Forecasts for Dynamic Line Rating

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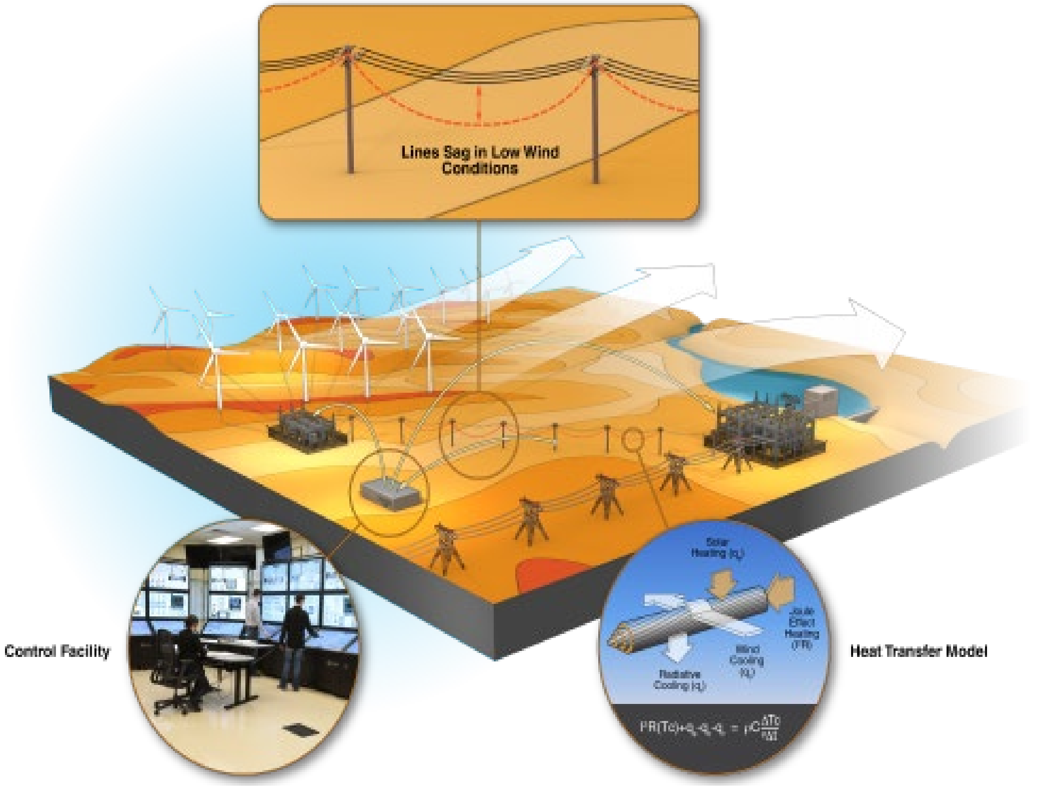

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Background

- IEEE/CIGRE standards provide a base for overhead transmission line ratings
  - Steady State Ampacity industry standard for Static Ratings using conservative environmental assumptions
- Measurement of many types of sensors provide a possibility to provide more capacity as a time varying capability
  - Direct sensors of line temperature, tension, or sag provide critical, location specific information.
  - Require complex transformation to determine line ampacity rating
  - Are direct measurements sensors placed at key location(s)?
  - Testing and careful calibration of sensors required
- Wide Area Weather based DLR can provide a calculation of the moment to moment steady state rating
  - Definition of weather station proximity to spans is critical – One weather station based calculation does not approximate a long line or a line with complex terrain.

Equations

- Heat balance of convective cooling, radiative heat loss, joule heating solar heating
- In order to solve the steady state equation, we need:

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

Where weather enters the equations directly

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

$$q_{c1} = K_{angle} \cdot \left[1.01 + 1.35 \cdot N_{Re}^{0.52}\right] \cdot k_f \cdot (T_s - T_a)$$

$$N_{Re} = \frac{D_0 \cdot \rho_f \cdot V_w}{\mu_f}$$

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

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

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

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

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

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

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

$$\theta = \arccos\left[\cos(H_c) \cdot \cos(Z_c - Z_l)\right]$$

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

$$q_s = \alpha \cdot Q_{se} \cdot \sin(\theta) \cdot A'$$

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

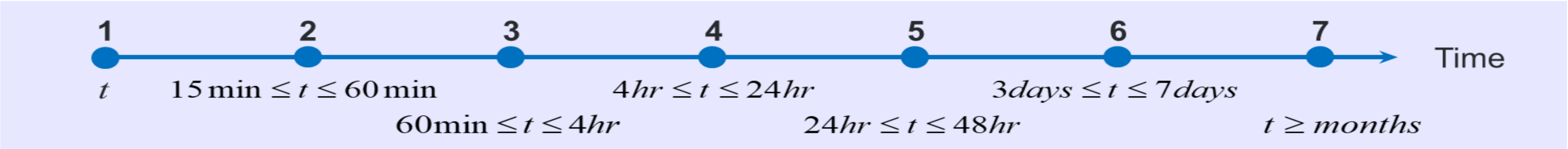
$$Z_c = C + \arctan(\chi)$$

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

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

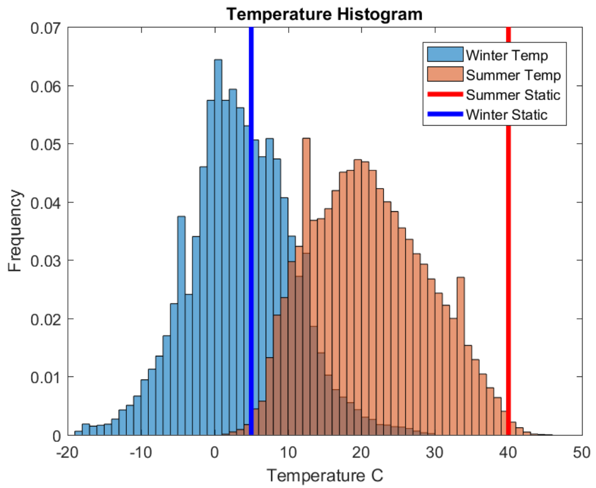
DLR Forecasting Suggested Timeline

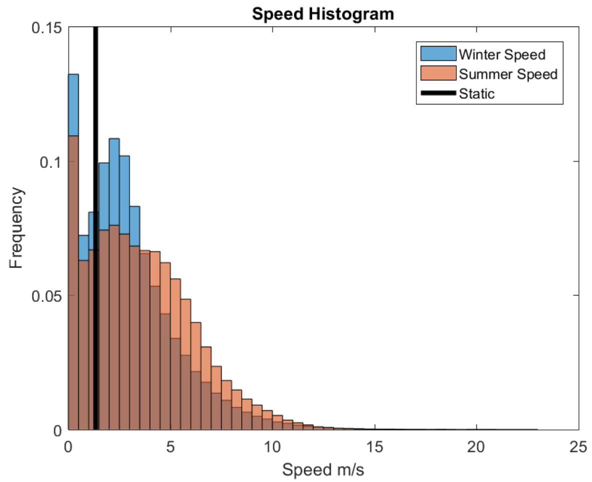
1. Instantaneous
2. Short-term: Thermal Inertia
3. Short-term look ahead
4. Daily Peak Loading, Generation Dispatch
5. Maintenance, Power Marketing
6. Maintenance, Marketing, Construction
7. Construction, Refurbishment, Voltage Upgrades

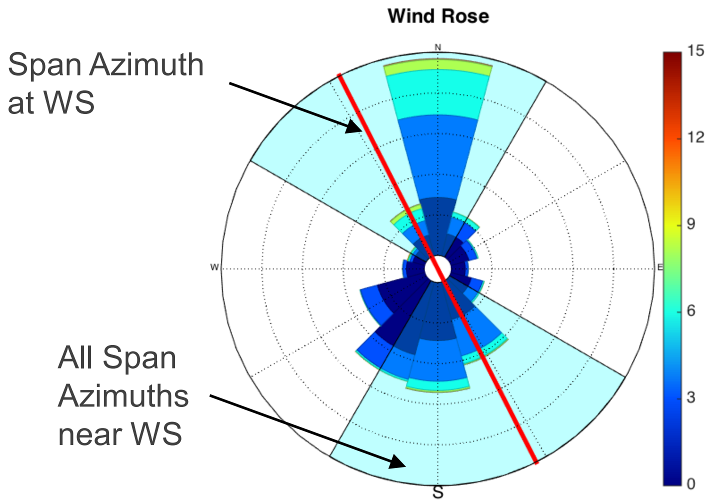


Visualization: How does weather data compare to static assumptions?

How does prevailing wind compare to transmission line direction?

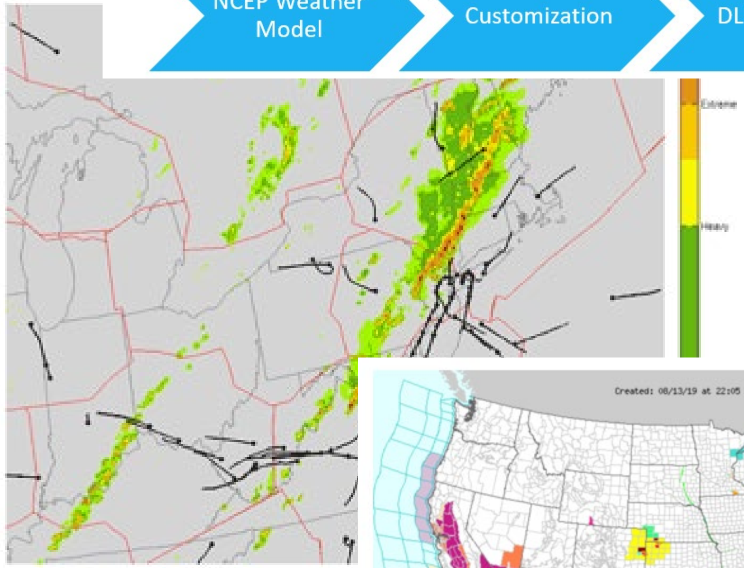


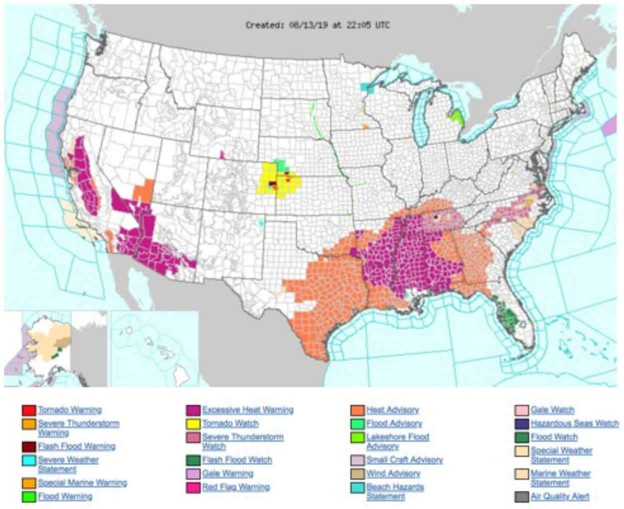




Regional Forecasting

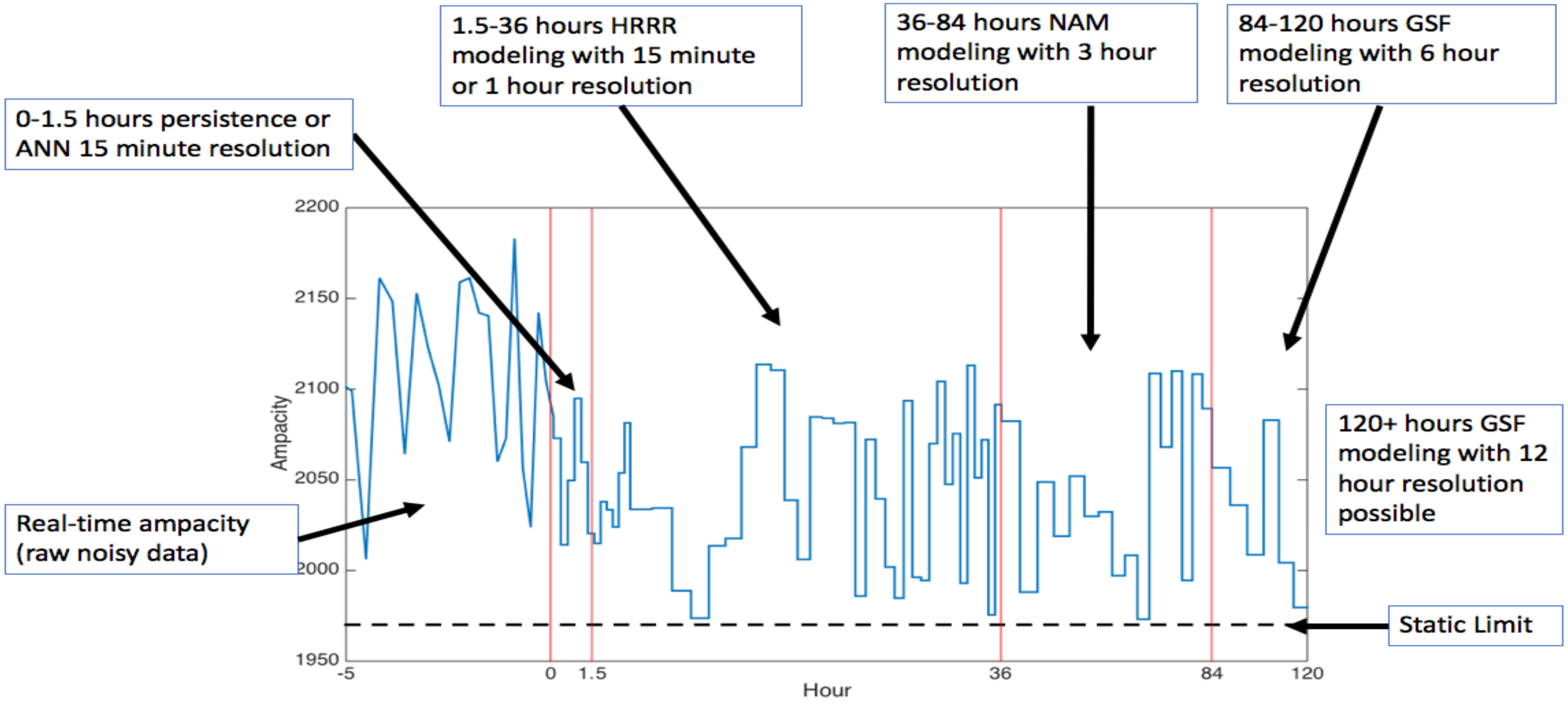
- Regularly used by FAA/NWS
- Use regional (mesoscale) forecasting to predict future line ratings
- Several US regional models openly available
  - Typically longer time range = less spatial accuracy
- High-Resolution Rapid Refresh (HRRR) model
  - 3 km spatial
  - 0-36 hour forecasts with 15 min - 1 hour (updated hourly)
- North America Mesoscale (NAM) model
  - 12 km spatial
  - 0-84 hours each 3 hours (updated 6 hours)
- Global Forecast System (GFS) model
  - 13 km spatial
  - 0-120 hours each hour, 120-249 each 3, 240-384 each 12 (updated 6 hours)
- HRRR has best potential for coupling with localized DLR calculations to spatial and temporal resolution
- Other models more applicable to longer-term applications
  - Maintenance, Power Marketing, Construction, Refurbishment, Voltage Upgrades





Regional Forecasting

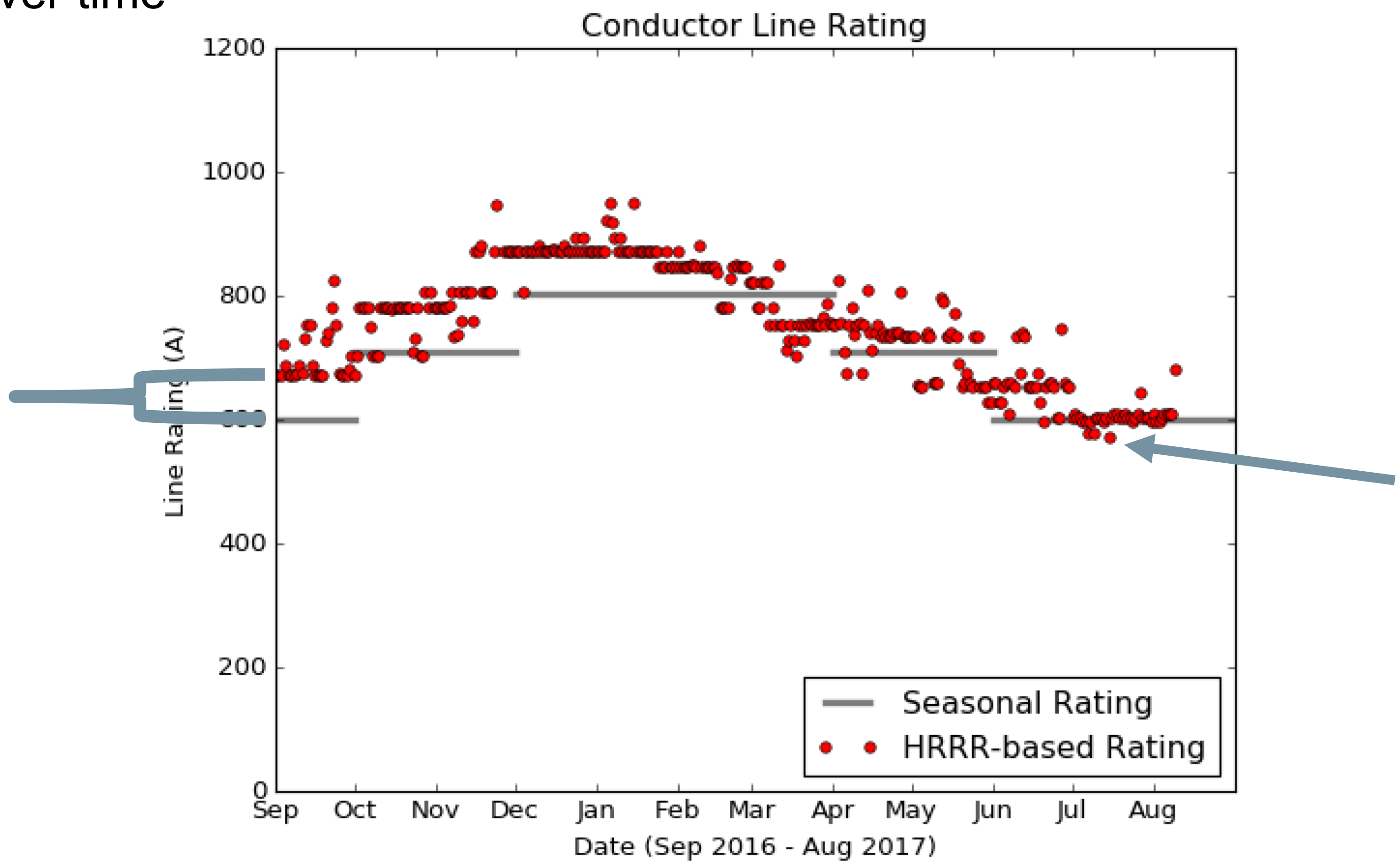
- Computation time frame delay occurs with obtaining updated regional forecast results
- Use ANN or persistence in region <1.5 hours in the future
- Beyond this, use regional forecasts with decreasing temporal updates based on how far in the future the forecast is needed



Line Rating with HRRR Forecasts

- To account for error, a 98th percentile threshold was applied to all HRRR data points
- Plot shows 3-hour ahead forecasts, but 18-hour forecast result is very similar as error does not increase much over time

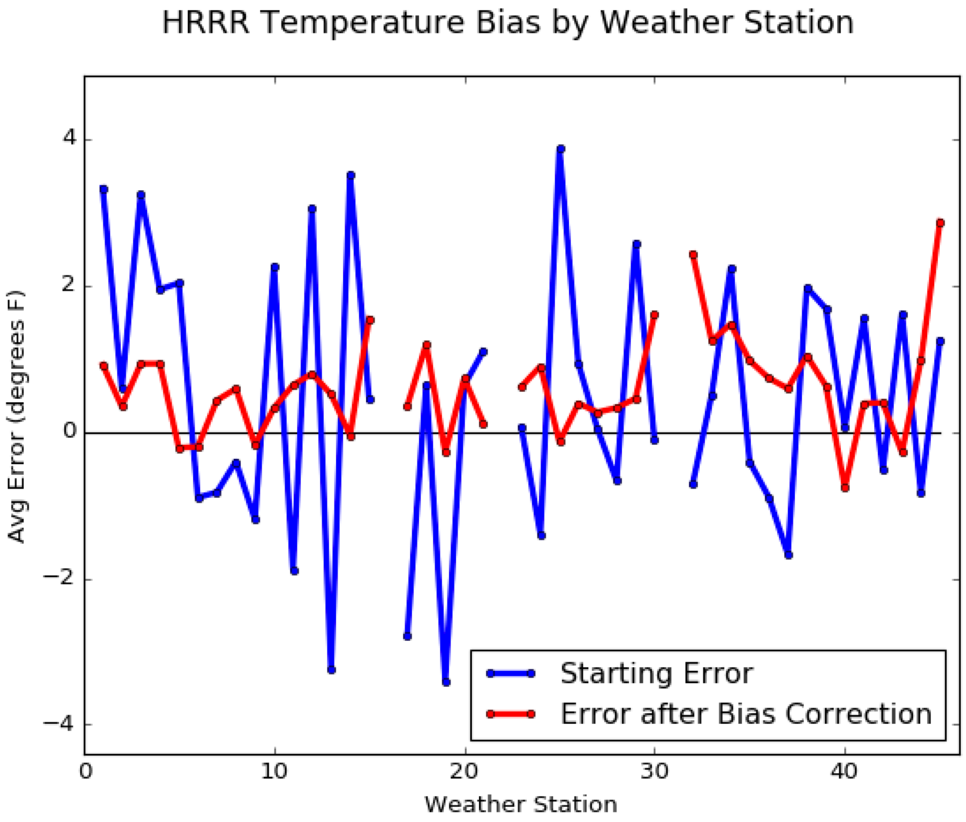
This is the additional capacity in the lines that could have been gained over the last year by using HRRR 90-minute forecasts



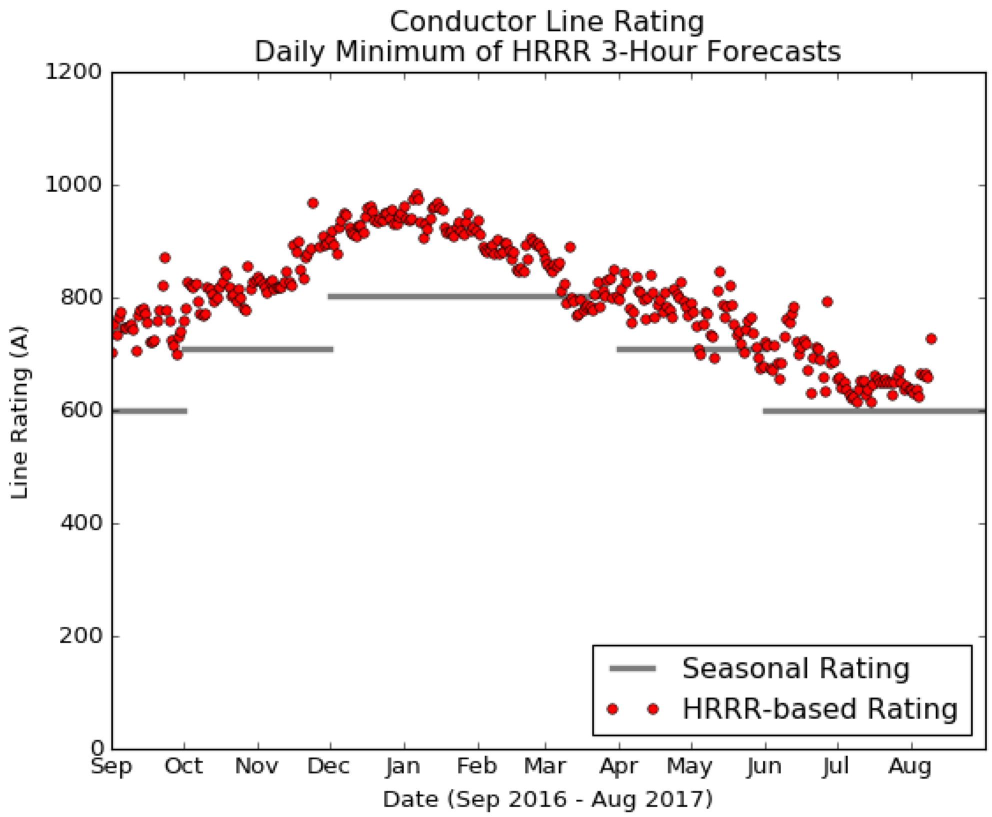
There are times, particularly during the spring and summer, where using the HRRR forecast would have led to a lower line rating, which includes the safety factor.

The Value of Local Weather Stations

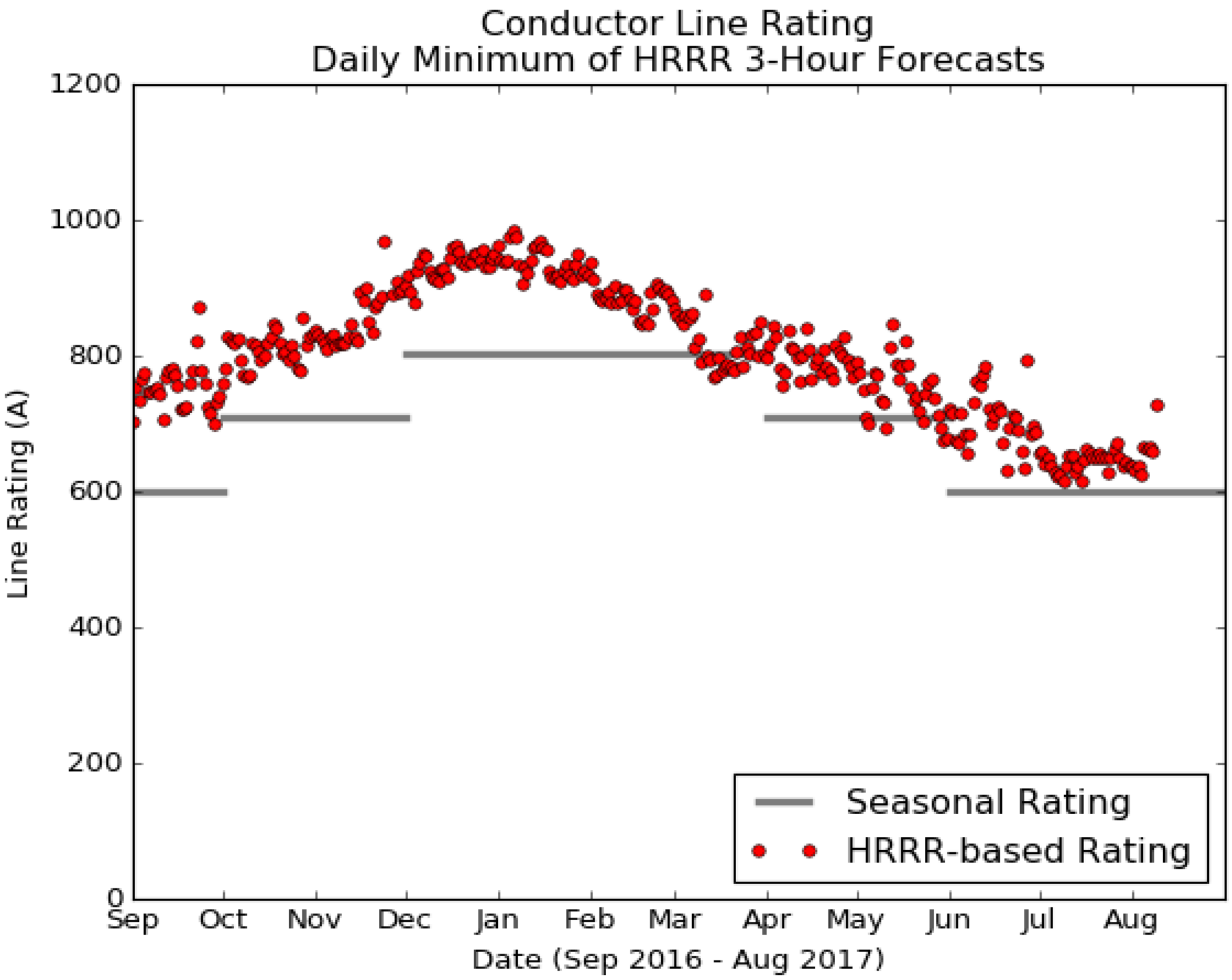
- Weather forecasts from models have biases that can be removed
  - Need weather stations along the lines to remove these biases



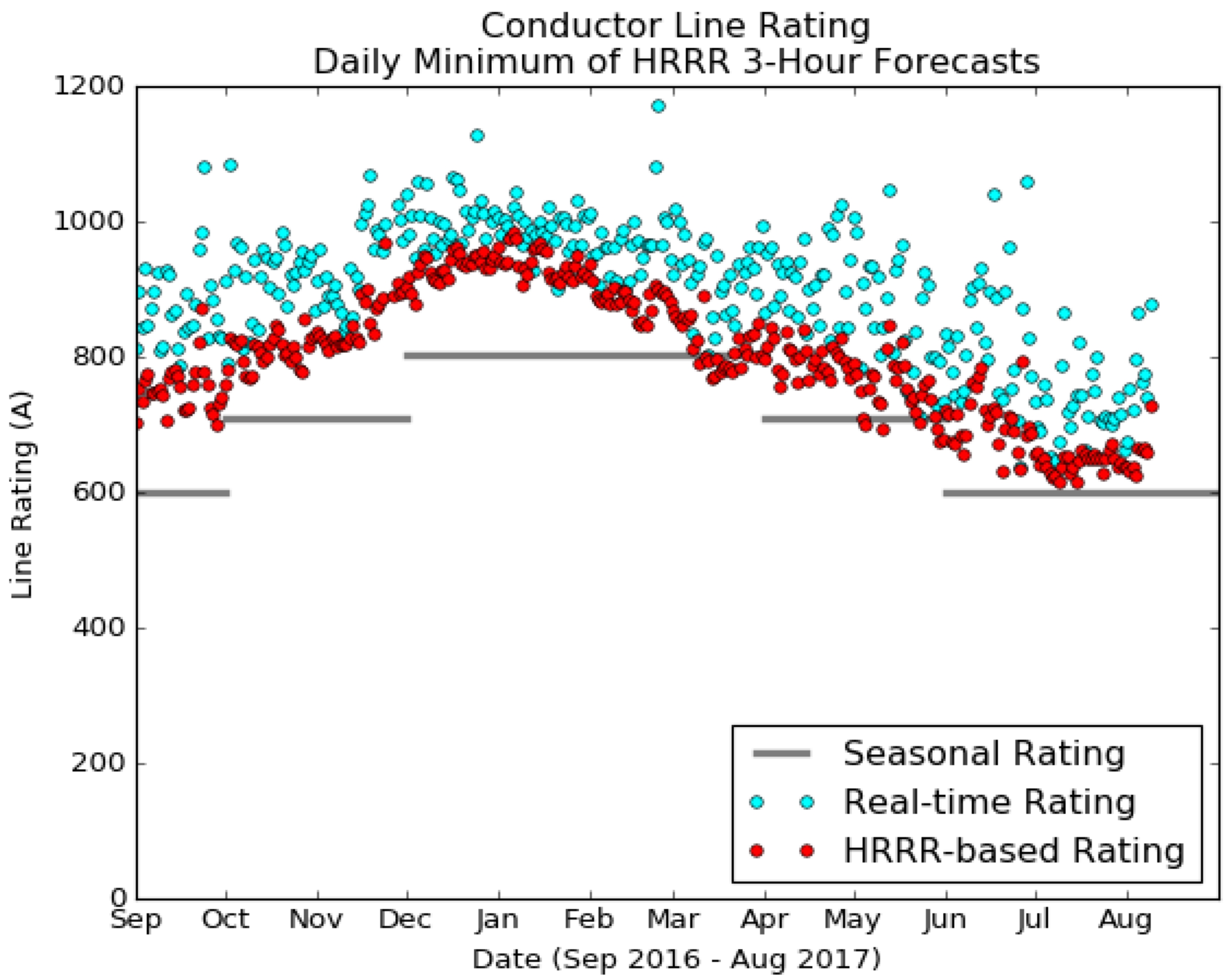
Bias Correction from Weather Stations



Line Rating with Raw HRRR Temperature

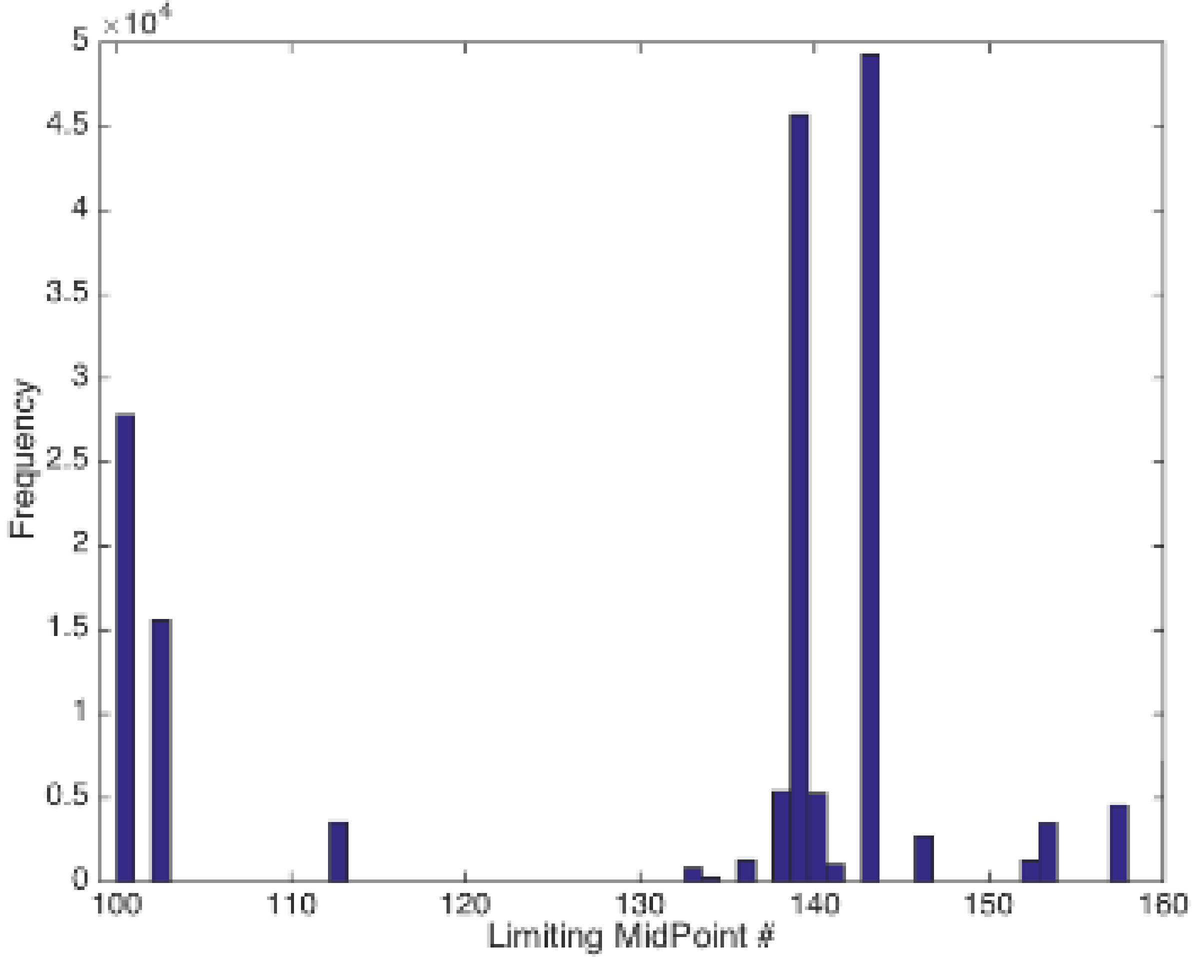


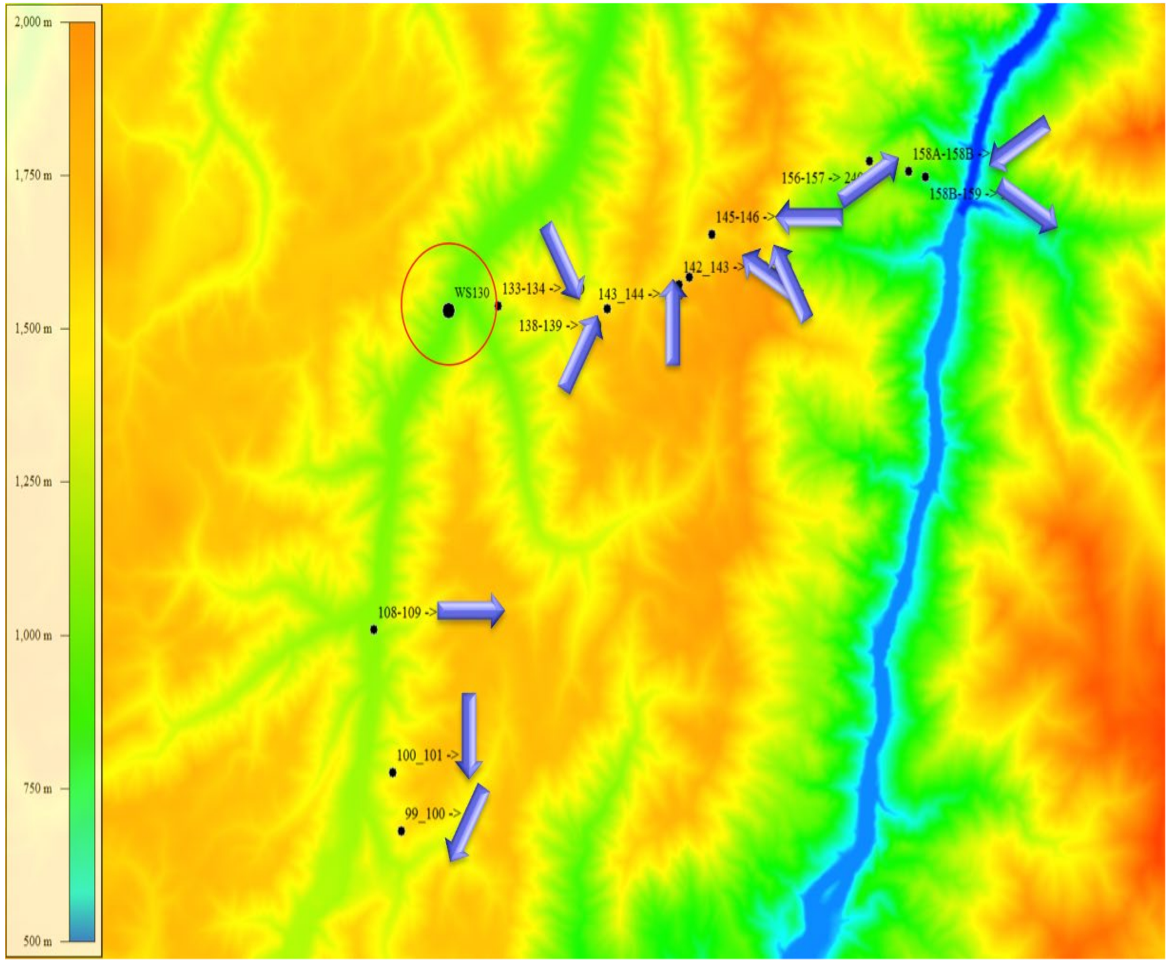
Line Rating with Raw HRRR Temperature



Limiting Span

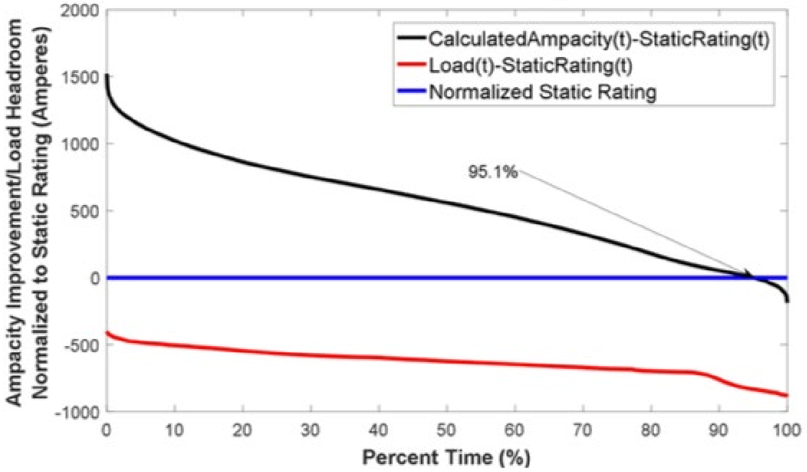
- Using weather based calculations, the limiting span can change based simply on wind direction

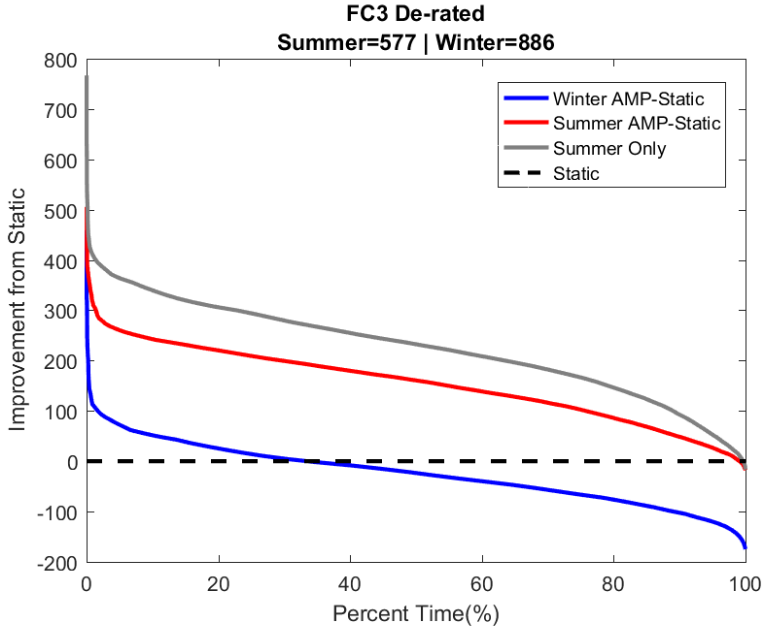




Various Case Studies of DLR Benefits

- REE: Spain, 400 kV transmission line potential
- Northern Ireland Electricity, 110 kV line 10-20% increase
- RTE: France, sag sensor on 400 kV lines
- Kepco, Worth Korea, 35% over static safely
- NYPA, demonstration 30 to 44% over static
- Oncor, 6-14% above AAR, 30-70% over static
- TERNA: Italy, stop-gap for network upgrades
- Idaho Power, situational awareness for 450 miles of lines
- Altalink, 22% capacity over static 76% of time
- World Bank: Vietnam, identified to improve efficiency for rapid growth
- AEP, study of 345-kV line shows $4M potential savings



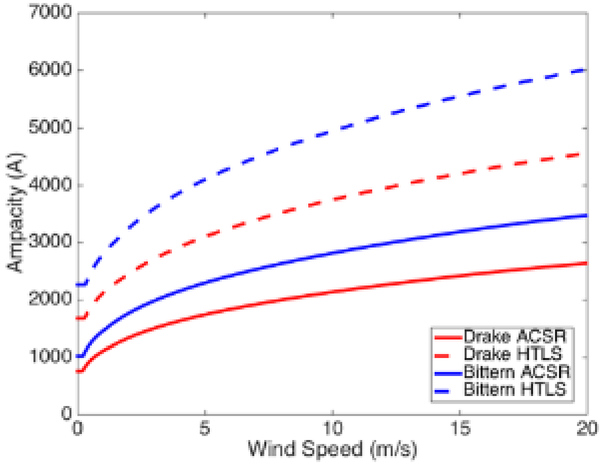


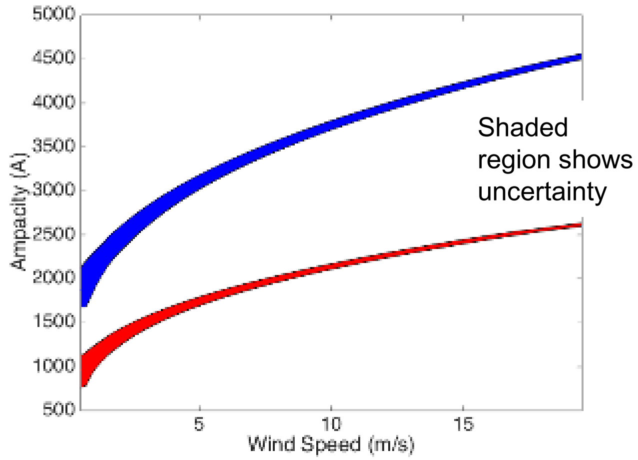
DLR Sensitivity & Error Propagation

- Spread shows 4, shaded shows Drake ACSR/HTLS (TC_{max} 80/200 C)
  - Slope of both direction and speed gets higher at larger conductor and higher TC_{max}
- Speed shows more spread at low speeds
- Direction shows more spread near parallel wind

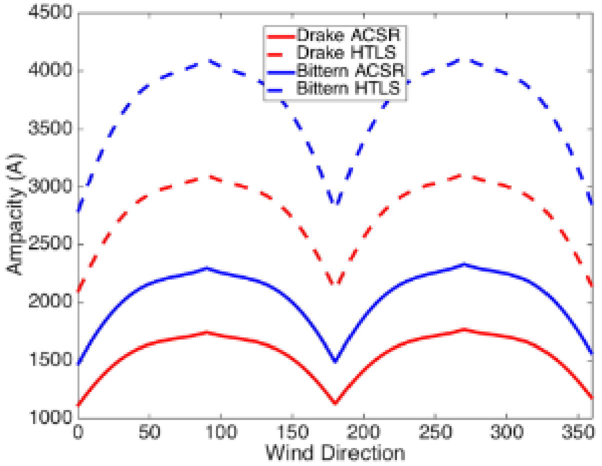
The impact of wind direction and speed increases at higher conductor temperatures and with larger conductor diameter

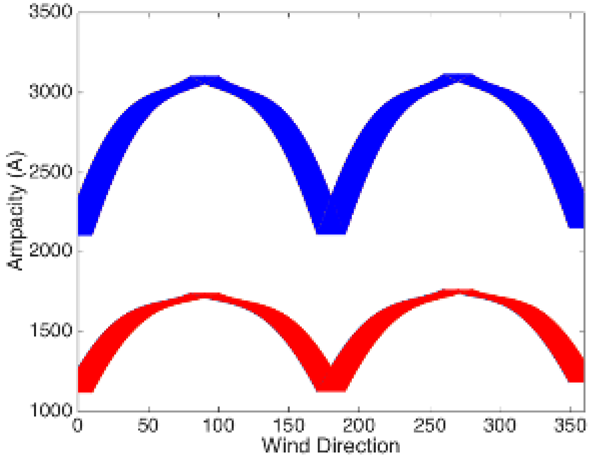
Wind Speed





Wind Direction



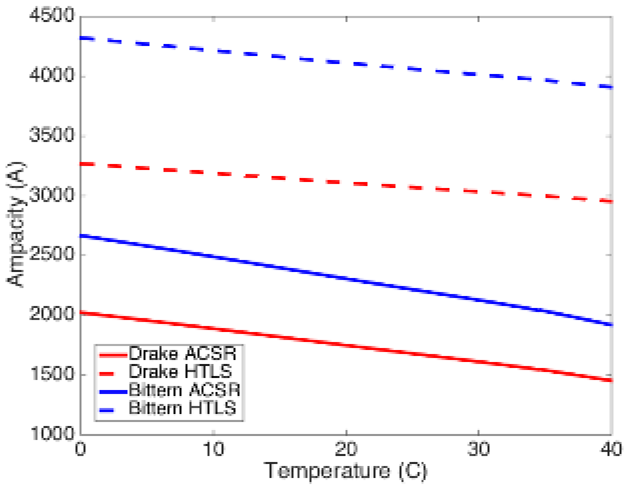


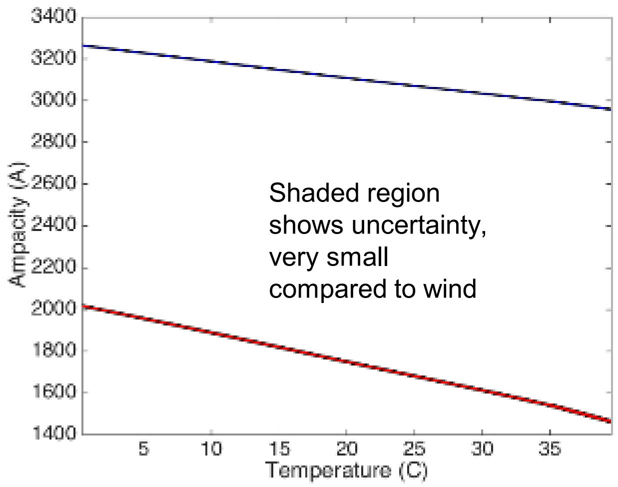
DLR Sensitivity & Error Propagation

- Spread shows 4, shaded shows Drake ACSR/HTLS (TC_{max} 80/200 C)
- Changes in ampacity from temperature are smaller than wind
- Changes from solar uncertainty are minor

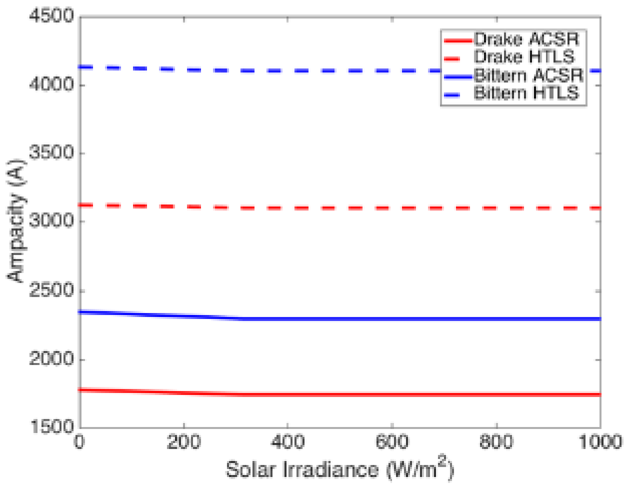
The impact of solar flux and ambient temperature decreases with higher conductor temperatures
Negligible change with conductor diameter

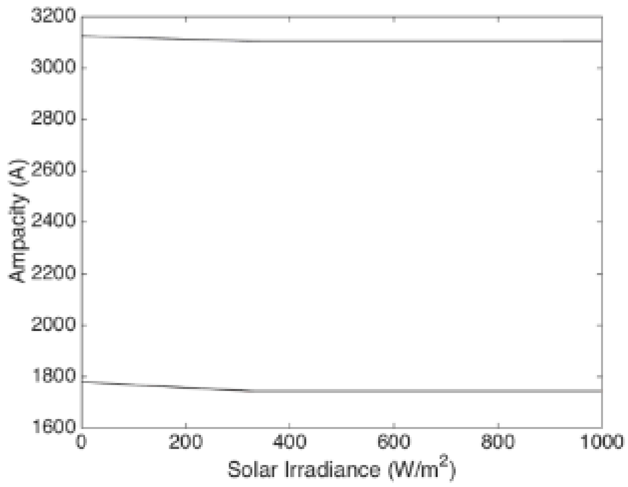
Temperature





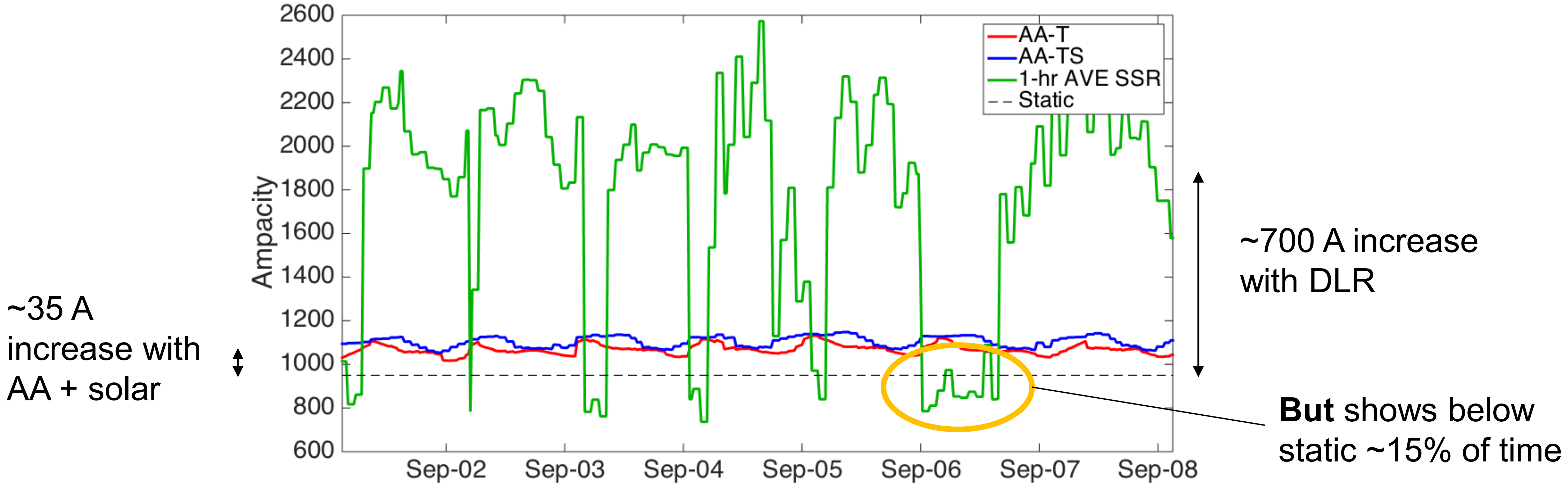
Solar Flux





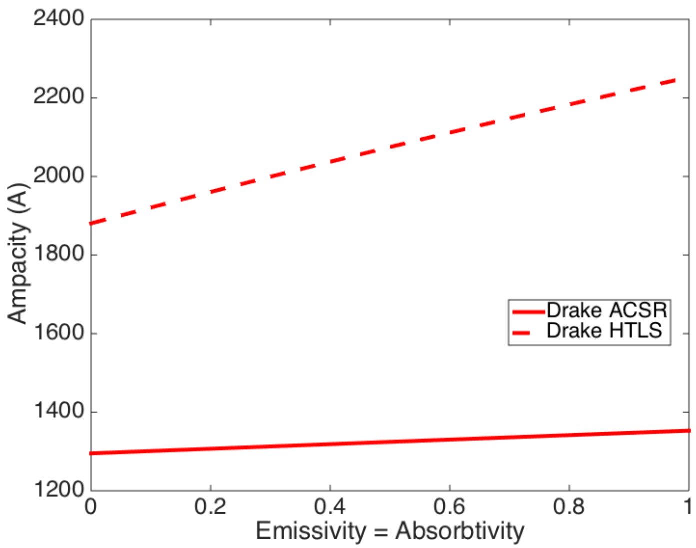
DLR vs Ambient Adjusted

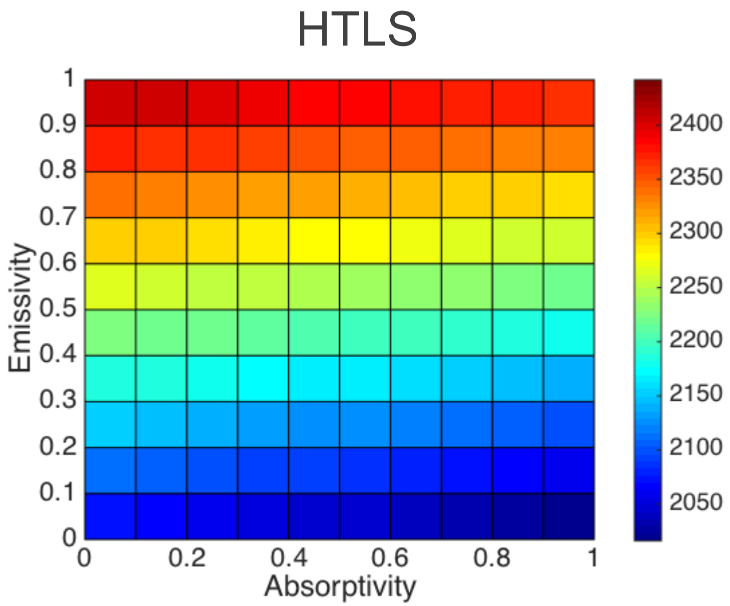
- As shown in previous sensitivity plots, more ampacity is gained from wind speed and direction than solar or temperature adjustments
  – This plot shows the risk when wind speed drops and you assume static values
- Utility reference line with static parallel wind at 3.0 m/s with AA – temperature (1000 A/m^2 solar), AA – temperature + solar and 1-hr averaged SSR (based on IEEE 738)
  – Increase using solar adjustments over typical AA is minor

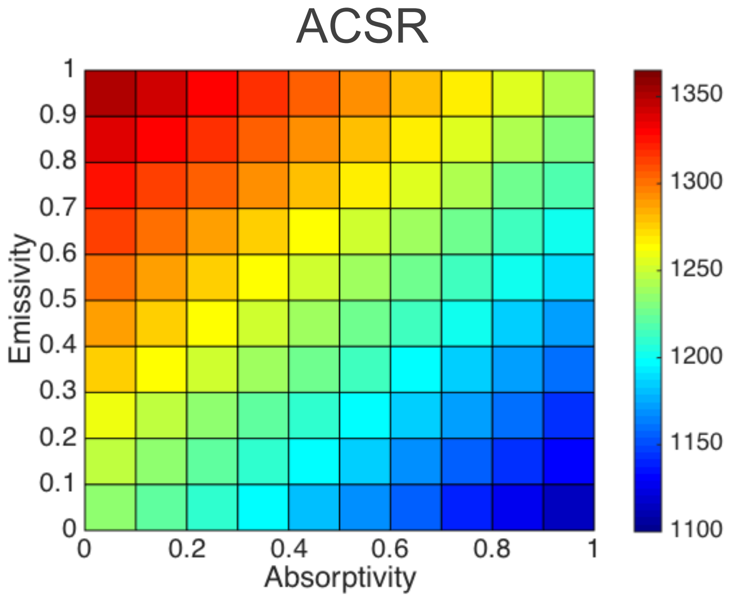


DLR Sensitivity – Line Properties at High Temperature

- For high temperature conductors, i.e. TC_{max} at 200 C instead of 80 C (ACSR vs. HTLS), the sensitivity changes
- Heat loss from thermal radiation becomes a more important factor
- ACSR, variation in emissivity ~50 A, increases to ~350 A with HTLS
  - **Characterization of this value is important for high Temp lines**
- More variation with absorptivity with ACSR







Continued Research

- Determination of localized forecast accuracy across different areas in CONUS
  - Idaho
  - New York
  - Texas
  - California

- Assess how uncertainties in the forecasts propagate through the system calculations in these case studies
- Improve uncertainty quantification of weather forecast impacts
- Determine set of best practices for using forecasts based on uncertainty
  - Specific cases for regions and line lengths

- Assess DLR impacts for economics benefits/costs & coupled with other grid topics (generation/storage/usage)

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