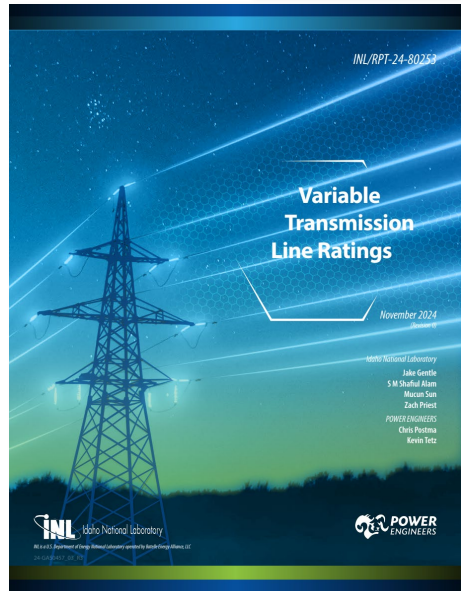
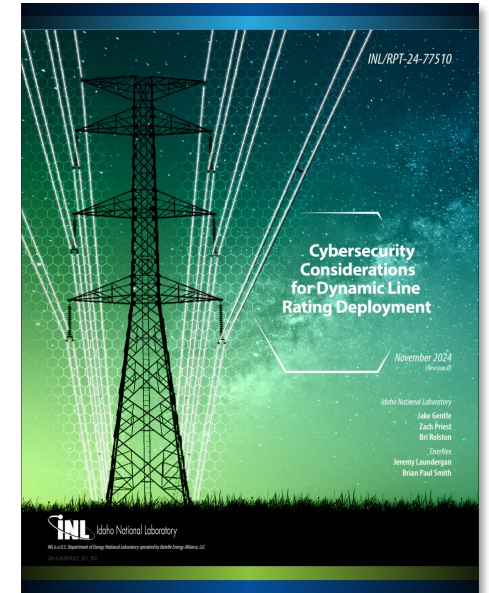
## The Basics



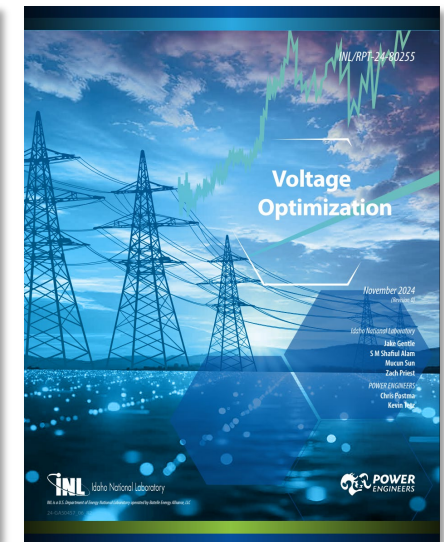
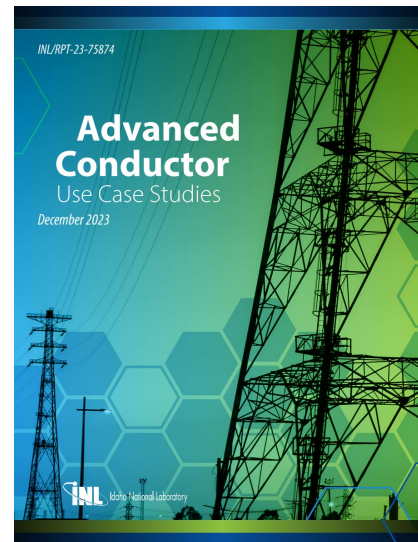
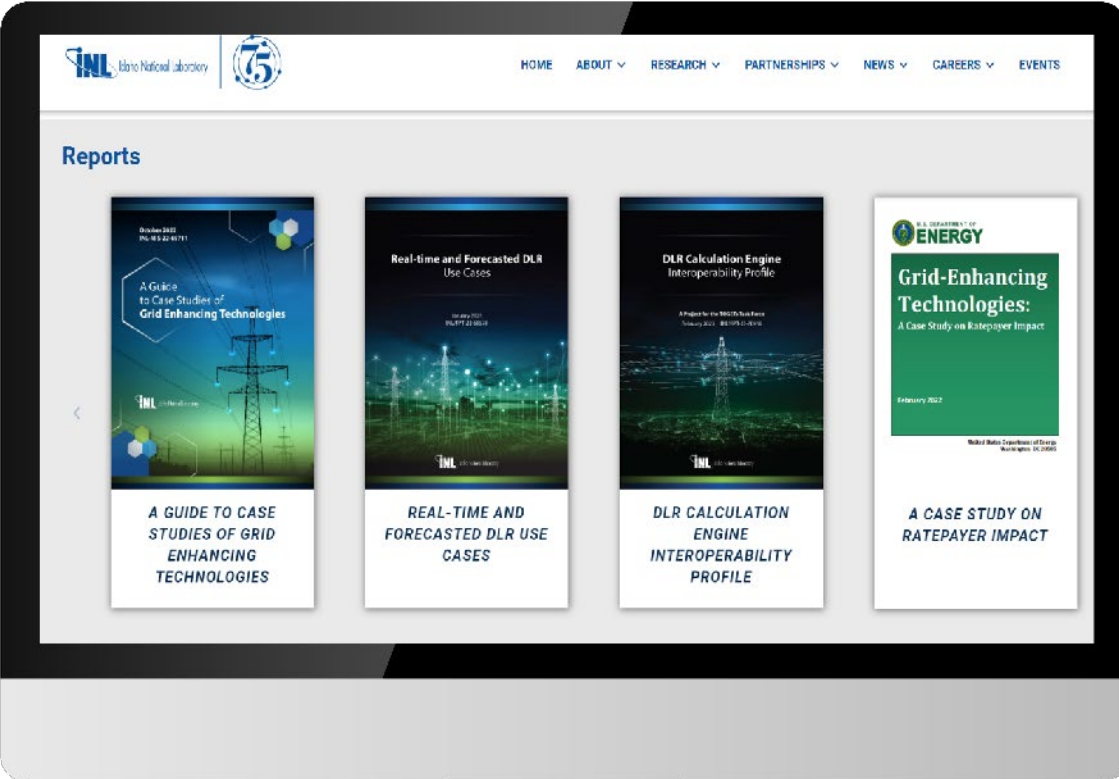
## The Control



## Cybersecurity



# Endless amounts of resources and expertise at INL



Email us with your questions!

Jake Gentle: [jake.gentle@inl.gov](mailto:jake.gentle@inl.gov)

S M Shafiul Alam: [smshafiul.alam@inl.gov](mailto:smshafiul.alam@inl.gov)



## Idaho National Laboratory

*Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.*