Hourly dynamic line ratings for existing transmission across the contiguous United States (preliminary results)

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Study context

Many studies have demonstrated the value of dynamic line ratings (DLR) :

- INL 2022 – A Guide to Case Studies of Grid Enhancing Technologies
- DOE 2022 – Grid-Enhancing Technologies: A Case Study on Ratepayer Impact
- DOE 2019 – Dynamic Line Rating
- Bhattarai et al. 2018 – Improvement of Transmission Line Ampacity Utilization by Weather-Based Dynamic Line Rating
- Karimi et al. 2018 - Dynamic thermal rating of transmission lines: A review
- Fernandez et al. 2016 - Review of dynamic line rating systems for wind power integration
- …

Many of these studies cover small collections of transmission lines or limited geographic regions.

But there are tens of thousands of transmission lines spread across the contiguous U.S., and quantitative findings for particular transmission lines or regions might not provide an accurate estimate of DLR benefits across the U.S. as a whole.

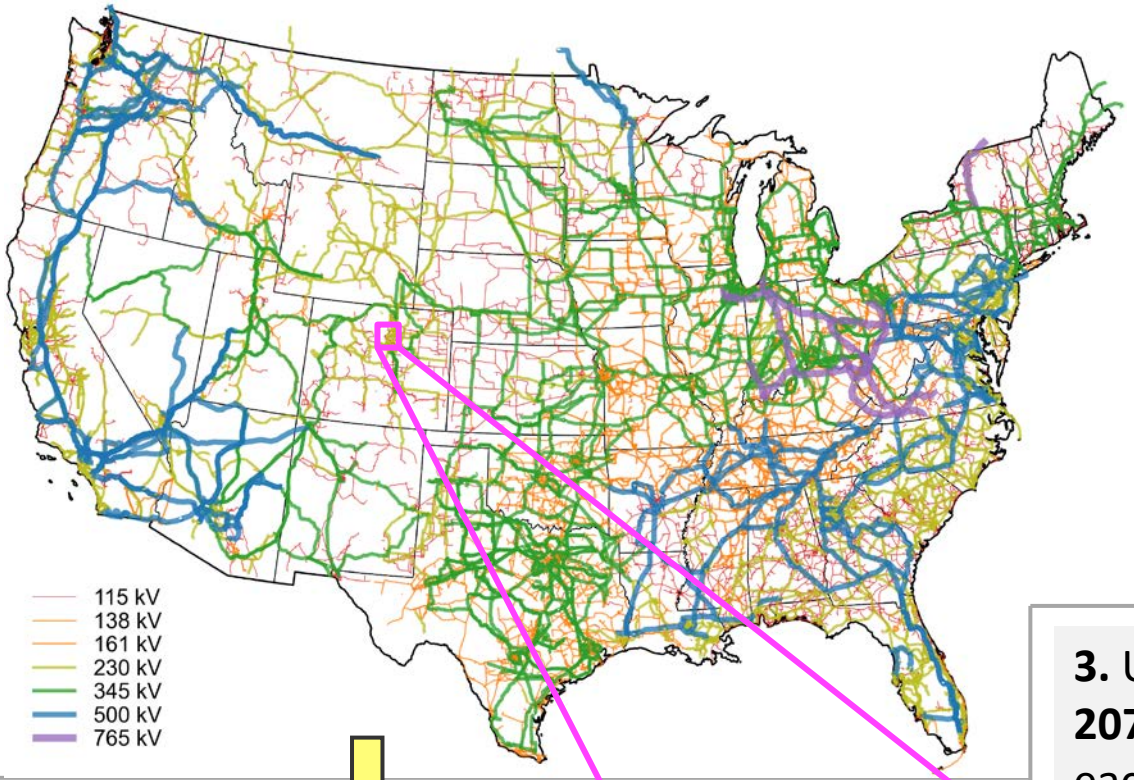
Here, we:

- Estimate hourly DLRs for ≥50,000 high-voltage transmission lines across the contiguous U.S. using publicly available line routes and historical weather for 2007–2013
- Compare ratings using different combinations of hourly weather data (air temperature, solar irradiance, and wind speed/direction)

Overview: Estimating dynamic line ratings (DLR) using historical weather

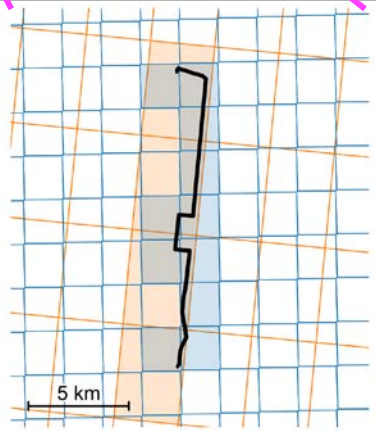
1. Transmission line routes [HIFLD]

https://hifld-geoplatform.hub.arcgis.com/datasets/geoplatform::transmission-lines



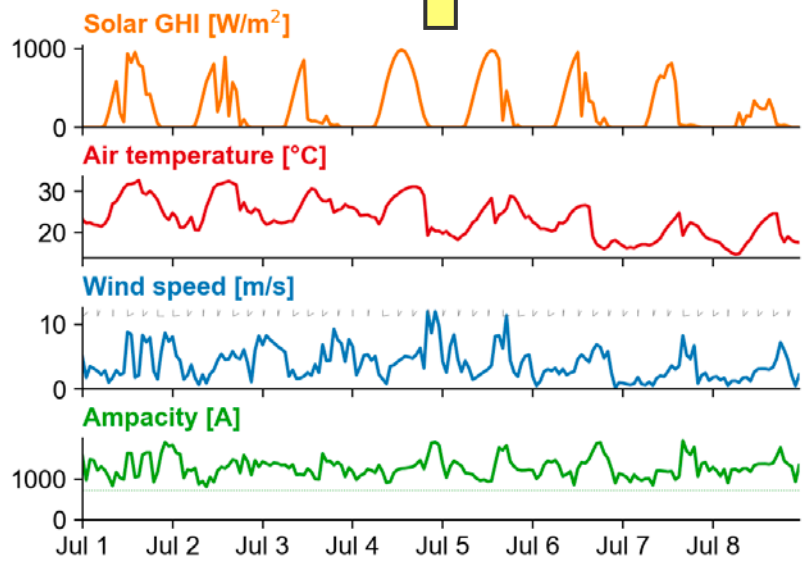
2. Line up routes with 2km **WIND Toolkit** and 4km **NSRDB** grid cells (hourly weather for 2007–2013)

https://nsrdb.nrel.gov/
https://www.nrel.gov/grid/wind-toolkit.html

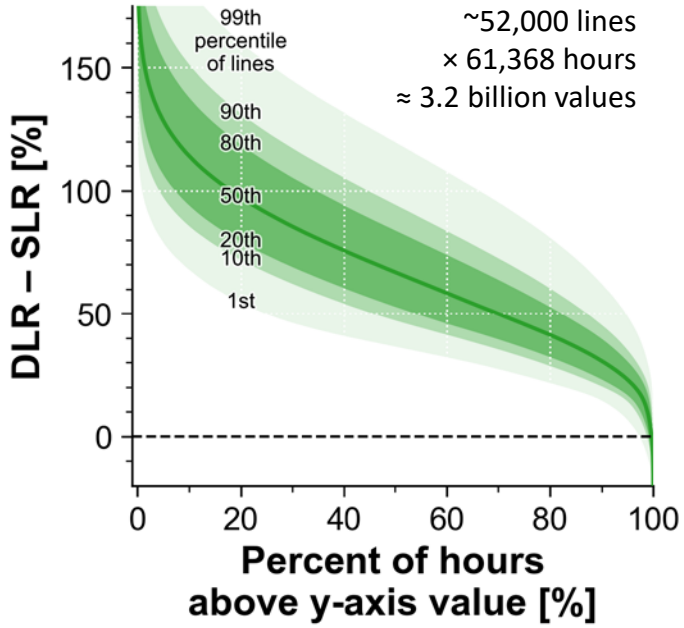


3. Use **IEEE 738** and **CIGRE 207** to calculate **ampacity** of each segment, assuming a fixed conductor temperature and factoring in:

- Convective cooling
- Radiative cooling
- Solar heating



4. Assemble **statistics** on the changes in ratings between different line rating frameworks across all **lines** and weather **hours**



Study scope: Estimating DLRs using historical weather

What does this study **do**?

- **Historical** assessment using 2007–2013 weather from WTK/NSRDB
- Calculate ratings consistent with a **steady-state conductor design temperature** using IEEE 738-2012
- Assume **ACSR** conductor parameters, with a **single representative conductor type** per voltage level
- Assess the impact of different line rating methods on **hourly ratings**

What does this study **NOT** do?

- Assess **forecastability**
- Account for **climate change** impacts
- Model line sag and clearance for **individual spans**
- Account for **wildfire** risk or **icing/wind loads**
- Consider **emergency** ratings
- Account for the **actual conductor type** installed on each line (which is not public information)
- Assess ratings of **transformers** / **breakers** / etc
- Assess the **cost** of implementing different rating methods
- Assess the economic/social **benefits** (congestion reduction, production cost savings, emissions mitigation) of different rating methods

Methodology: Line ratings (IEEE 738 and CIGRE 207)

Convective cooling (IEEE)

$$q_c = \max\left(q_c^{zero}, q_c^{low}, q_c^{high}\right)$$

$$q_c^{zero} = 3.645 \cdot \rho_{air}^{1/2} \cdot D^{3/4} \cdot (T_{conductor} - \boldsymbol{T_{air}})^{5/4}$$

$$q_c^{low} = K \cdot \left(1.01 + 1.35 \cdot N_{Re}^{0.52}\right) \cdot k_{air} \cdot (T_{conductor} - \boldsymbol{T_{air}})$$

$$q_c^{high} = K \cdot 0.754 \cdot N_{Re}^{0.6} \cdot k_{air} \cdot (T_{conductor} - \boldsymbol{T_{air}})$$

$$N_{Re} = \frac{D \cdot \rho_{air} \cdot \boldsymbol{v_{wind}}}{\mu_{air}}$$

$$K = 1.194 - \cos(\boldsymbol{\phi}) + 0.194\cos(2\boldsymbol{\phi}) + 0.368\sin(2\boldsymbol{\phi})$$

$$\rho_{air} = \frac{\boldsymbol{P_{air}}}{N_A k_B \boldsymbol{T_{air}}}$$

Radiating cooling (IEEE)

$$q_r = \pi \cdot D \cdot \mathrm{k_B} \cdot \left(T_{conductor}^4 - \boldsymbol{T_{air}^4}\right)$$

Solar heating (CIGRE)

$$q_s = \alpha \cdot D \cdot \mathrm{GHI}$$

Ampacity

$$q_{resistive} = I^2 R = q_c + q_r - q_s$$

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

https://doi.org/10.1109/IEEESTD.2013.6692858
https://www.e-cigre.org/publications/detail/207-thermal-behaviour-of-overhead-conductors.html

Physical parameters

k_{air} = thermal conductivity of air
μ_{air} = dynamic viscosity of air
N_{Re} = Reynolds number
N_A = Avogadro's number
k_B = Boltzmann constant

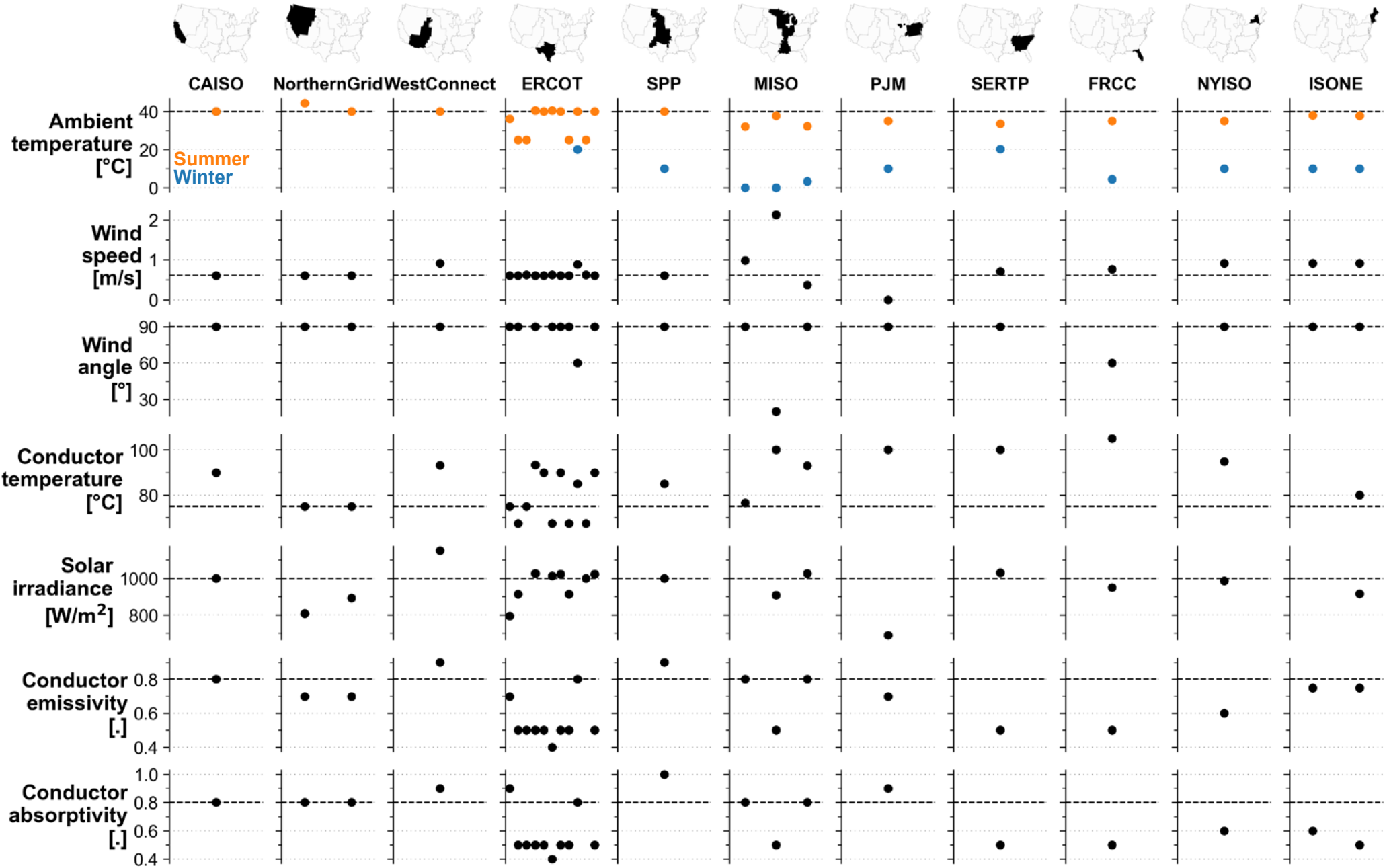
Conductor parameters

R = resistance
D = diameter
α = absorptivity (0.8)
ε = emissivity (0.8)
$T_{conductor}$ = max temperature (75°C)

Hourly weather parameters

T_{air} = air temperature (10m, WTK)
v_{wind} = wind speed (10m, WTK)
ϕ = angle between wind and conductor headings (10m, WTK)
P_{air} = air pressure (0m, WTK)
GHI = global horizontal irradiance (NSRDB)

Literature review: Static & seasonal line rating parameters



Data source (x axis):

CAISO
- Southern California Edison

NorthernGrid
- Nevada Power Company
- Sierra Pacific Power Company

WestConnect
- Southwest Transmission Cooperative

ERCOT
- CenterPoint
- TNP
- CPS
- LCRA
- Austin Energy
- STEC
- TXUED
- BPUB
- AEP
- TMPA
- Garland

SPP
- SPP

MISO
- Hoosier Energy
- MidAmerican Energy Company
- American Transmission Company

PJM
- PJM

SERTP
- Progress Energy Carolinas

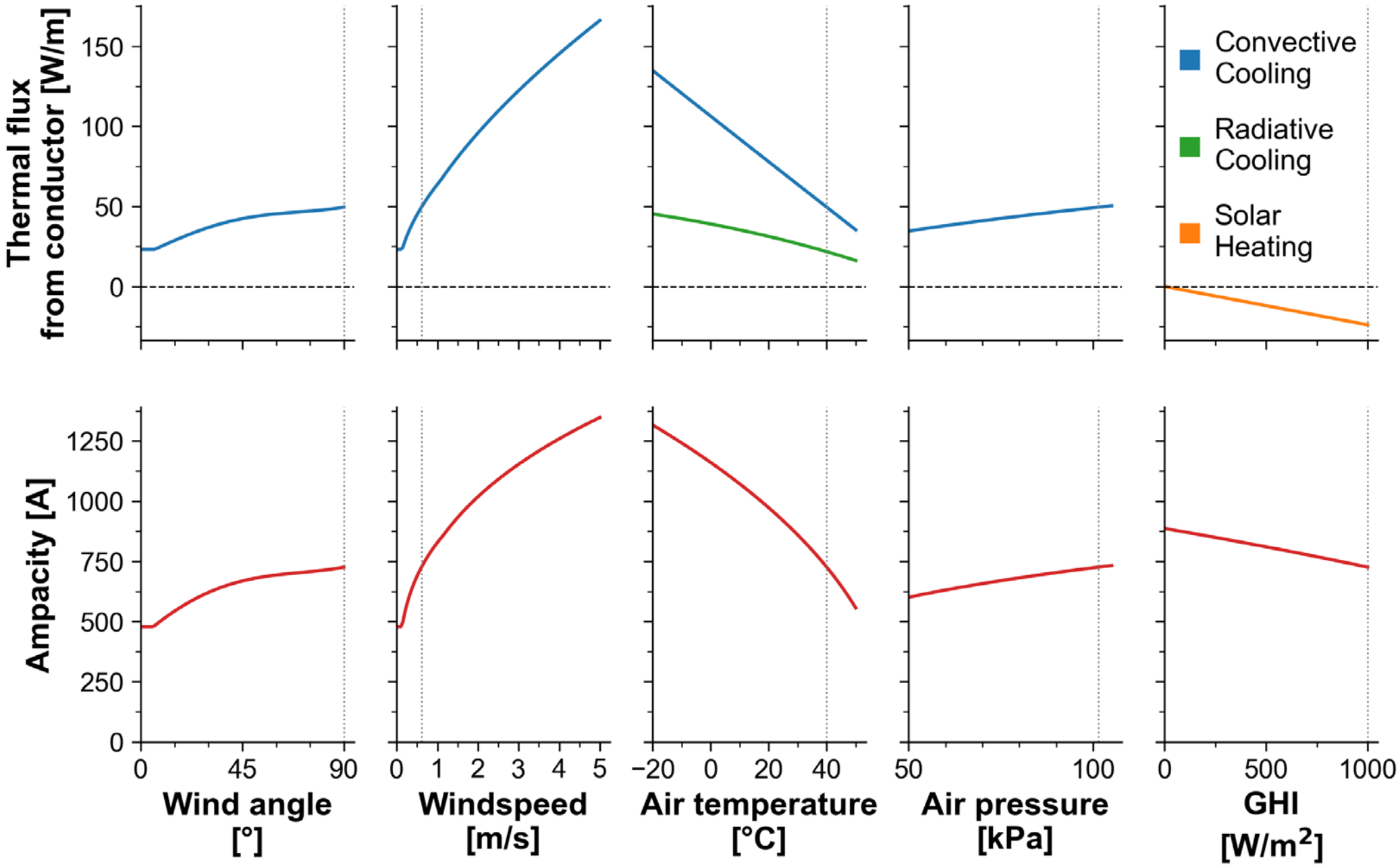
FRCC
- Duke Energy Florida

NYISO
- NYISO

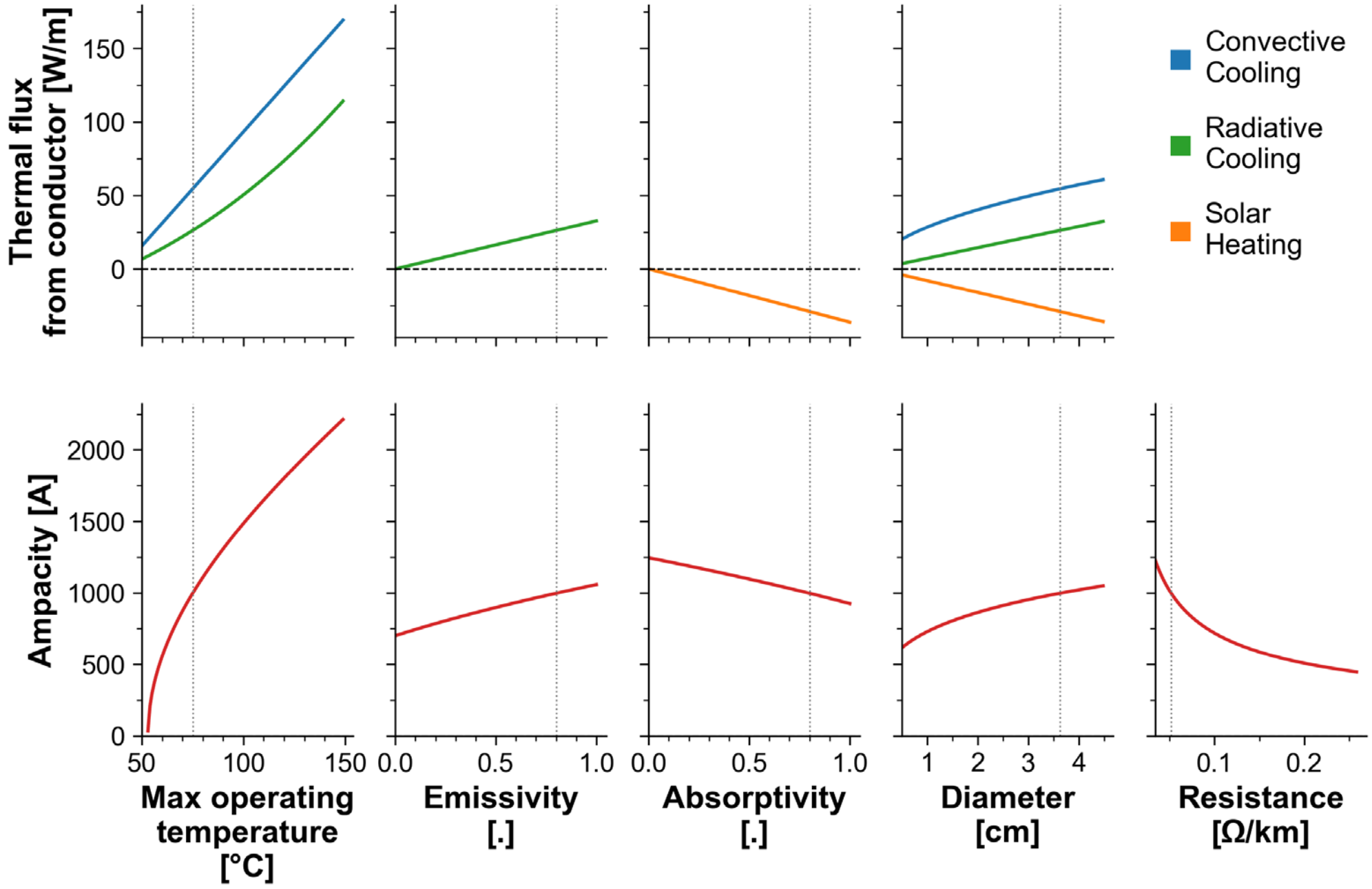
ISONE
- ISONE
- Unitil Energy Systems

Similar review: Abboud et al. 2020

Sensitivity analysis: Weather parameters



Sensitivity analysis: Conductor parameters



Validation against industry conductor datasheets

Industry conductor datasheets providing:

- Conductor diameter
- Resistance at 75°C
- Ampacity under specified conductor temperature, conductor emissivity and absorptivity, ambient air temperature, irradiance, and wind speed

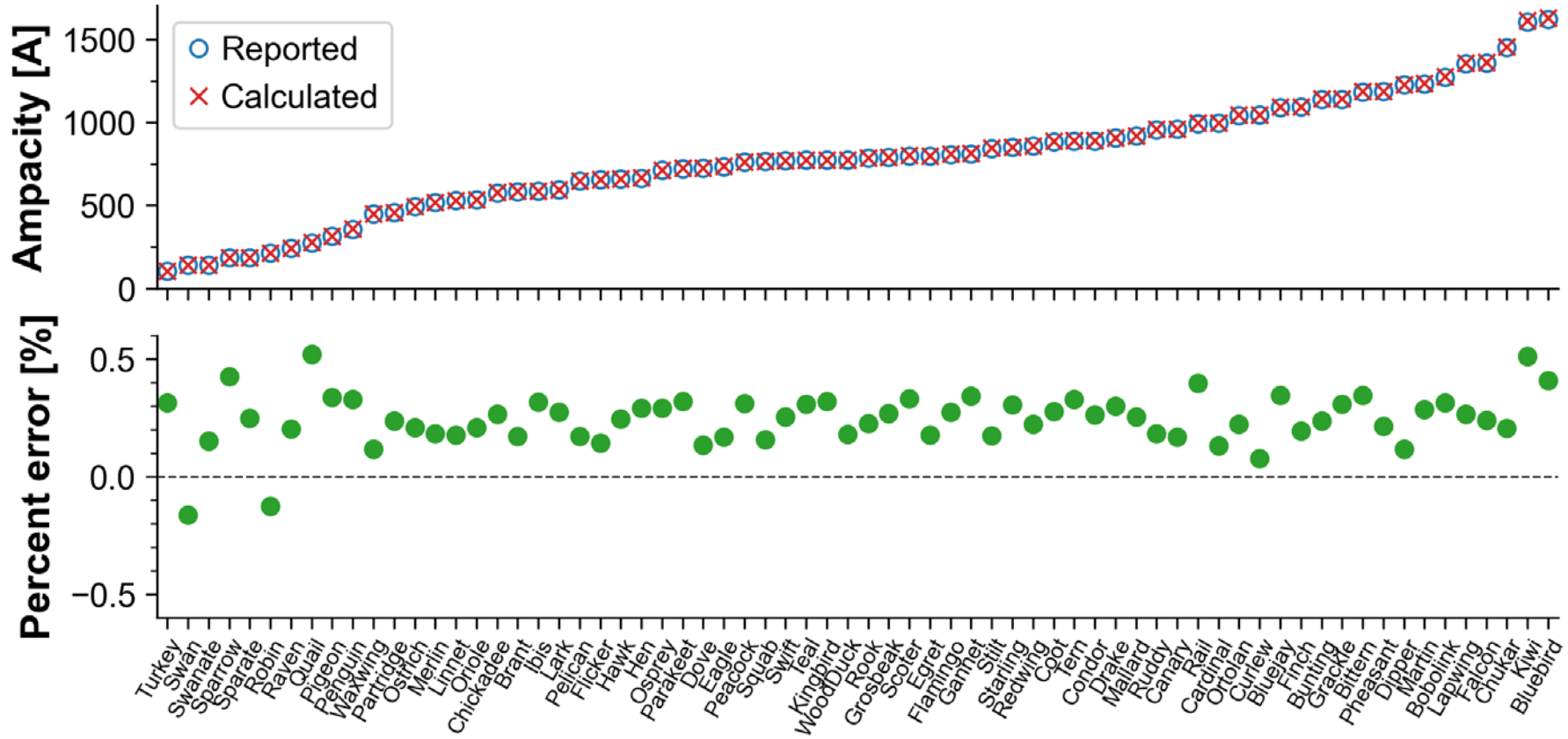
https://www.southwire.com/wire-cable/bare-aluminum-overhead-transmission-distribution/acsr/p/ALBARE6

Our assumed conductor type:

(Bartos et al. 2016)

- 69 kV: Linnet
- 115 kV: Condor
- 230 kV: Martin
- 345+ kV: Cardinal

Calculate bottom-up ampacity using matching diameter, resistance, and weather conditions; compare to reported ampacity



Methodology: Spatial resolution

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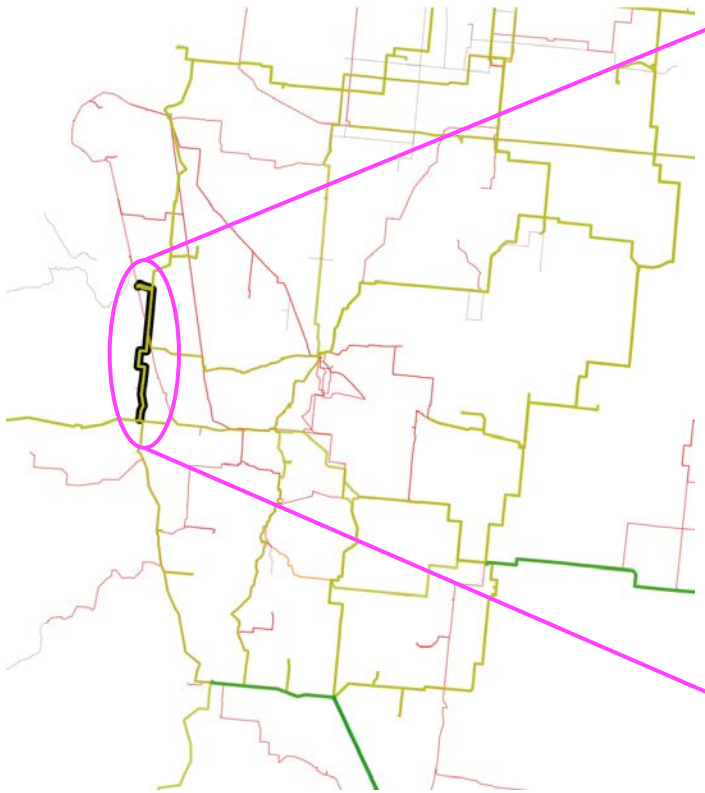
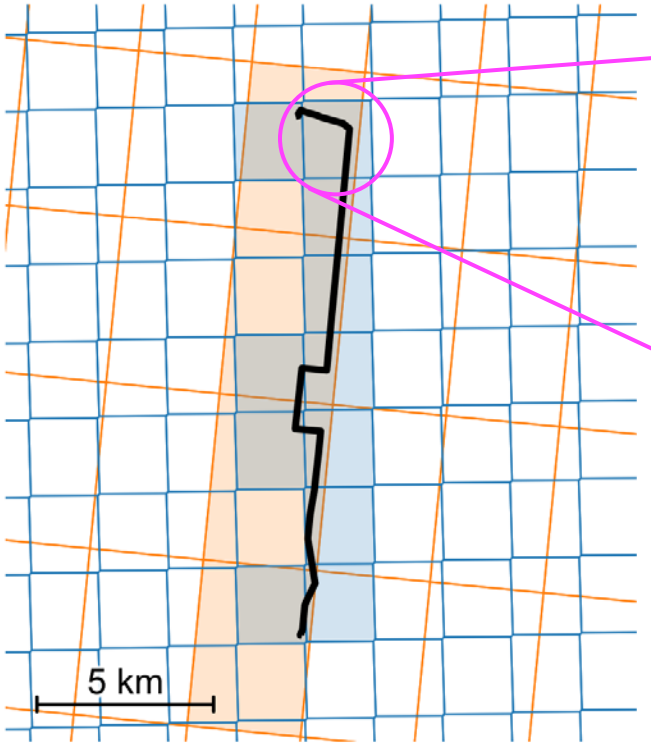
Wind speed, wind direction, air temperature, and air pressure resolved at ~2 km resolution (NREL WIND Toolkit)

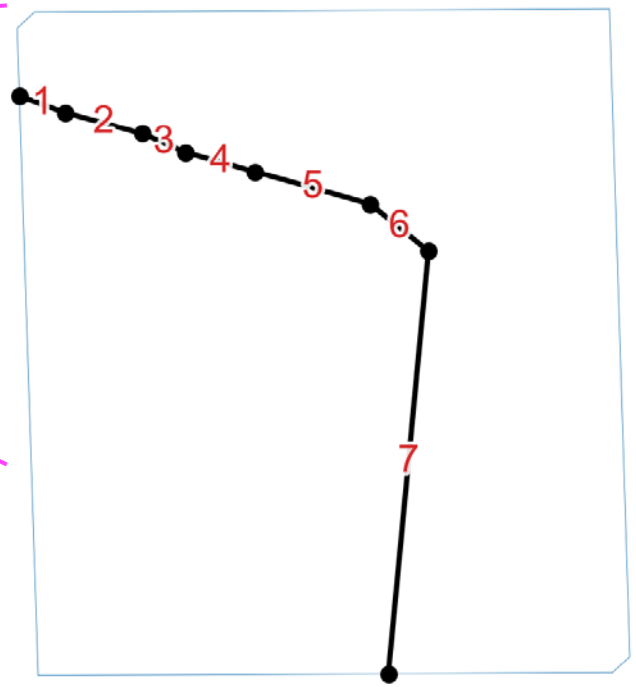
Global horizontal solar irradiance resolved at ~4 km resolution (NREL NSRDB)

1. Each linear **segment** is modeled independently to account for the angle between the wind direction and conductor orientation
2. The hourly rating of each line is defined as the **minimum** rating over **all constituent segments** in each hour



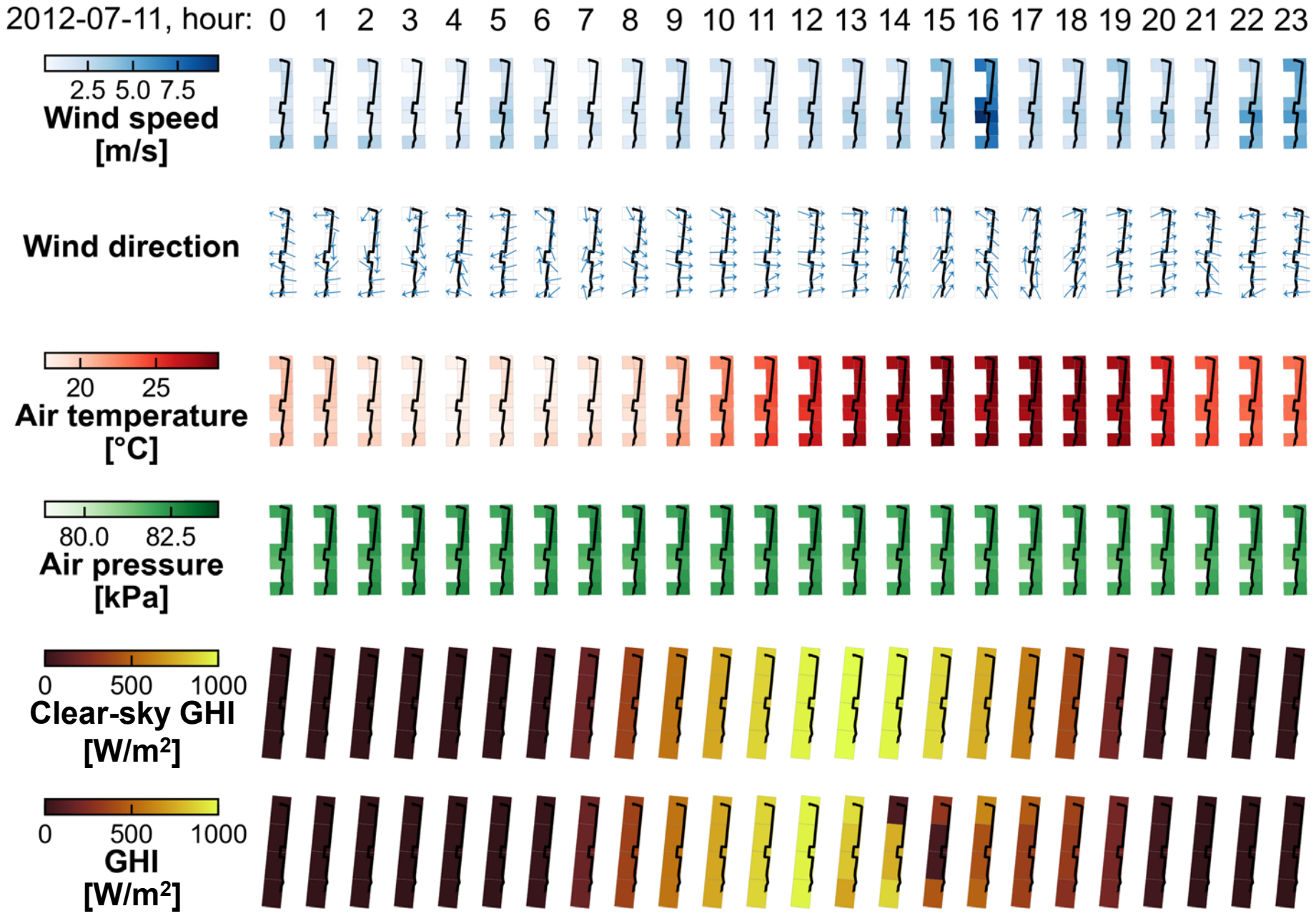


HIFLD ID = 202132
NSRDB
WTK



Methodology: Spatial resolution

HIFLD line 202132

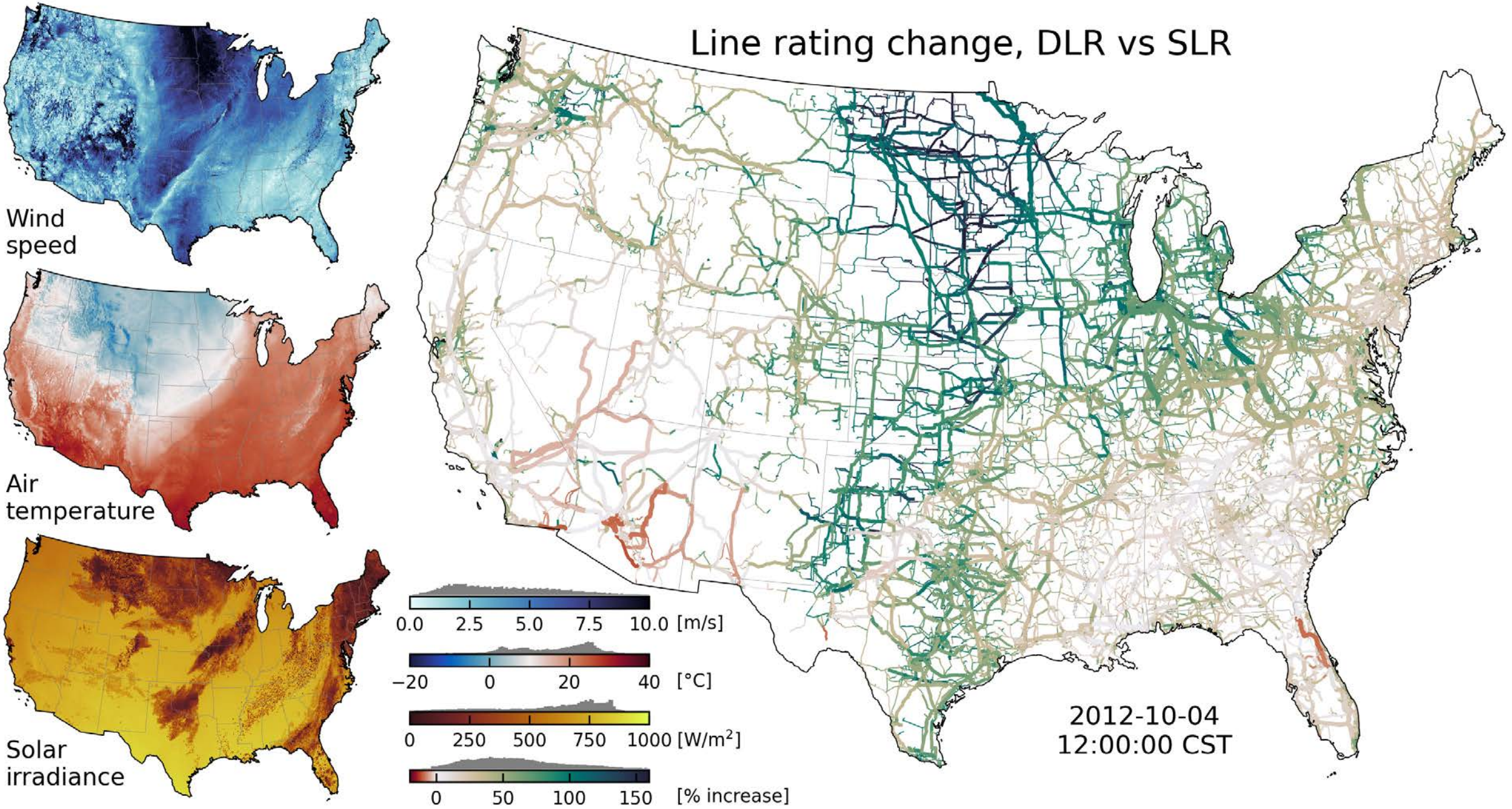


Hourly weather parameters for each NSRDB and WTK grid cell intersected by the transmission line (here shown for a single 24-hour day for a single line) are used to calculate the hourly line rating

Caveats and Limitations

1. Results are sensitive to the weather data used; if 2007–2013 windspeed in the WIND Toolkit is biased high (for example), the calculated DLR will be biased high as well
    1. Validation studies on the WIND Toolkit and NSRDB are available at:
        - King, J. et al. "Validation of Power Output for the WIND Toolkit", **2014** (NREL/TP-5D00-61714)
        - Draxl, C. et al. "Overview and Meteorological Validation of the Wind Integration National Dataset Toolkit", **2015** (NREL/TP-5000-61740)
        - Sengupta, M. et al. "Validation of the National Solar Radiation Database (NSRDB) (2005–2012)", **2015** (NREL/CP-5D00-64981)
        - Habte, A. et al. "Evaluation of the National Solar Radiation Database (NSRDB Version 2): 1998–2015", **2017** (NREL/TP-5D00-67722)
    2. Future work could explore other weather datasets and more recent weather years
    3. More work is required to determine how well ratings calculated from NSRDB and WIND Toolkit data reflect the actual ratings observed by installed sensors (such as sag or tension monitors); in general, ratings calculated from modeled weather data are not a substitute for direct sensor data
2. Assuming a single representative conductor type (ACSR of a single diameter) for each voltage level is an important simplification; reported line ratings at a given voltage level can vary widely
    1. Focusing on the relative change between rating methods (rather than absolute ampacities) partially mitigates this limitation
3. HIFLD line routes are primarily based on imagery instead of exact construction data and may have errors
4. We use historical weather data directly; calculated line ratings are thus more indicative of real-time ratings than forecasted ratings
    1. Future work could explore the use of forecast error margins to estimate weather-adjusted ratings under realistically forecastable conditions

Dynamic line ratings: One-hour snapshot



Line rating frameworks explored here

Rating system (definitions used in this study; not necessarily standard)	**Abbrev**	**Ambient temperature**	**Solar irradiance**	**Windspeed †**
Static line ratings	SLR	40°C	1000 W/m^2	0.61 m/s
Seasonal line ratings	ZLR	Industry data	1000 W/m^2	0.61 m/s
Ambient-adjusted line ratings	ALR	Hourly	1000 W/m^2	*
Nighttime-adjusted line ratings	NLR	Hourly	[0,1000] W/m^2	*
Clear-sky-adjusted line ratings	CLR	Hourly	Hourly clear-sky	*
Irradiance-adjusted line ratings	ILR	Hourly	Hourly	*
Dynamic line ratings	DLR	Hourly	Hourly	Hourly

Current practice

Required by FERC Order 881

Proposed in FERC ANOPR on 2024-06-27

* Not directly specified; here, we compare static windspeed assumptions of 0.61 m/s (default) and 0 m/s

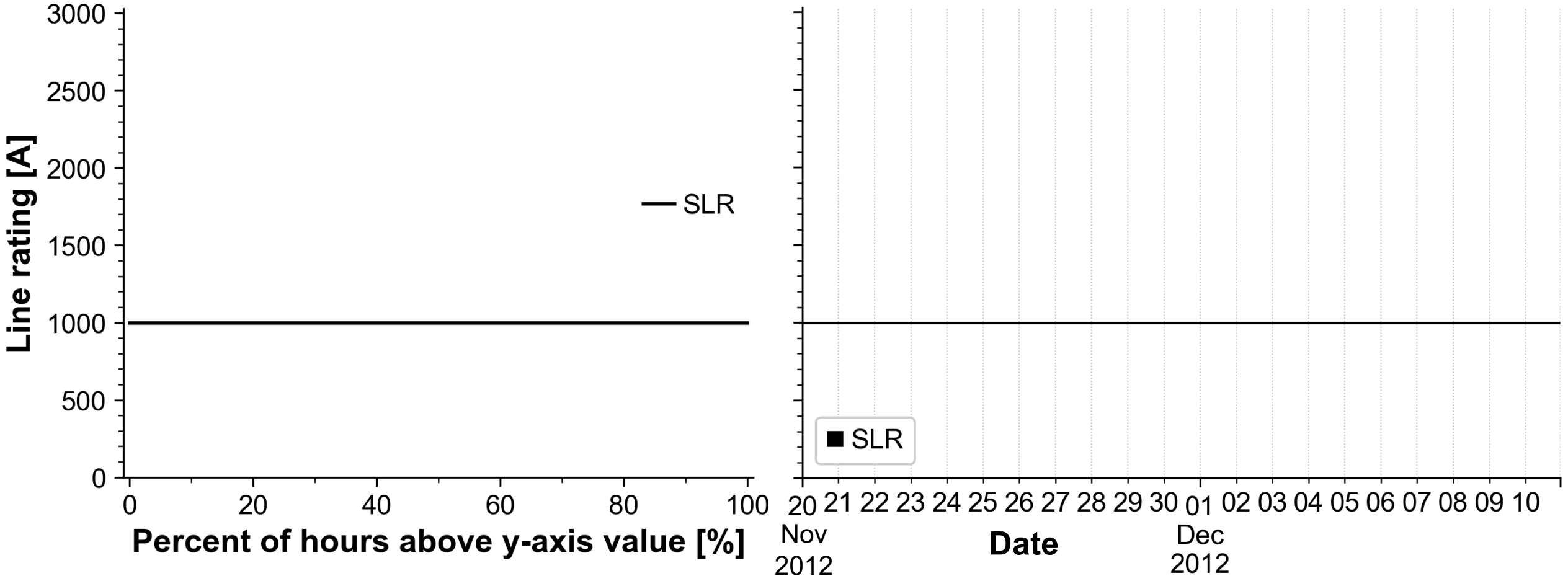
† In the results shown here, only DLR uses location-specific hourly air pressure; all other rating methods use 1 standard atmosphere

1. What are the benefits of clear-sky-adjusted ratings (**CLR**) over the nighttime-adjusted ratings (**NLR**) required by FERC Order 881?
2. What are the benefits of measured-irradiance-adjusted ratings (**ILR**) over **CLR**?
3. What are the benefits of full dynamic line ratings (**DLR**, including windspeed) over **ILR**?
4. Do heuristics based on **average wind conditions** effectively predict the benefits of DLR?

One transmission line: All rating options

HIFLD line
202132

Illustrative results



Rating system	Abbrev	Ambient temperature	Solar irradiance	Windspeed
Static line ratings	SLR	40°C	1000 W/m^2	0.61 m/s

One transmission line: All rating options

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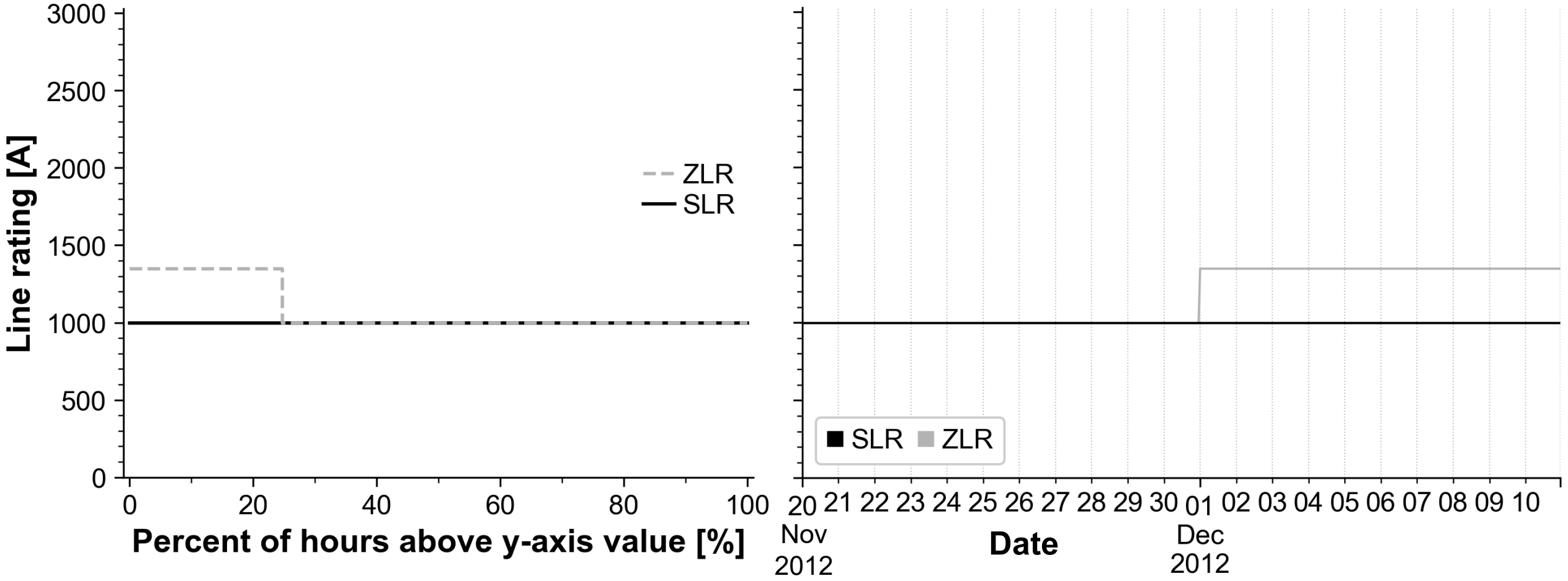
Illustrative results



Rating system	Abbrev	Ambient temperature	Solar irradiance	Windspeed
Seasonal line ratings	ZLR	Table 1	1000 W/m^2	0.61 m/s

One transmission line: All rating options

HIFLD line
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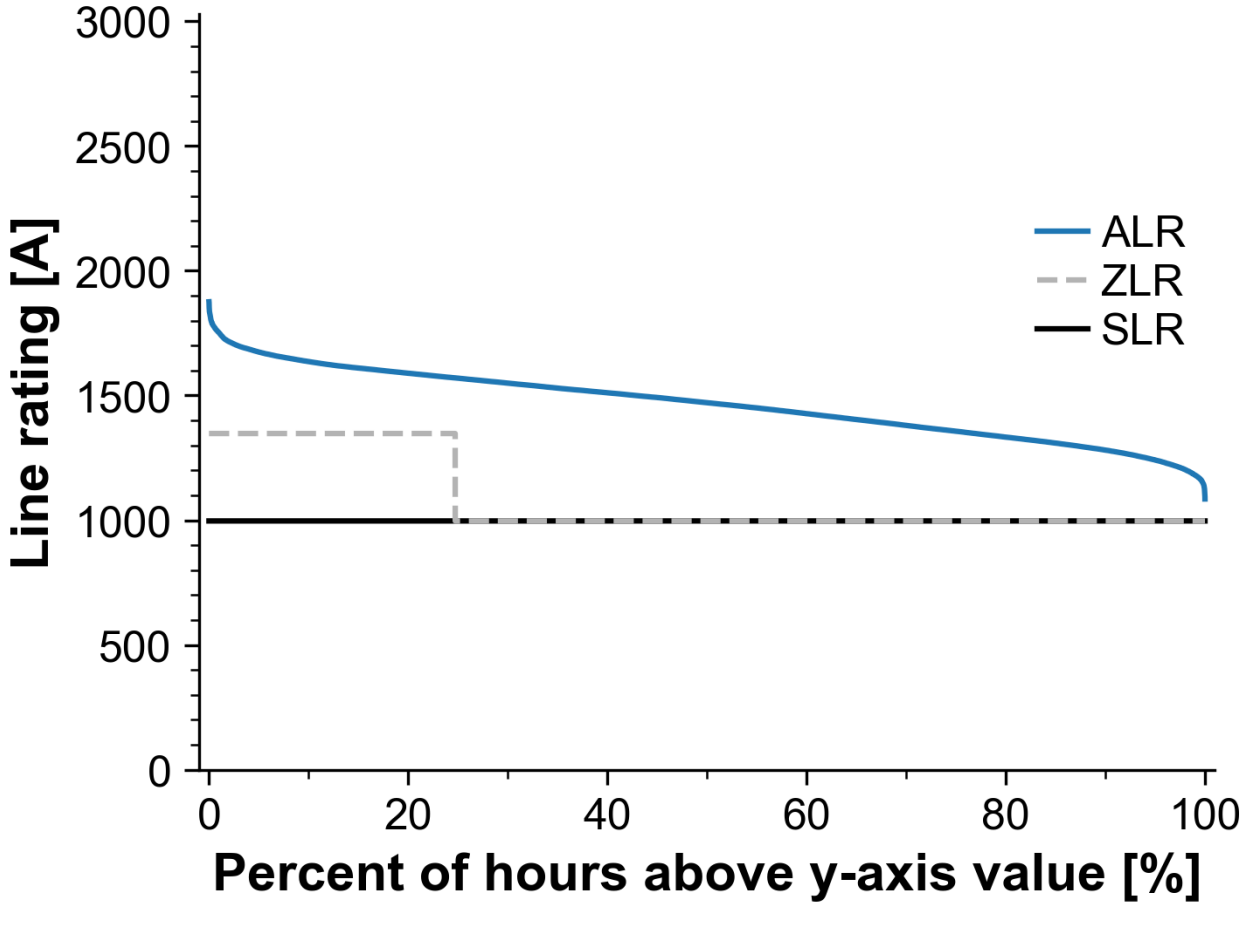
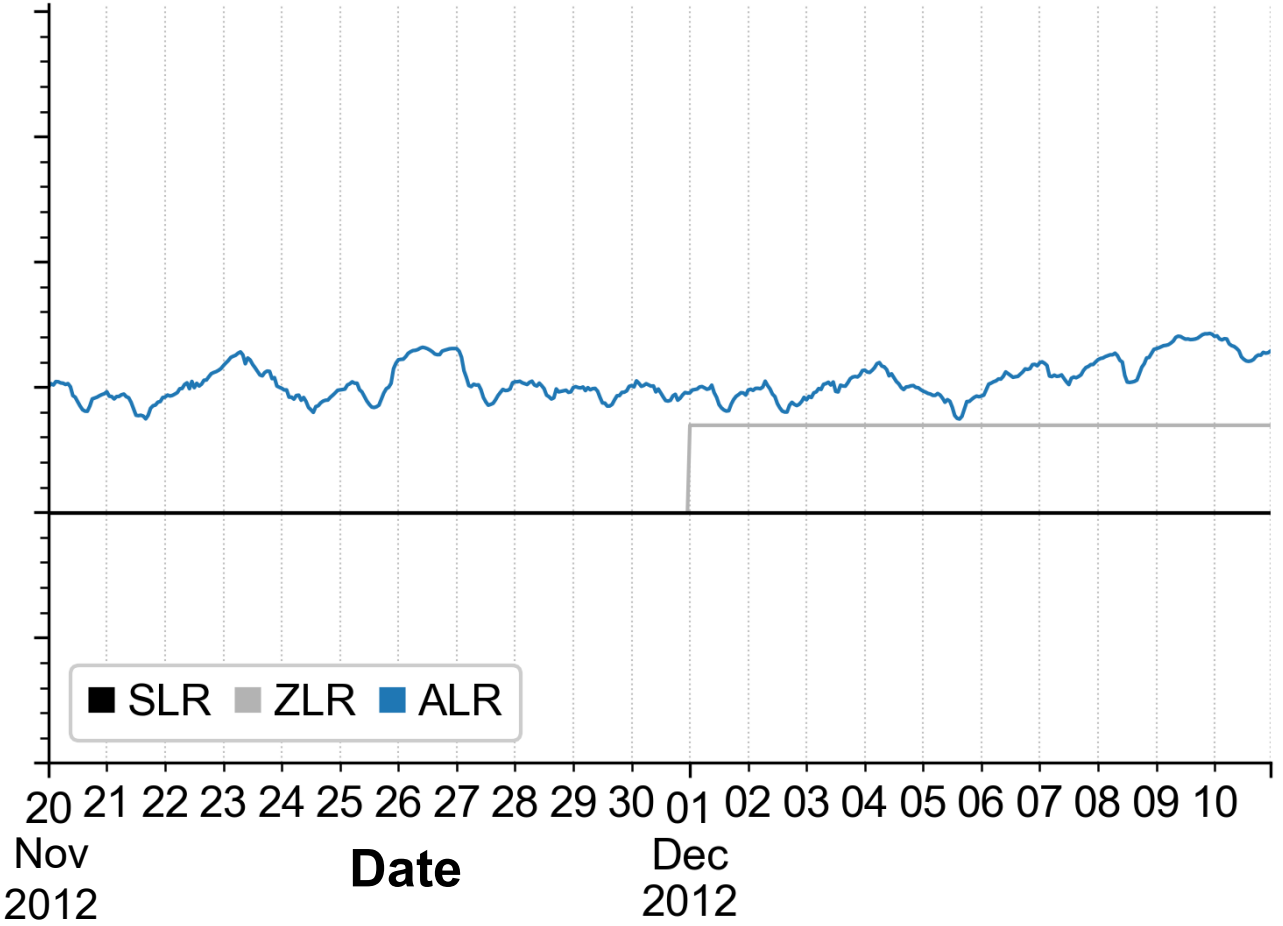
Illustrative results





Rating system	Abbrev	Ambient temperature	Solar irradiance	Windspeed
Ambient-adjusted line ratings	ALR	Hourly	1000 W/m^2	0.61 m/s

One transmission line: All rating options

HIFLD line
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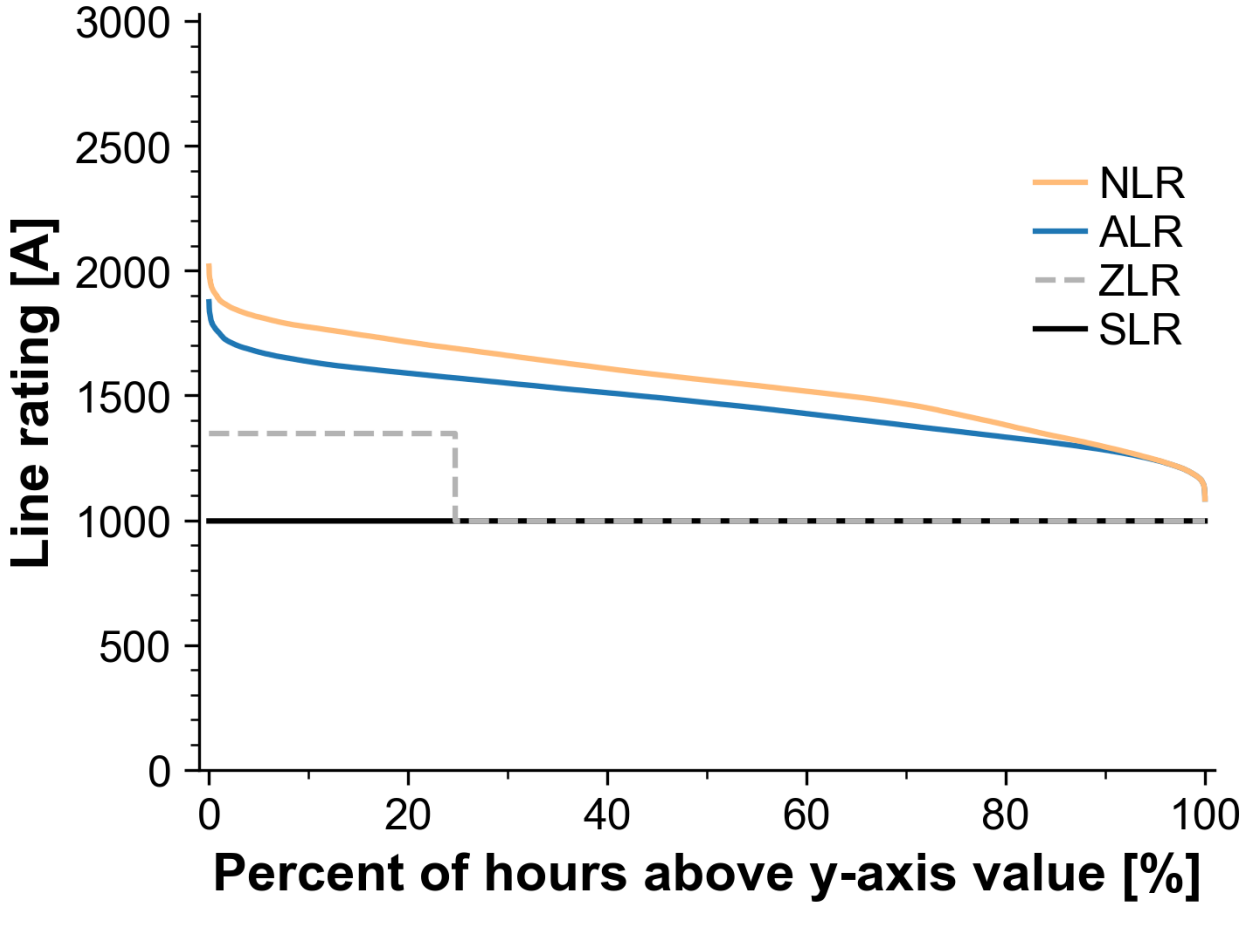
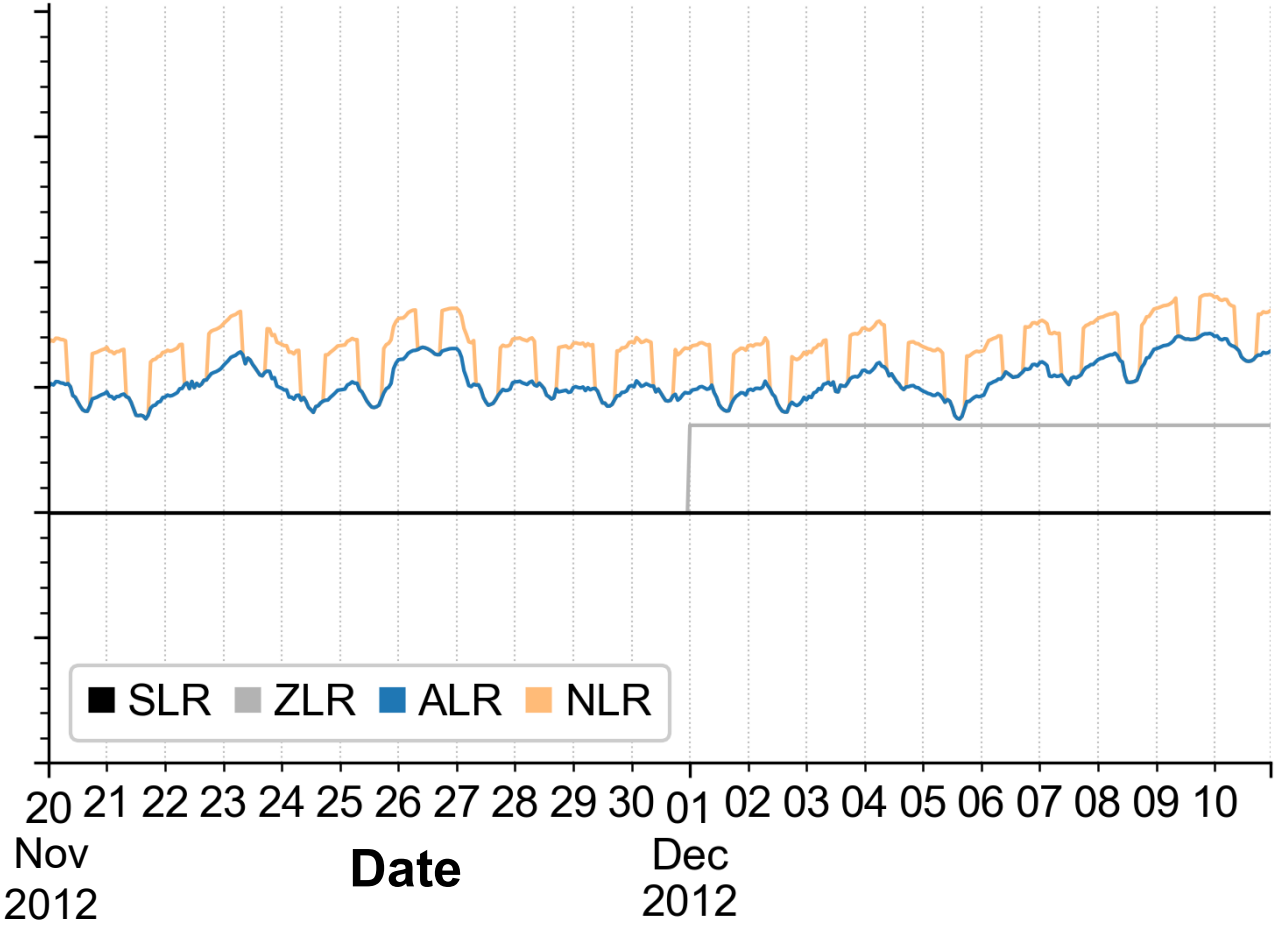
Illustrative results





Rating system	Abbrev	Ambient temperature	Solar irradiance	Windspeed
Nighttime-adjusted line ratings	NLR	Hourly	[0,1000] W/m^2	0.61 m/s

One transmission line: All rating options

HIFLD line
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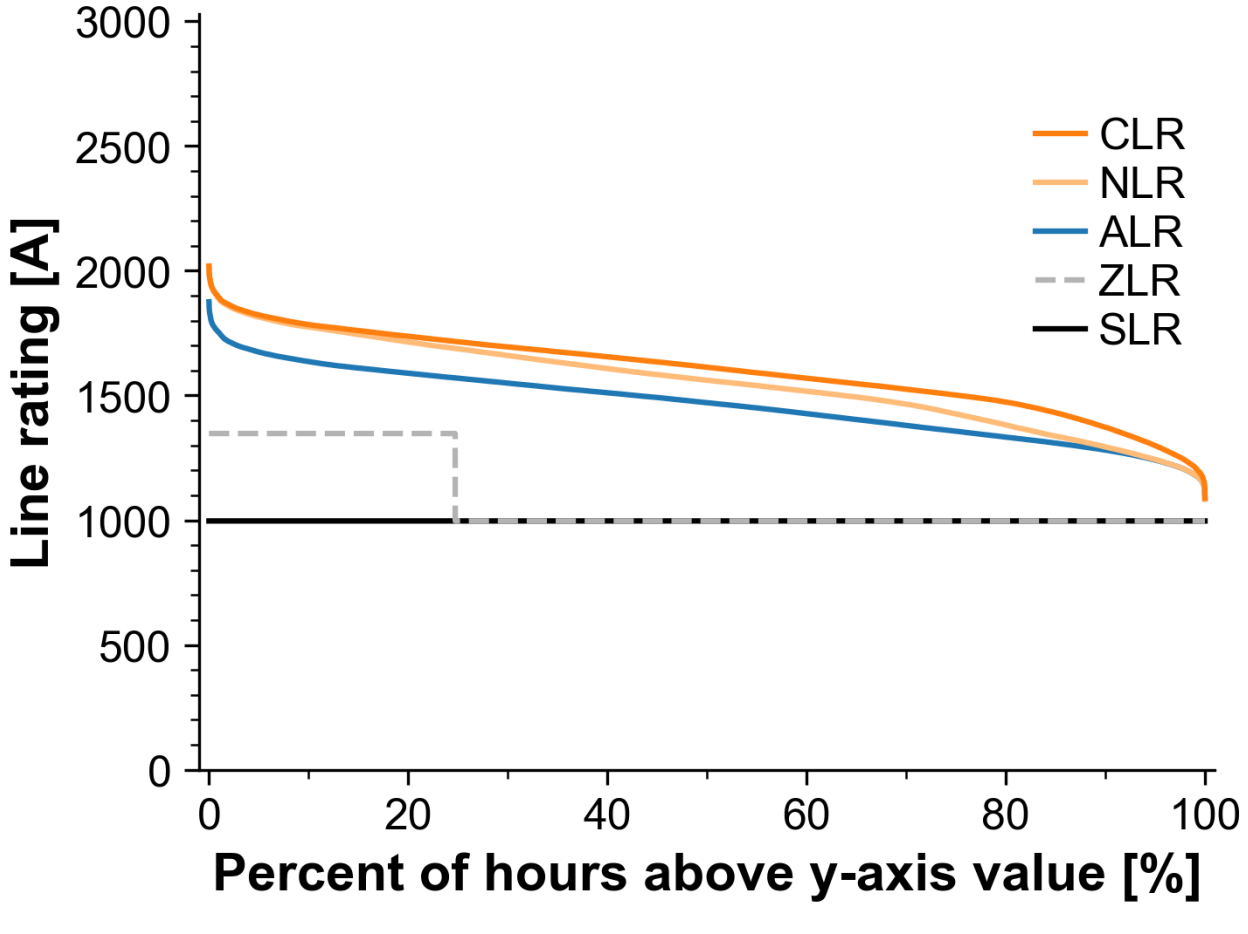
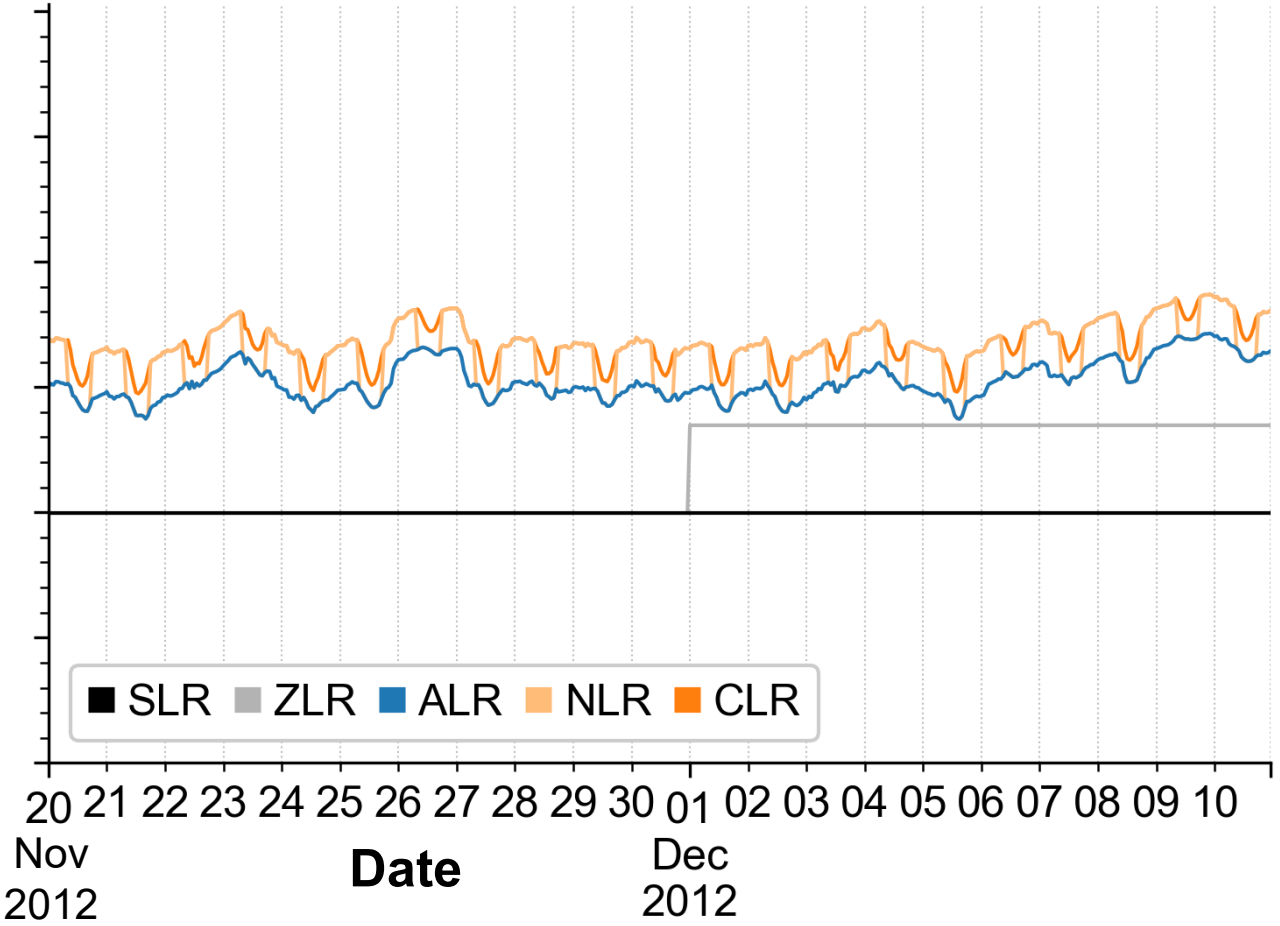
Illustrative results



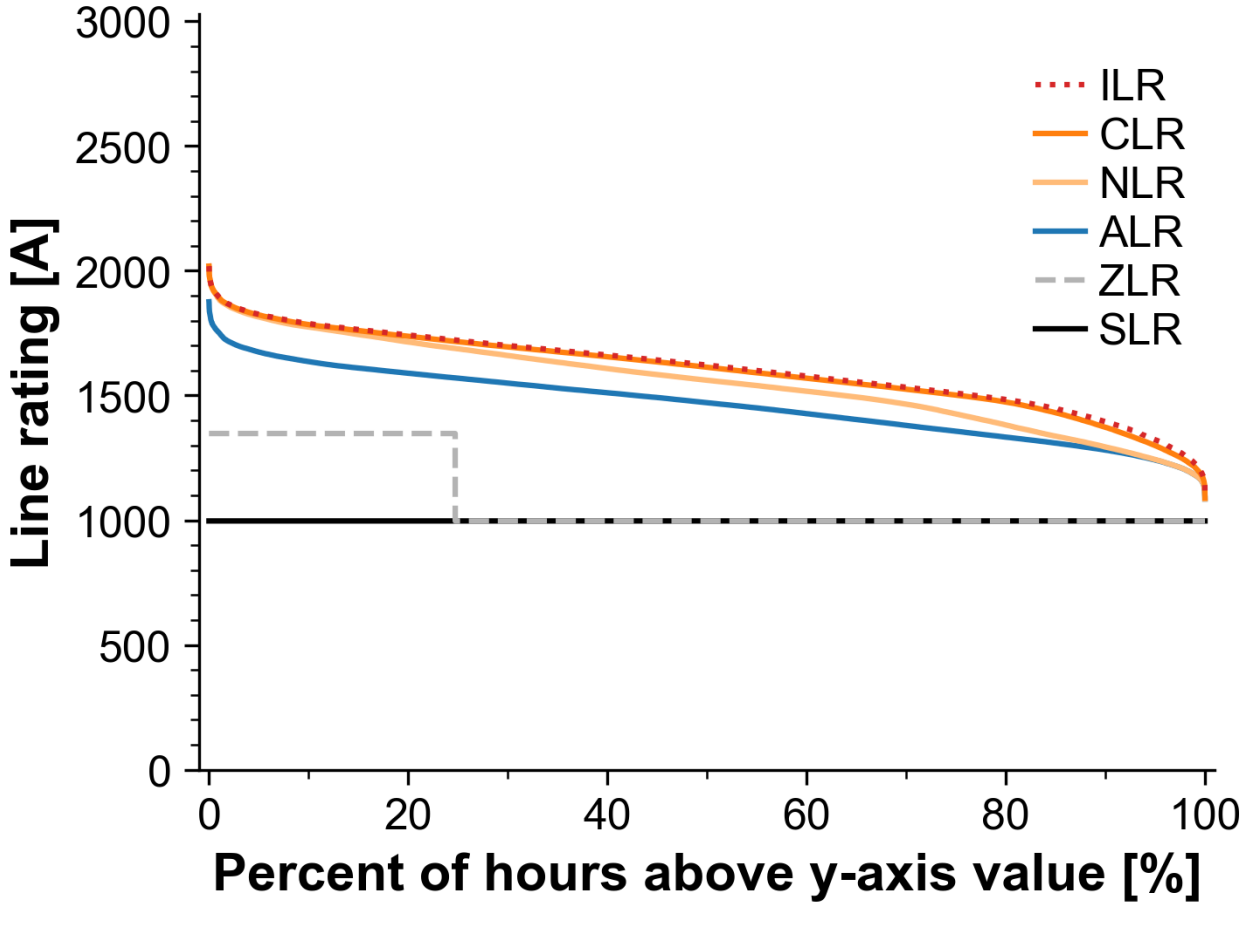


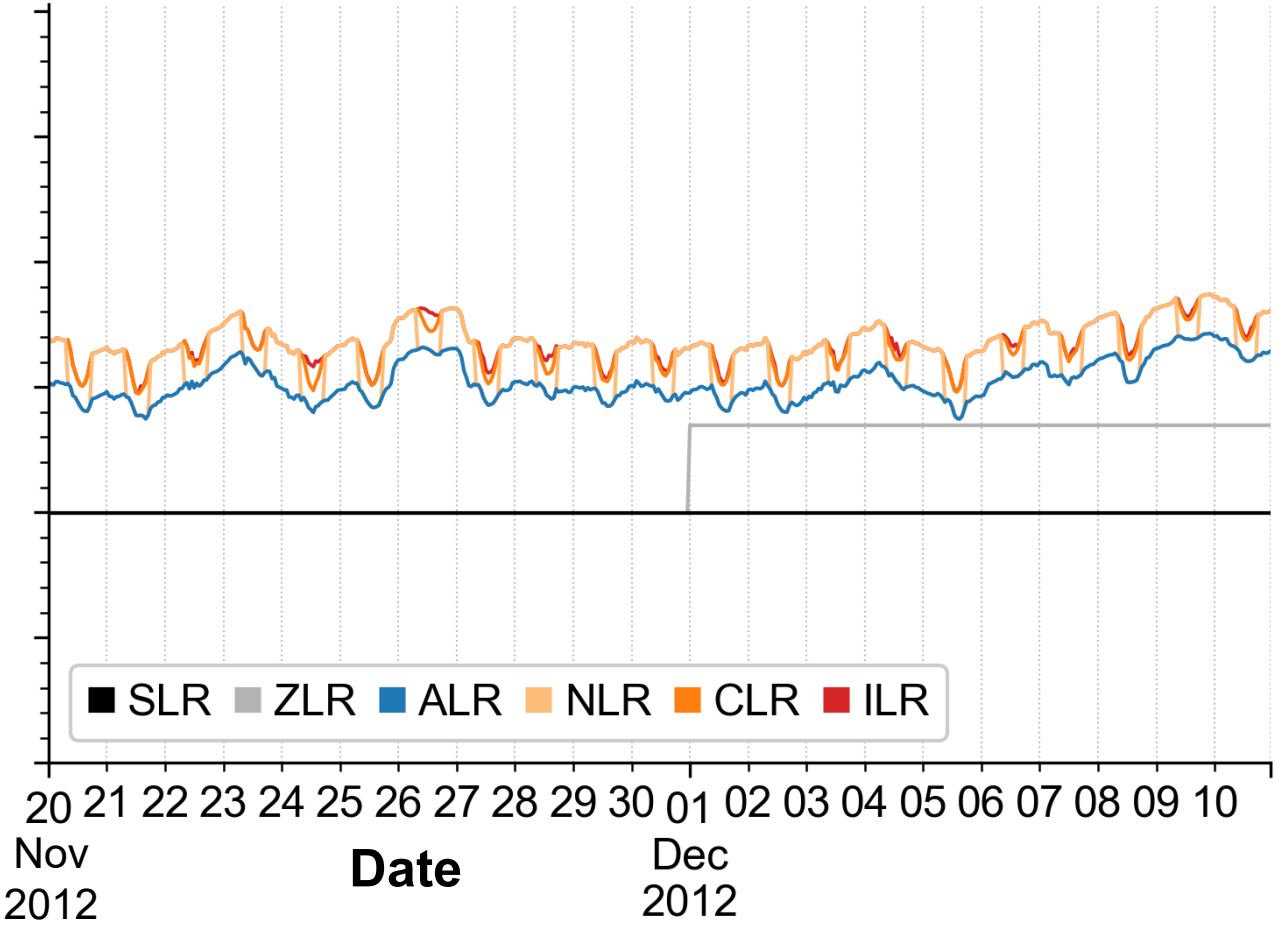
Rating system	Abbrev	Ambient temperature	Solar irradiance	Windspeed
Clear-sky-adjusted line ratings	CLR	Hourly	Hourly clear-sky	0.61 m/s

One transmission line: All rating options

HIFLD line
202132

Illustrative results



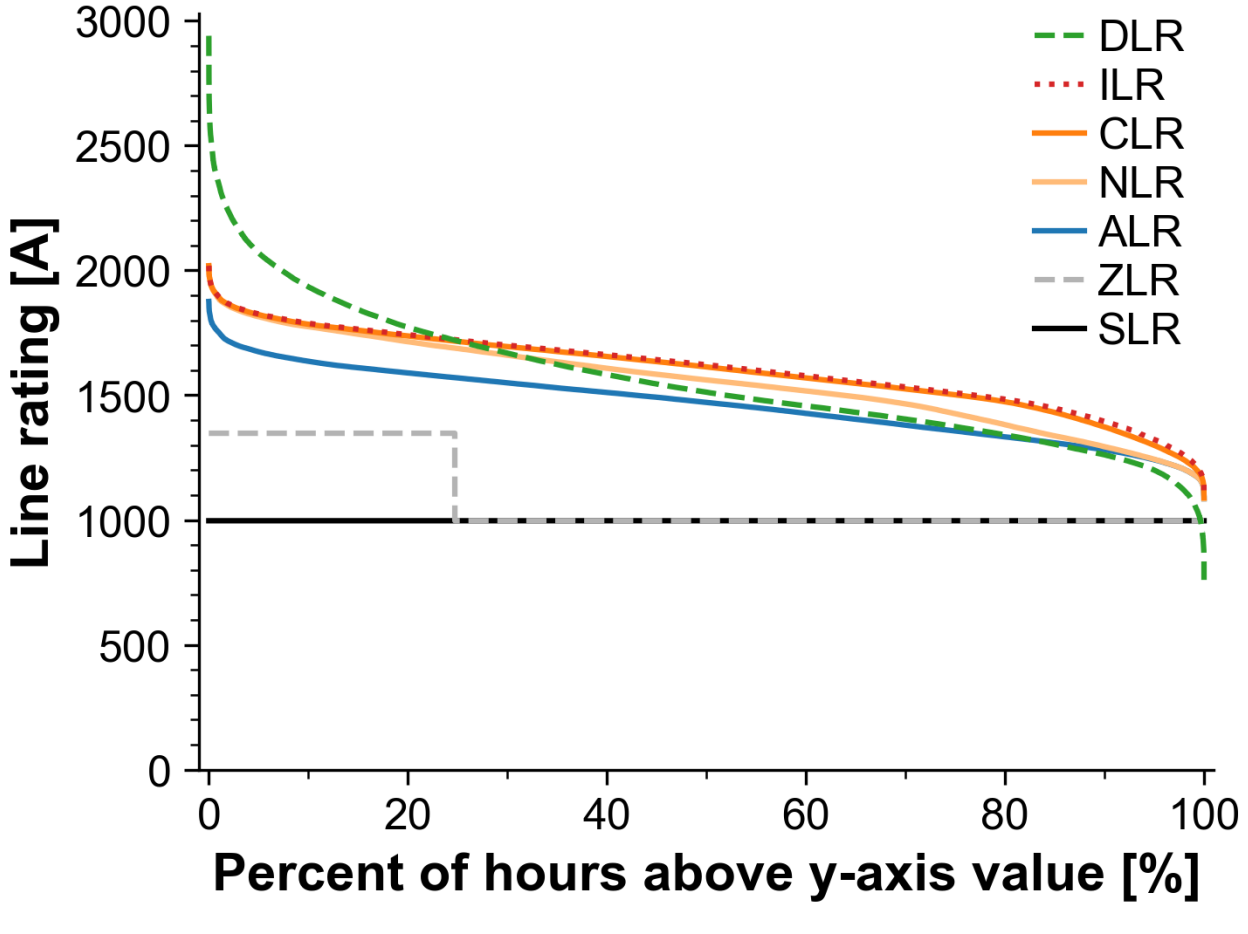


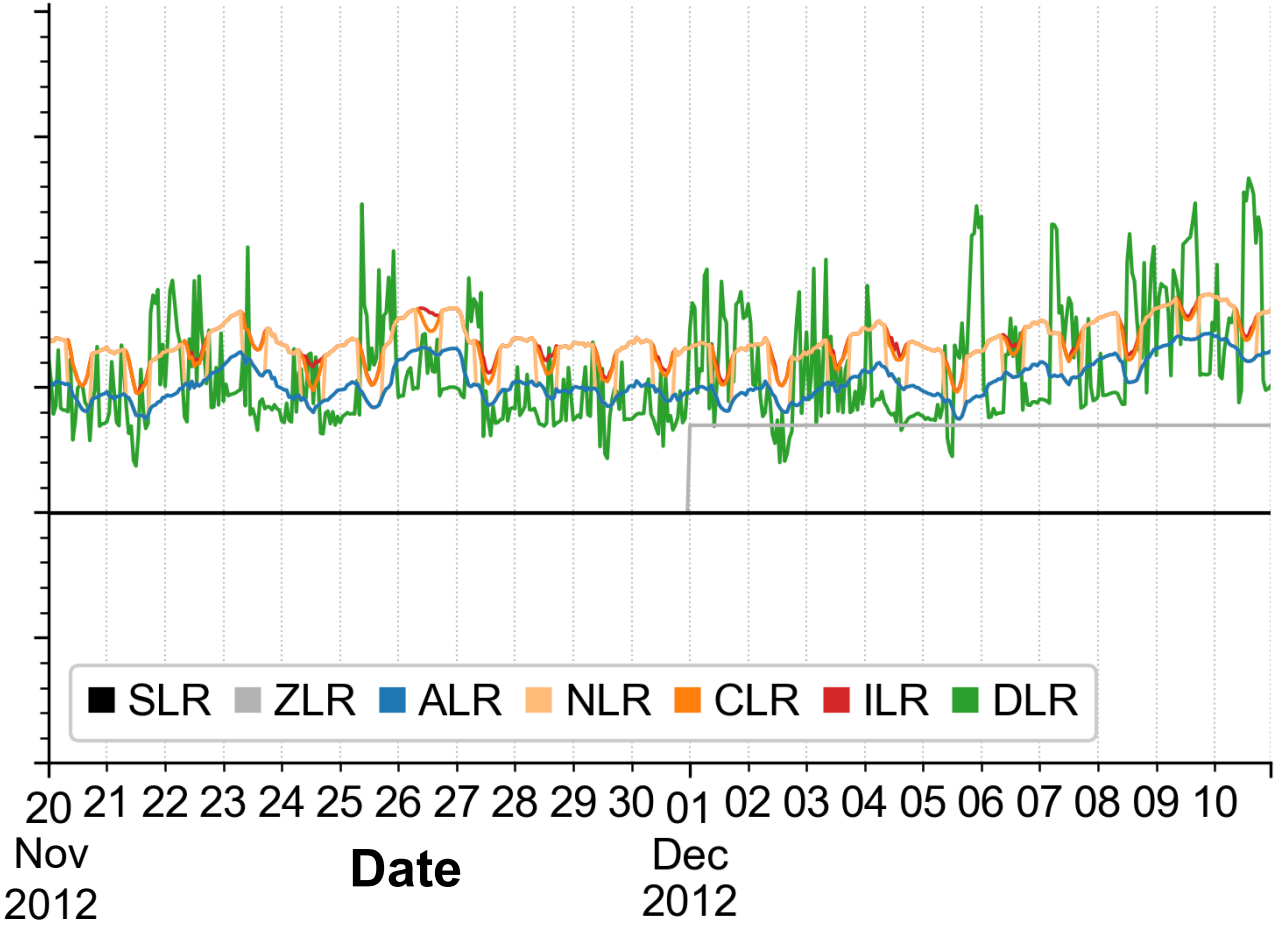
Rating system	Abbrev	Ambient temperature	Solar irradiance	Windspeed
Irradiance-adjusted line ratings	ILR	Hourly	Hourly	0.61 m/s

One transmission line: All rating options

HIFLD line
202132

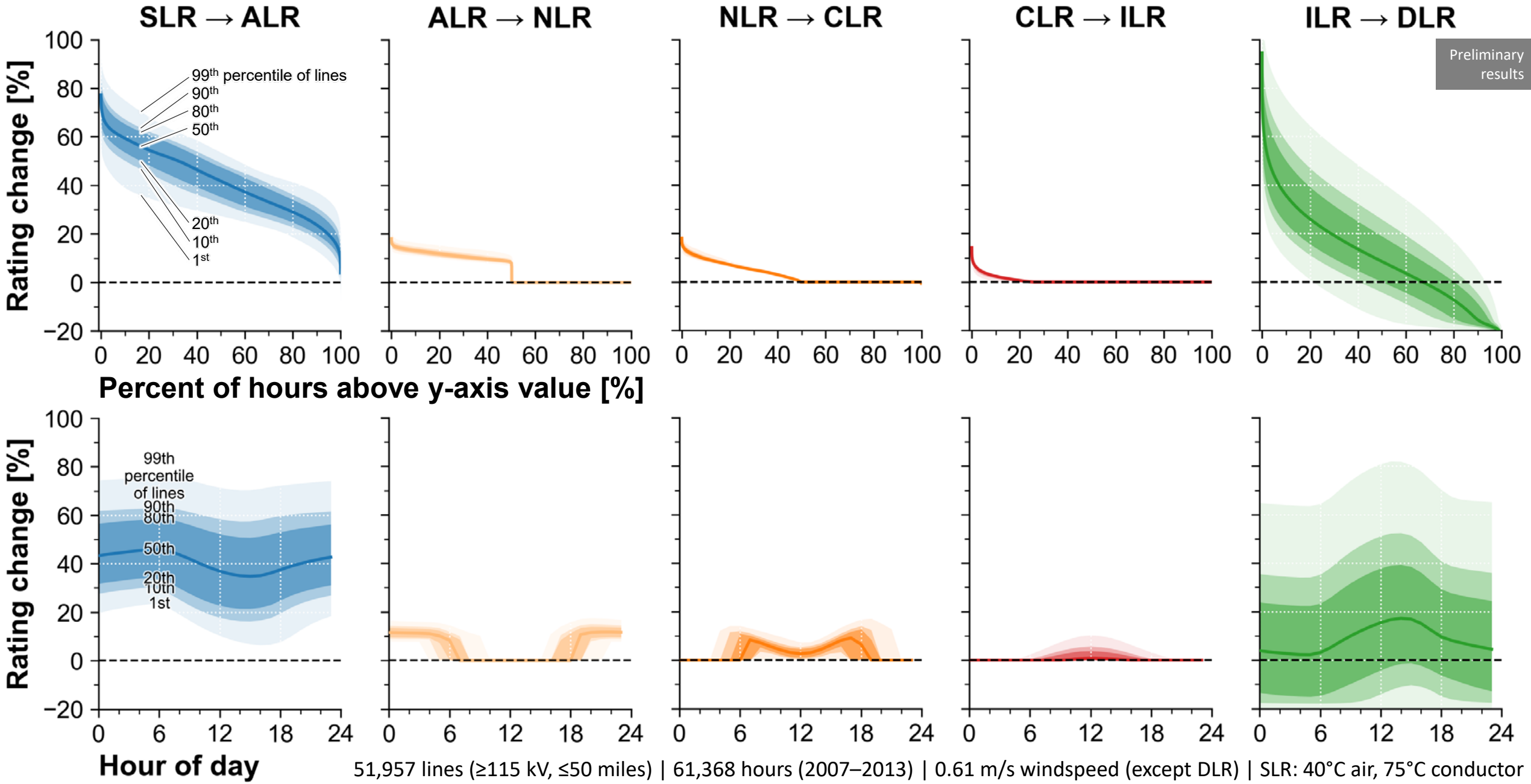
Illustrative results





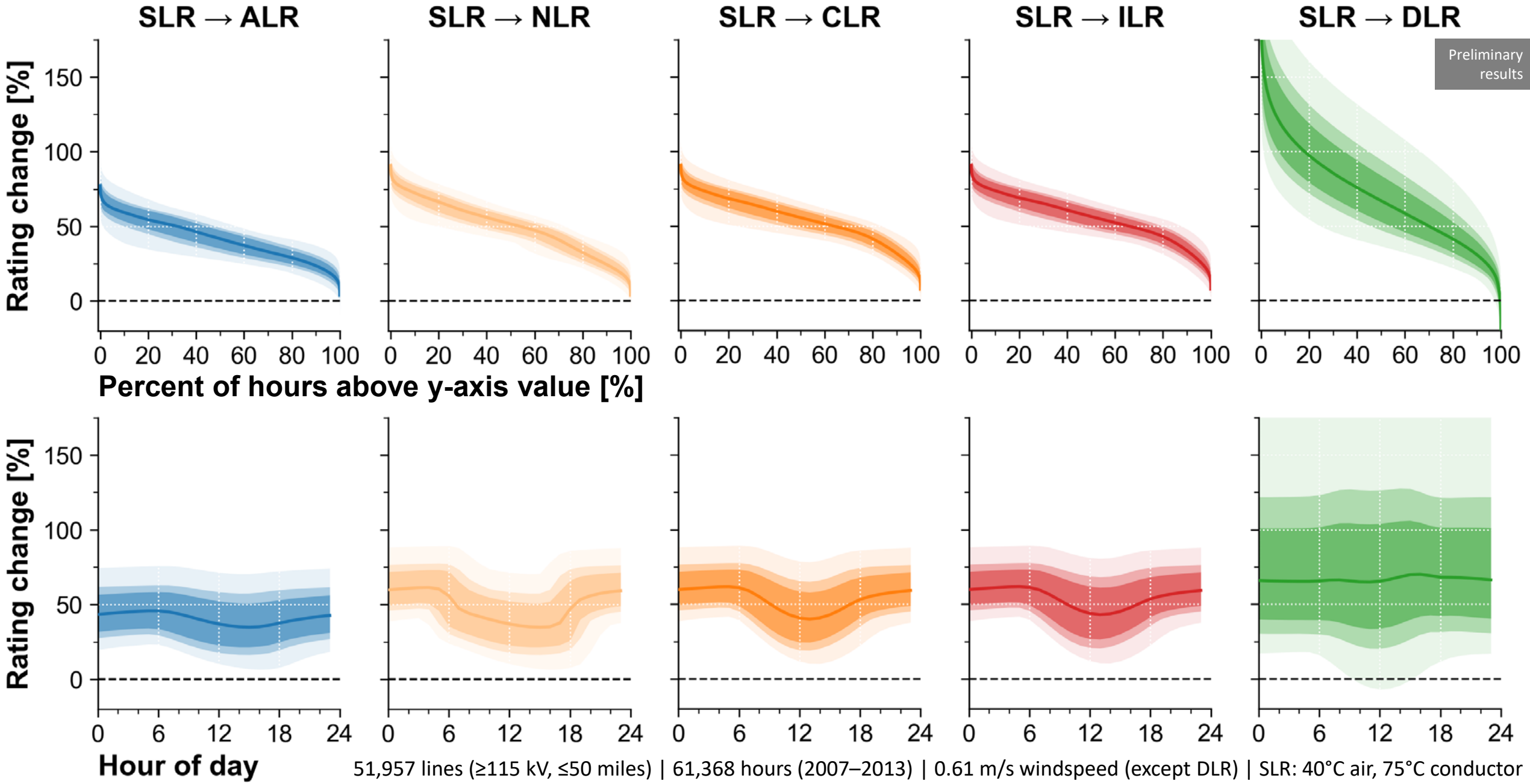
Rating system	Abbrev	Ambient temperature	Solar irradiance	Windspeed
Dynamic line ratings	DLR	Hourly	Hourly	Hourly

How do different ratings compare? (marginal change)



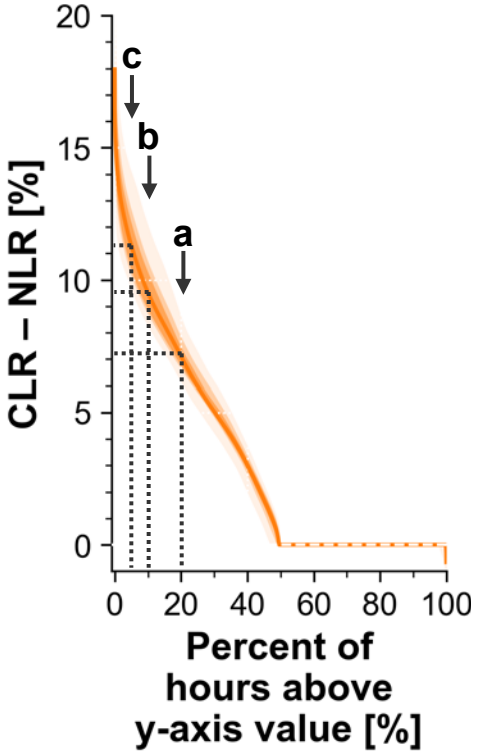
51,957 lines (≥115 kV, ≤50 miles) | 61,368 hours (2007–2013) | 0.61 m/s windspeed (except DLR) | SLR: 40°C air, 75°C conductor

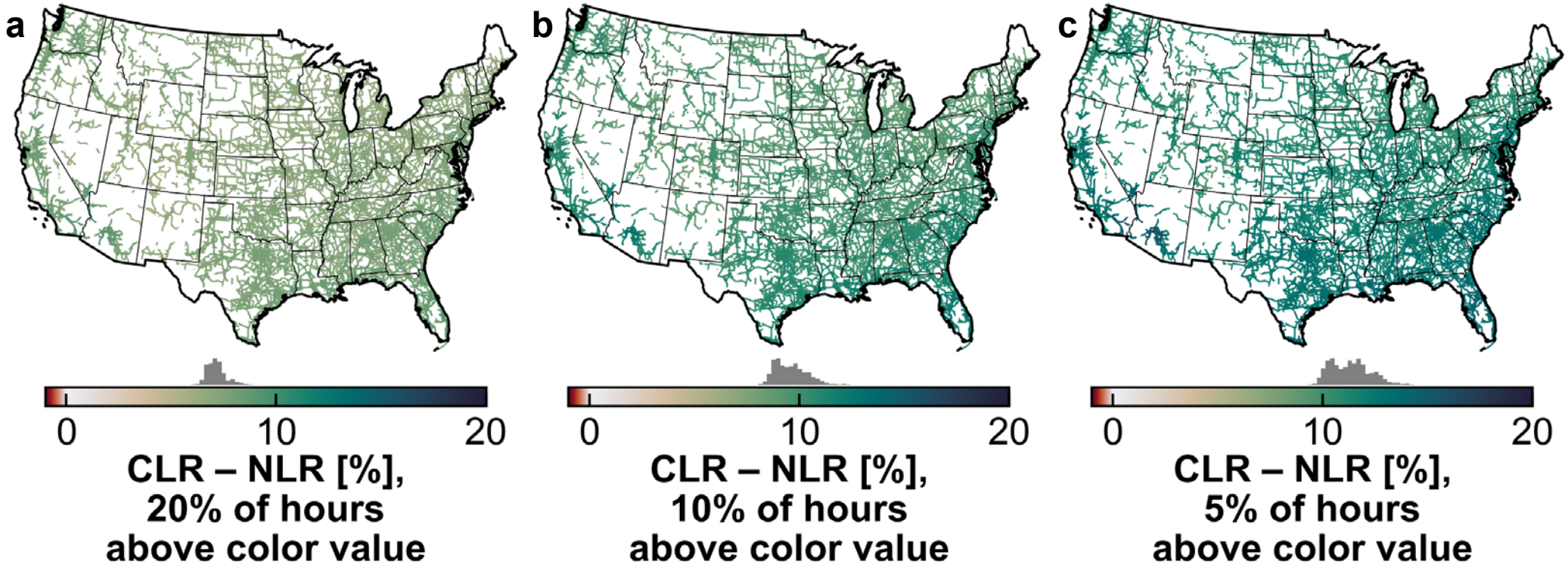
How do different ratings compare? (total change)



51,957 lines (≥115 kV, ≤50 miles) | 61,368 hours (2007–2013) | 0.61 m/s windspeed (except DLR) | SLR: 40°C air, 75°C conductor

How does clear-sky compare to day/night?





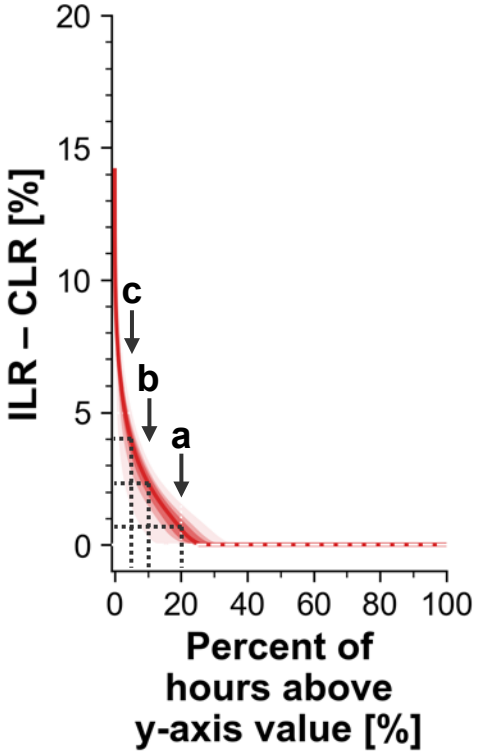
For **50%** of lines, the clear-sky rating is…

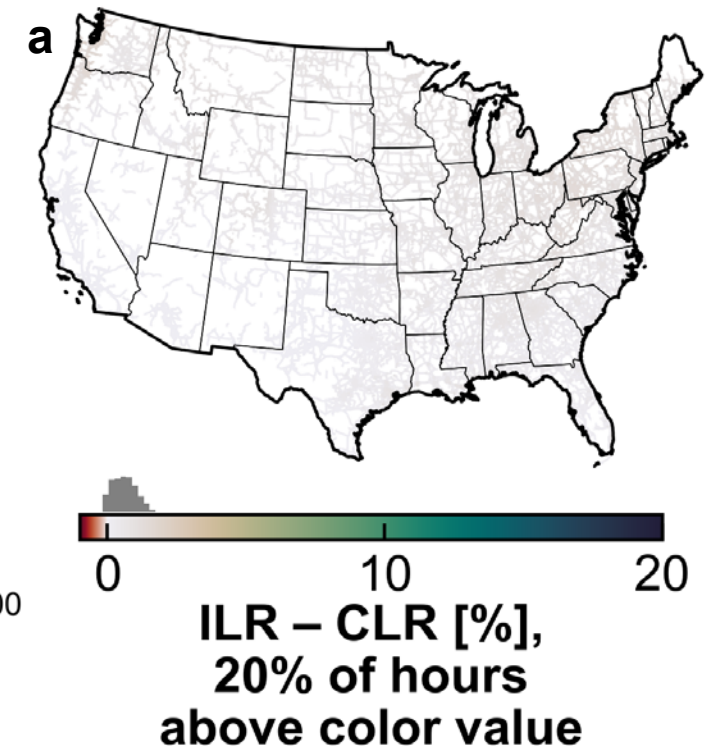
- **7%** higher than the day/night rating in **20%** of hours
- **10%** higher in **10%** of hours
- **11%** higher in **5%** of hours

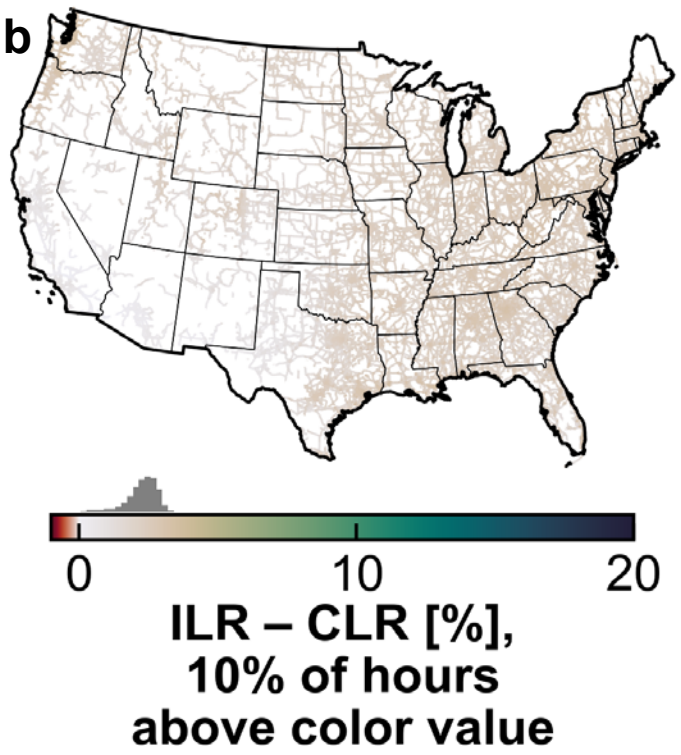
Preliminary results

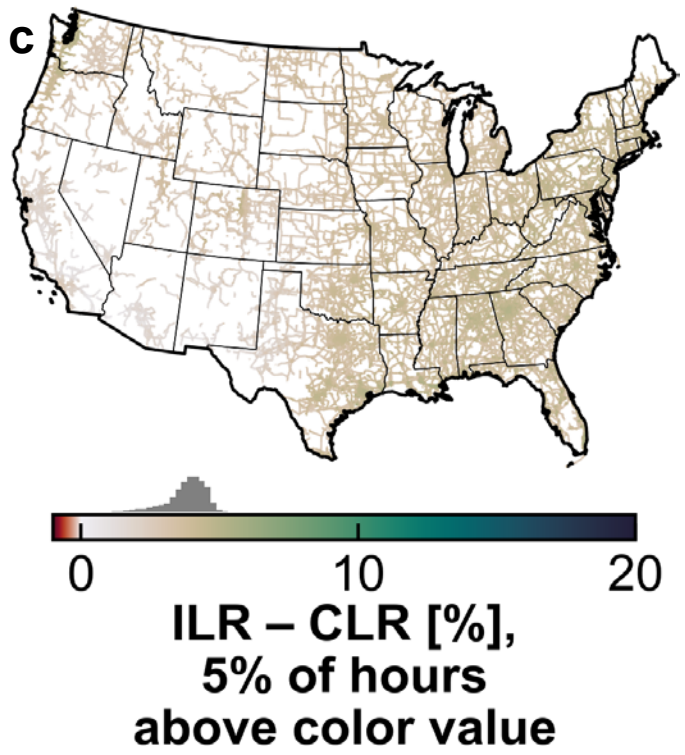
51,957 lines (≥115 kV, ≤50 miles) | 61,368 hours (2007–2013) | 0.61 m/s windspeed (except DLR) | SLR: 40°C air, 75°C conductor

How does actual irradiance compare to clear-sky?









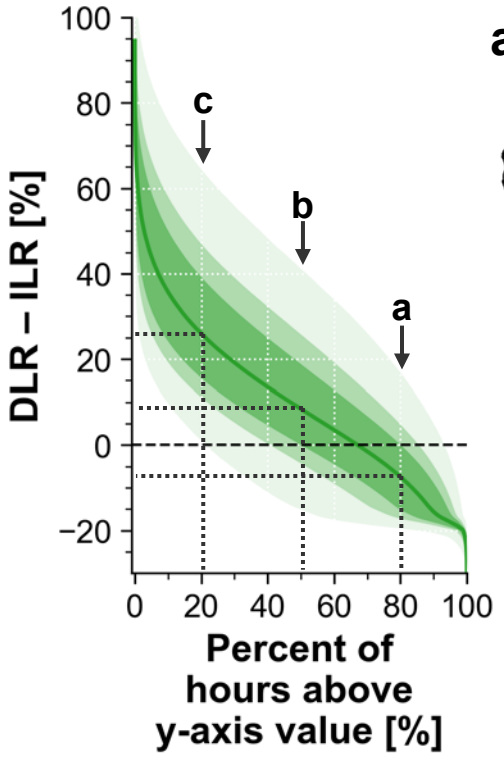
For **50%** of lines, the actual-irradiance rating is…

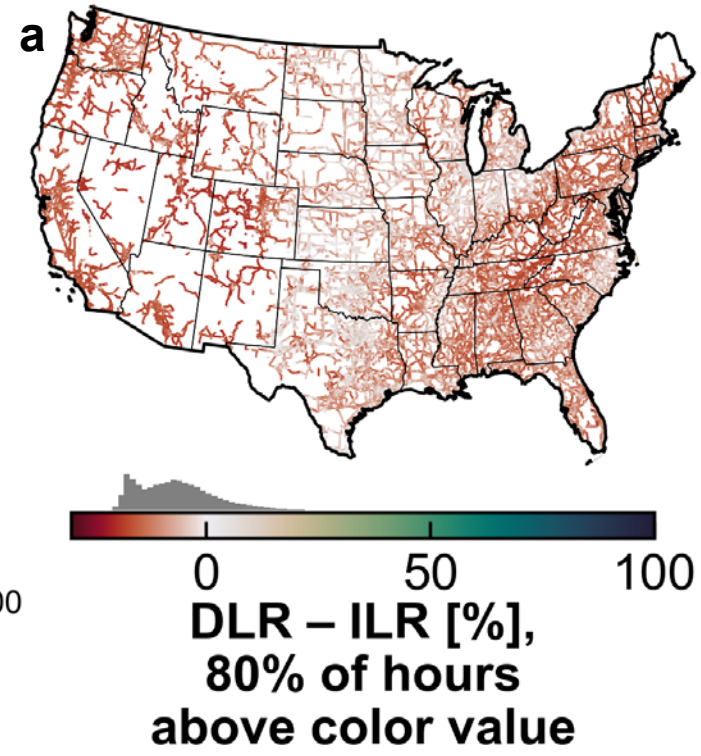
- **1%** higher than the clear-sky rating in **20%** of hours
- **2%** higher in **10%** of hours
- **4%** higher in **5%** of hours

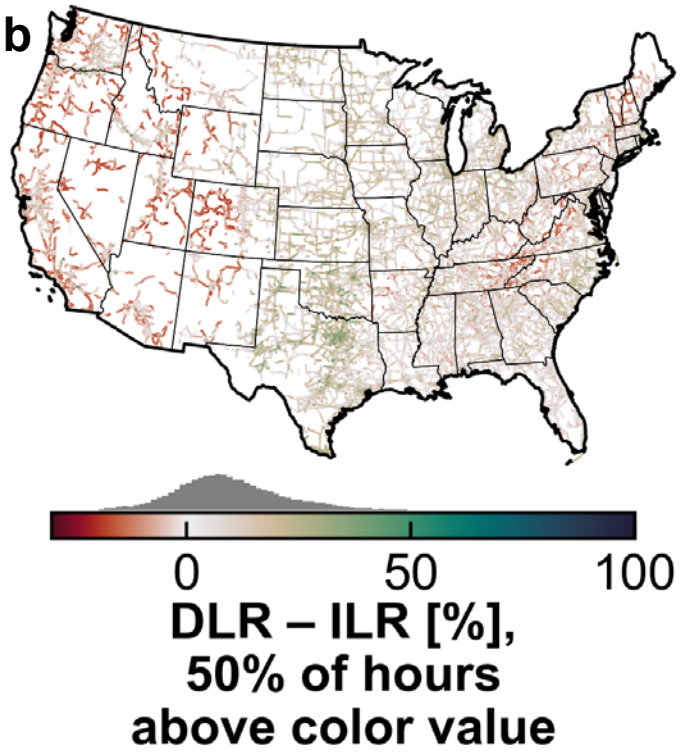
Preliminary results

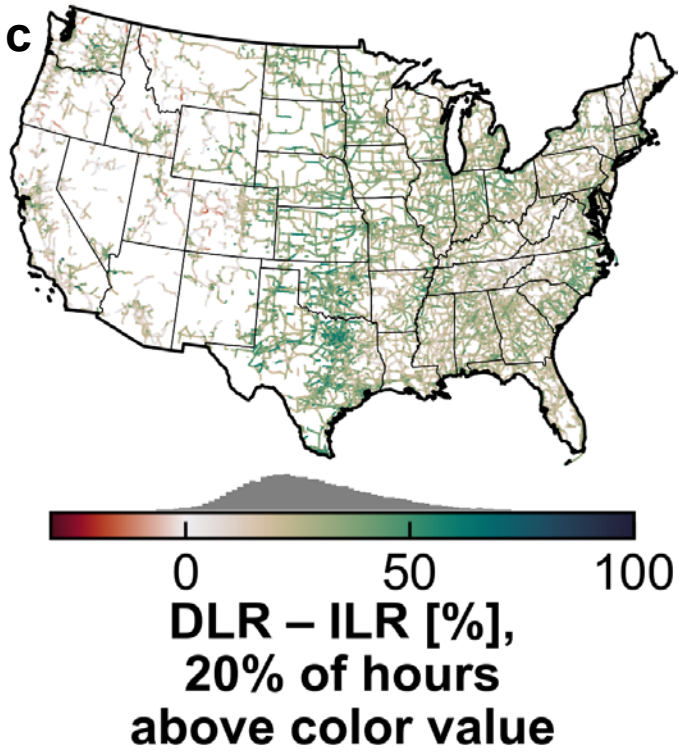
51,957 lines (≥115 kV, ≤50 miles) | 61,368 hours (2007–2013) | 0.61 m/s windspeed (except DLR) | SLR: 40°C air, 75°C conductor

What changes when actual windspeed is used?









For **50%** of lines, the full dynamic (including windspeed) rating is…

- **7% lower** than the actual-irradiance rating in **20%** of hours
- **8%** higher in **50%** of hours
- **26%** higher in **20%** of hours

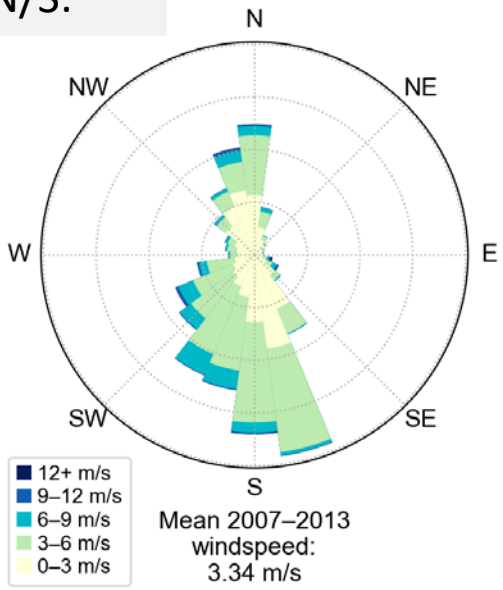
Preliminary results

51,957 lines (≥115 kV, ≤50 miles) | 61,368 hours (2007–2013) | 0.61 m/s windspeed (except DLR) | SLR: 40°C air, 75°C conductor

“Overrated” hours are sensitive to windspeed assumptions

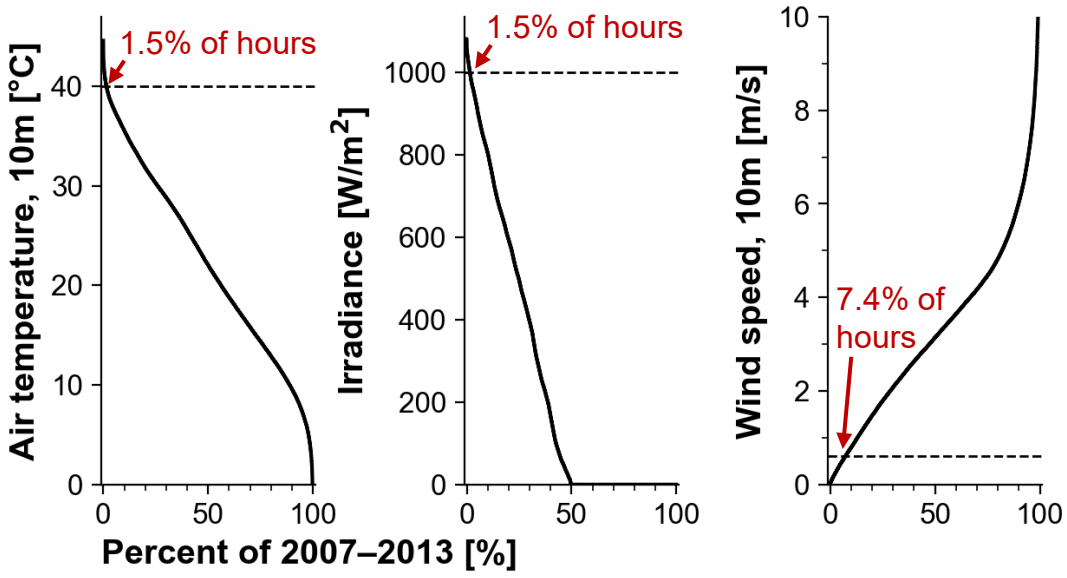
Explore two short artificial lines; one heading N/S, one heading E/W:

In this location, the prevailing wind direction is N/S:

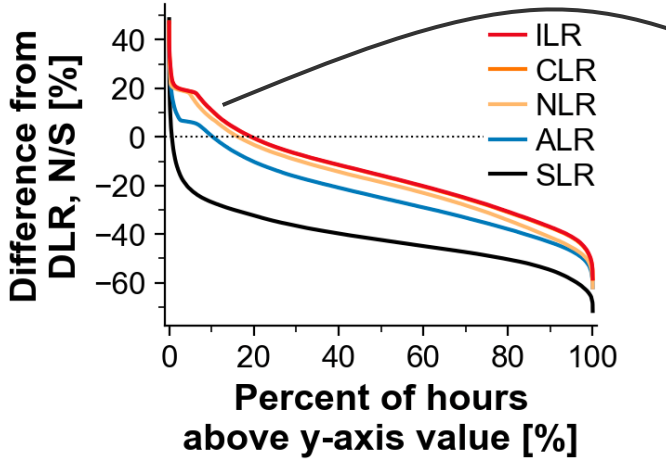


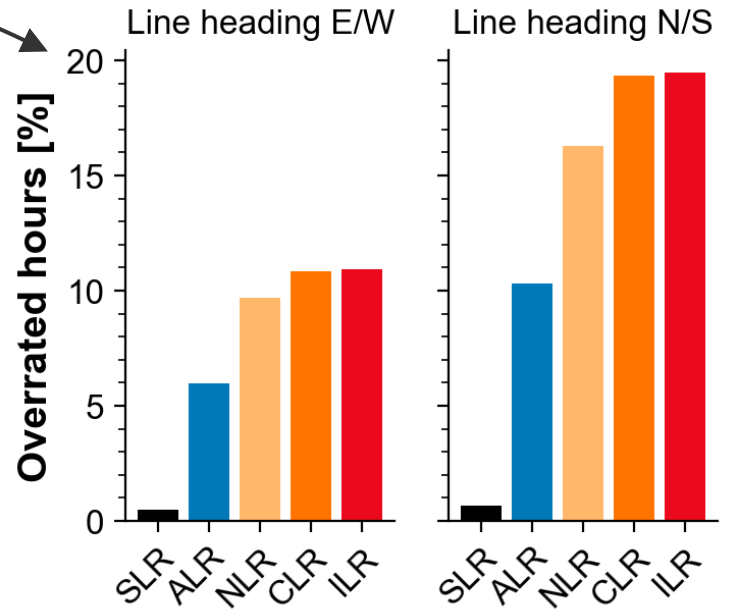
Preliminary results

- **1 hour (0.002%)** from 2007–2013 meets SLR conditions, where:
  - Temperature ≥ 40°C
  - GHI ≥ 1000 W/m²
  - Wind speed ≤ 0.61 m/s (ignoring direction)
- **4,511 hours (7.4%)** where windspeed ≤ 0.61 m/s



Compare each rating to actual (dynamic) rating:





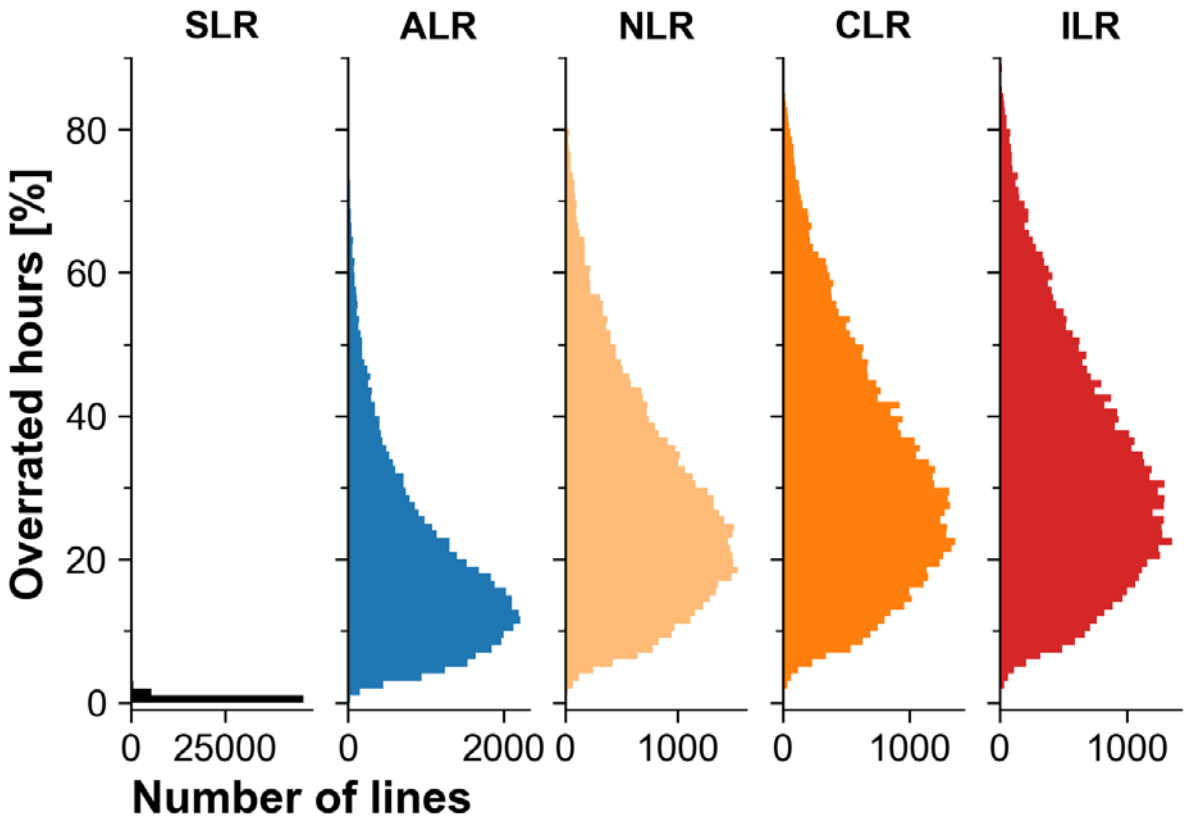
When stopping short of full DLR, using SLR wind assumptions (0.61 m/s perpendicular) results in many “overrated” hours

“Overrated” hours are sensitive to windspeed assumptions

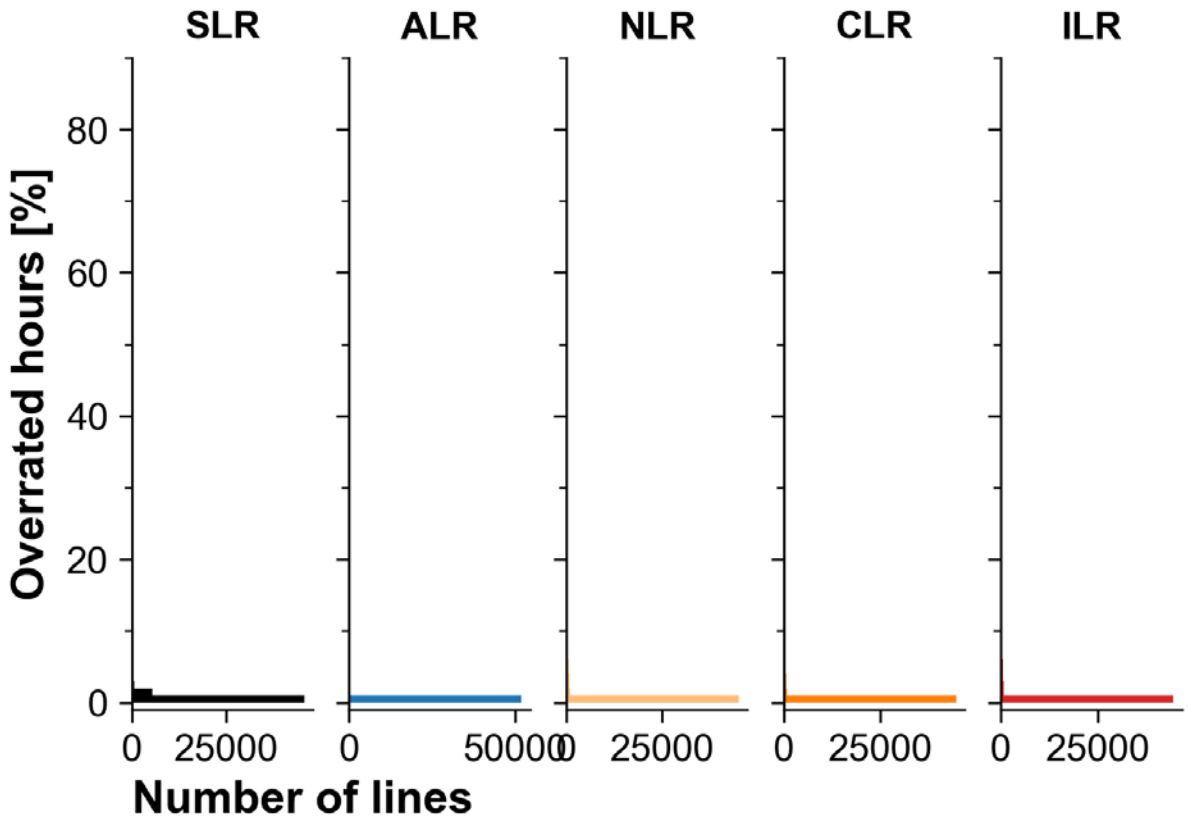
Preliminary results

For each rating method, in how many hours is the rating ≥1% greater than the actual rating (taking DLR as the actual rating)?

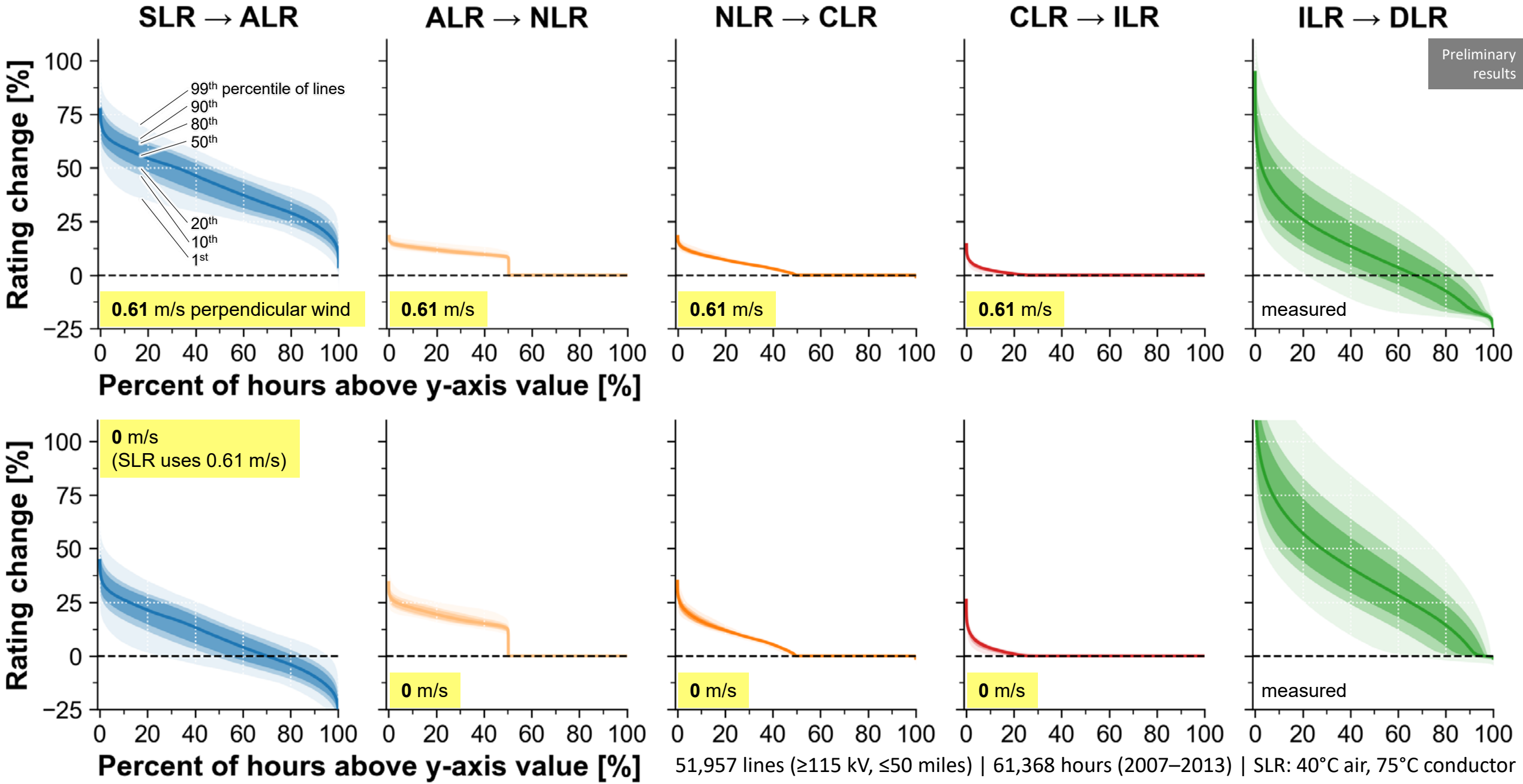
0.61 m/s perpendicular windspeed for SLR, ALR, NLR, CLR, ILR:



Zero windspeed for ALR, NLR, CLR, ILR:

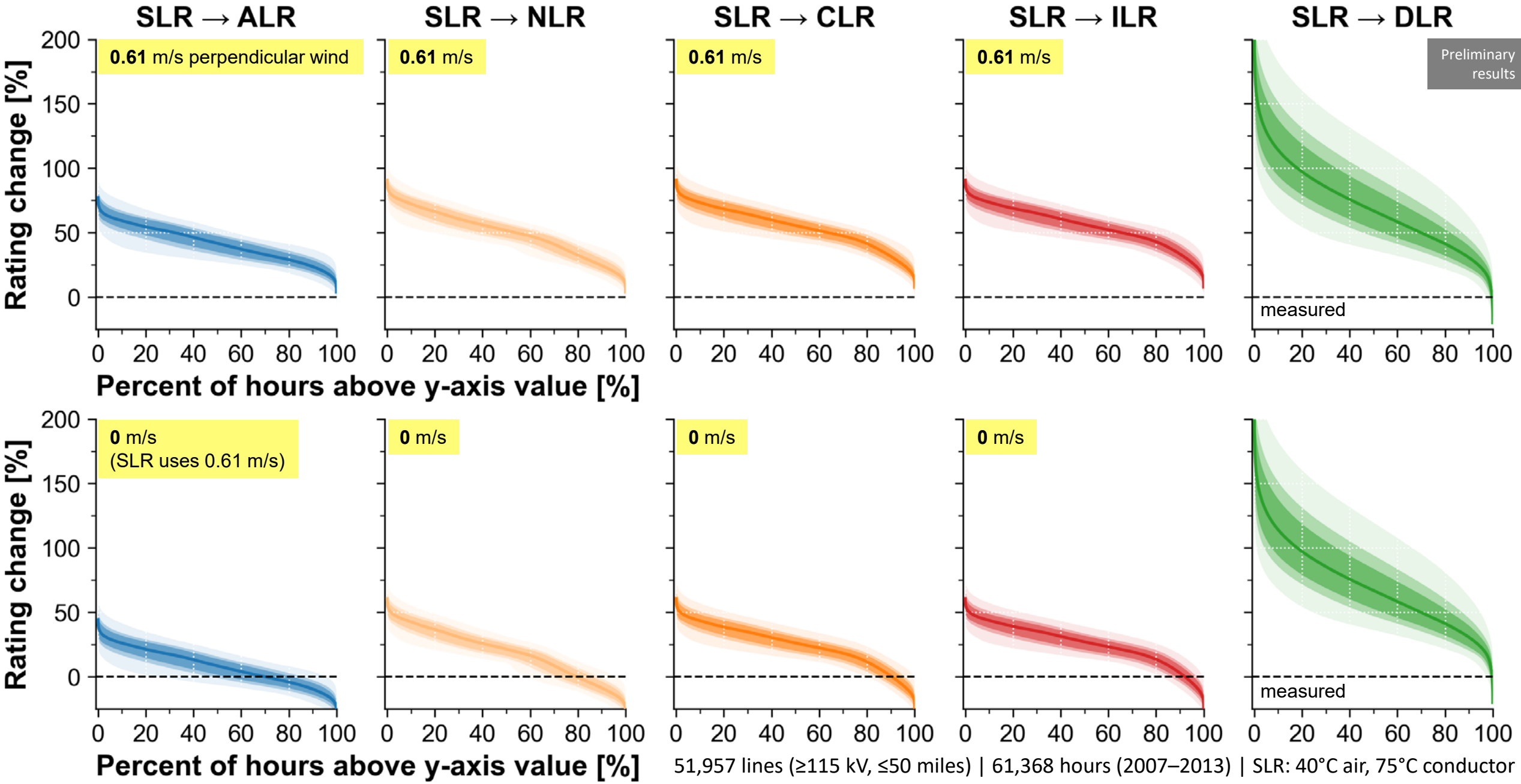


What if we assume **zero** windspeed for ALR, NLR, CLR, ILR? (marginal change)



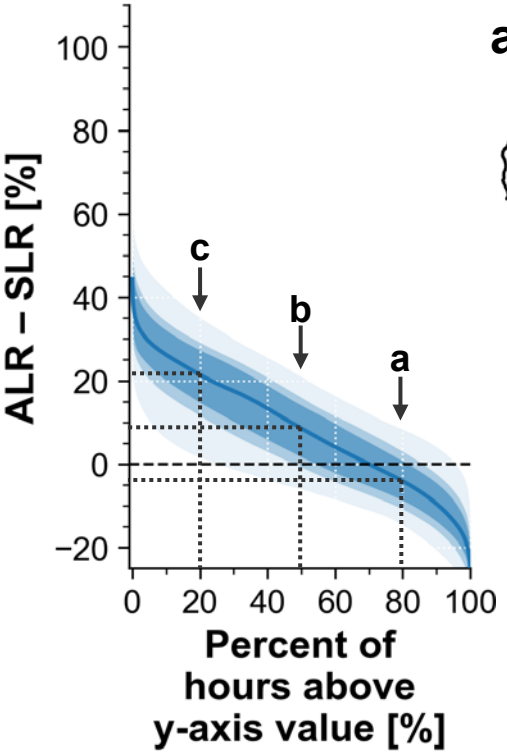
51,957 lines (≥115 kV, ≤50 miles) | 61,368 hours (2007–2013) | SLR: 40°C air, 75°C conductor

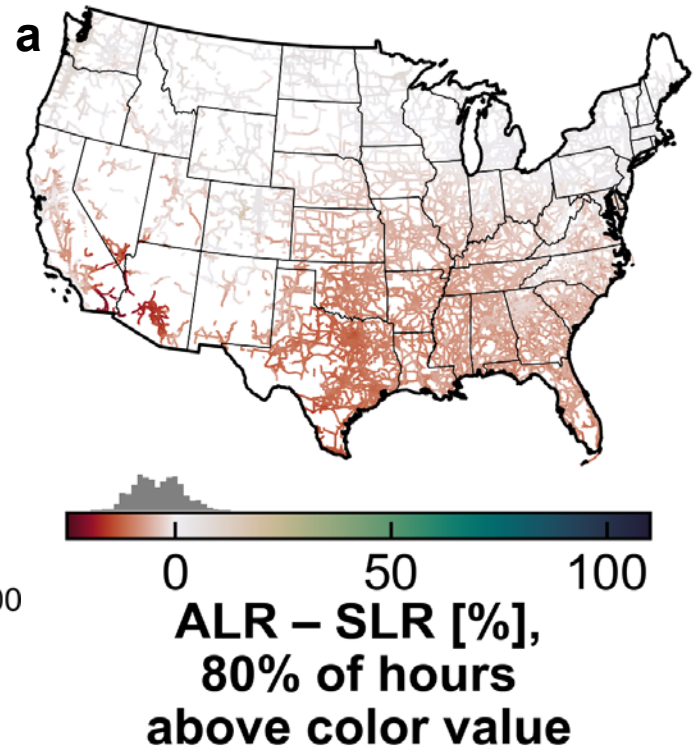
What if we assume **zero** windspeed for ALR, NLR, CLR, ILR? (total change)

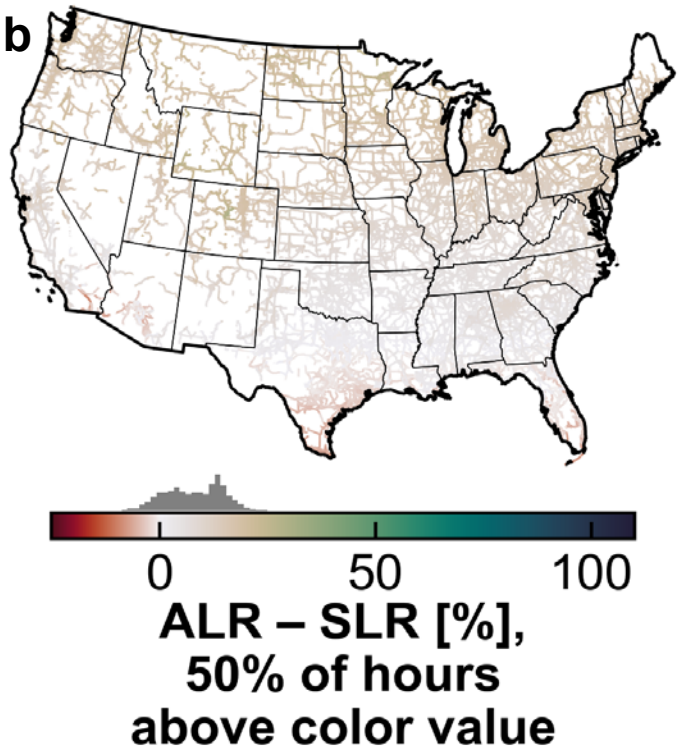


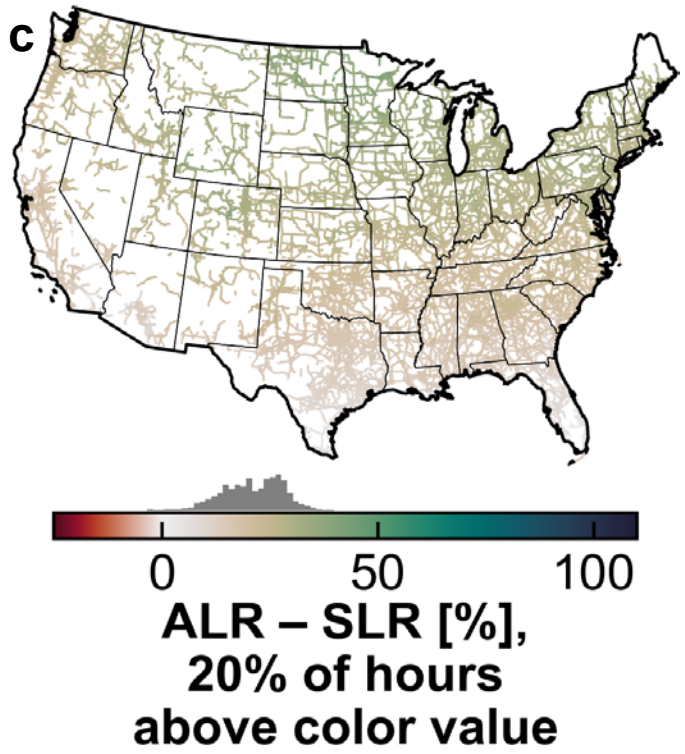
51,957 lines (≥115 kV, ≤50 miles) | 61,368 hours (2007–2013) | SLR: 40°C air, 75°C conductor

What if we assume **zero** windspeed for ALR, NLR, CLR, ILR? (marginal change)









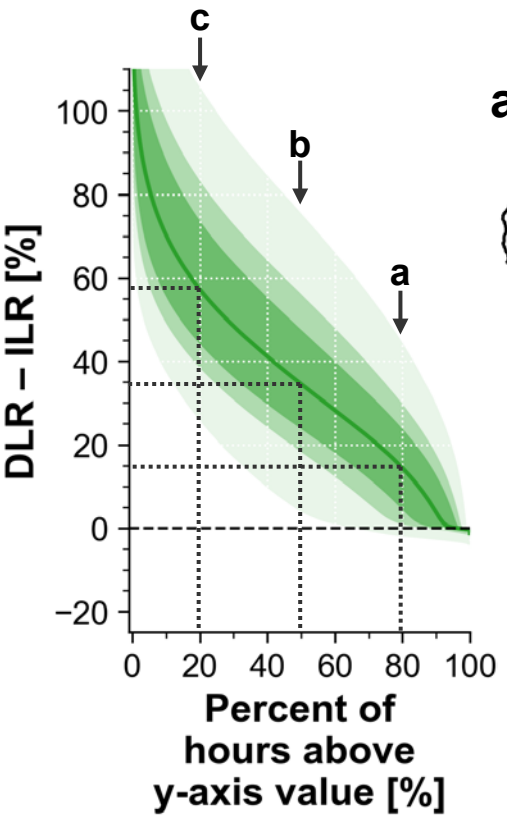
For **50%** of lines, the **ambient** (temperature-adjusted) rating is…

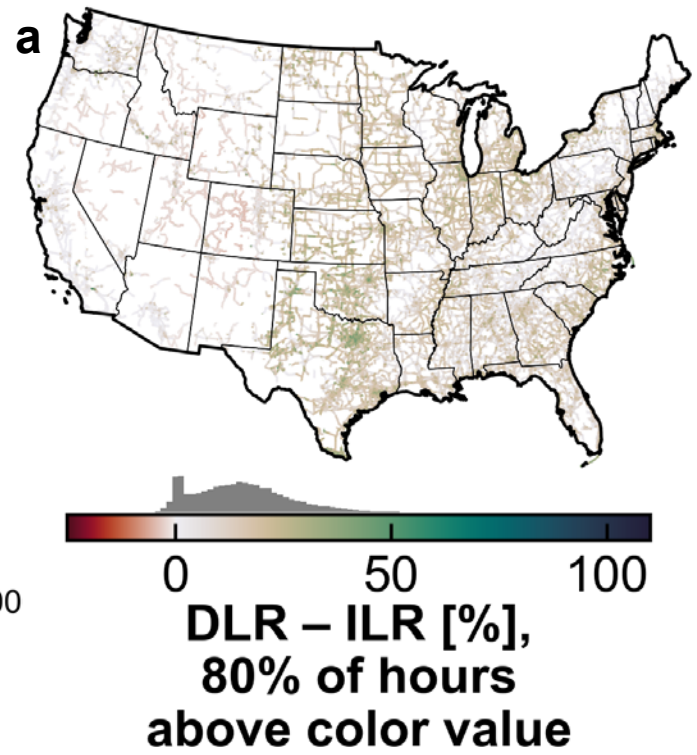
- **4% lower** than the **static** rating in **20%** of hours
- **9%** higher in **50%** of hours
- **21%** higher in **20%** of hours

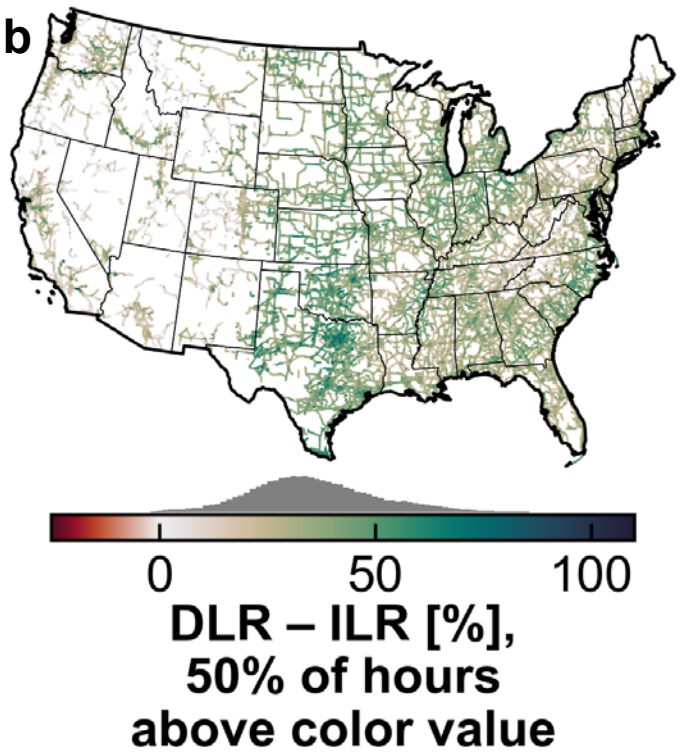
Preliminary results

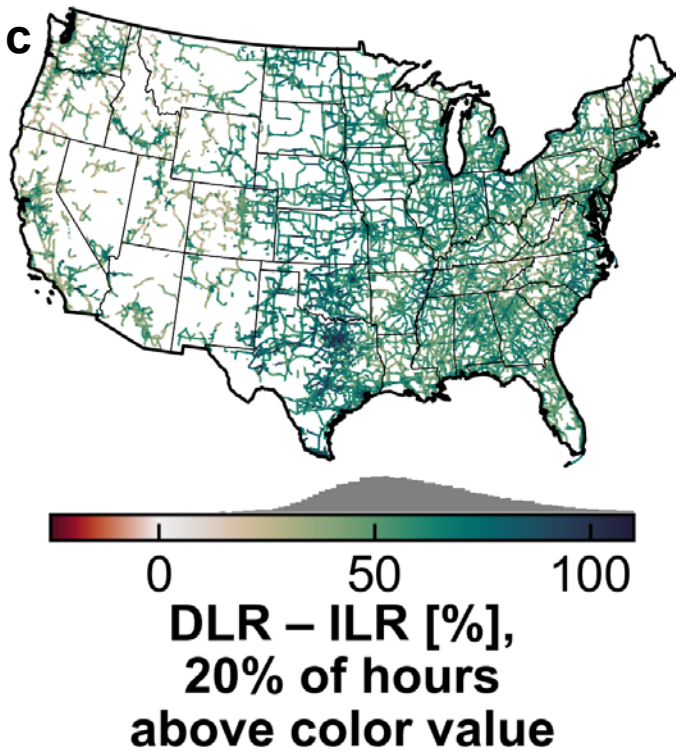
51,957 lines (≥115 kV, ≤50 miles) | 61,368 hours (2007–2013) | 0.61 m/s windspeed (except DLR) | SLR: 40°C air, 75°C conductor

What if we assume **zero** windspeed for ALR, NLR, CLR, ILR? (marginal change)









For **50%** of lines, the full **dynamic** (including windspeed) rating is…

- **14%** higher than the **actual-irradiance** rating in **80%** of hours
- **35%** higher in **50%** of hours
- **57%** higher in **20%** of hours

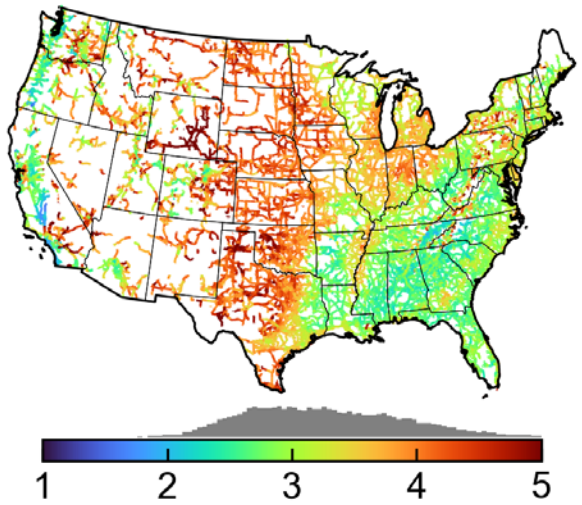
Preliminary results

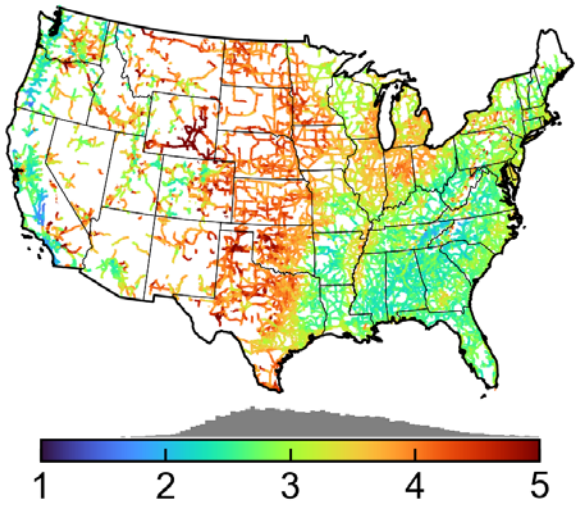
51,957 lines (≥115 kV, ≤50 miles) | 61,368 hours (2007–2013) | 0.61 m/s windspeed (except DLR) | SLR: 40°C air, 75°C conductor

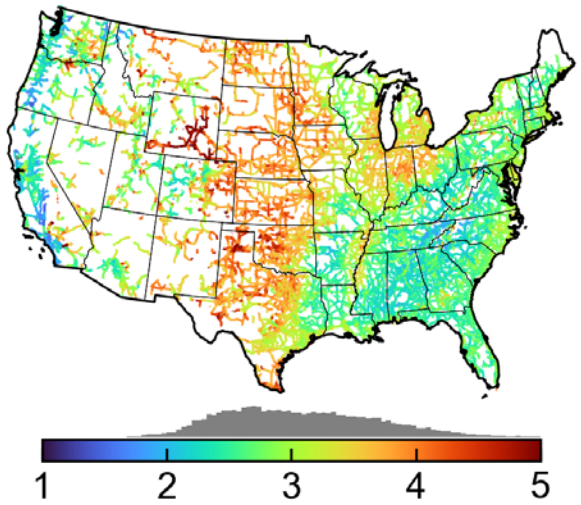
Exploring an average-windspeed threshold

Combine with HIFLD routes and quantify the fraction of each line above a given average windspeed

https://www.nrel.gov/gis/wind-resource-maps.html





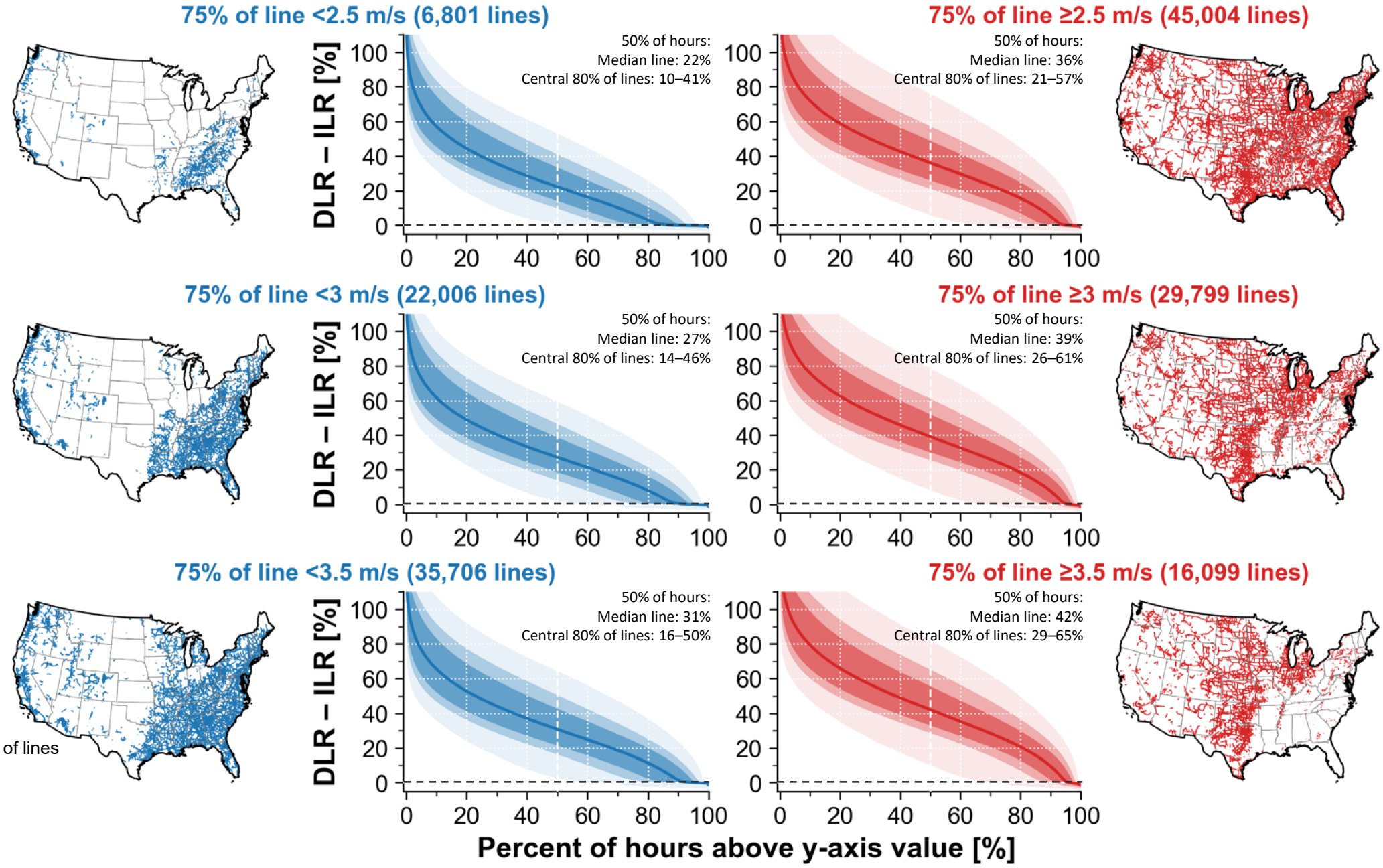


Examine distribution of DLR benefits for lines above/below different thresholds (next slide)

Preliminary results

Exploring an average-windspeed threshold

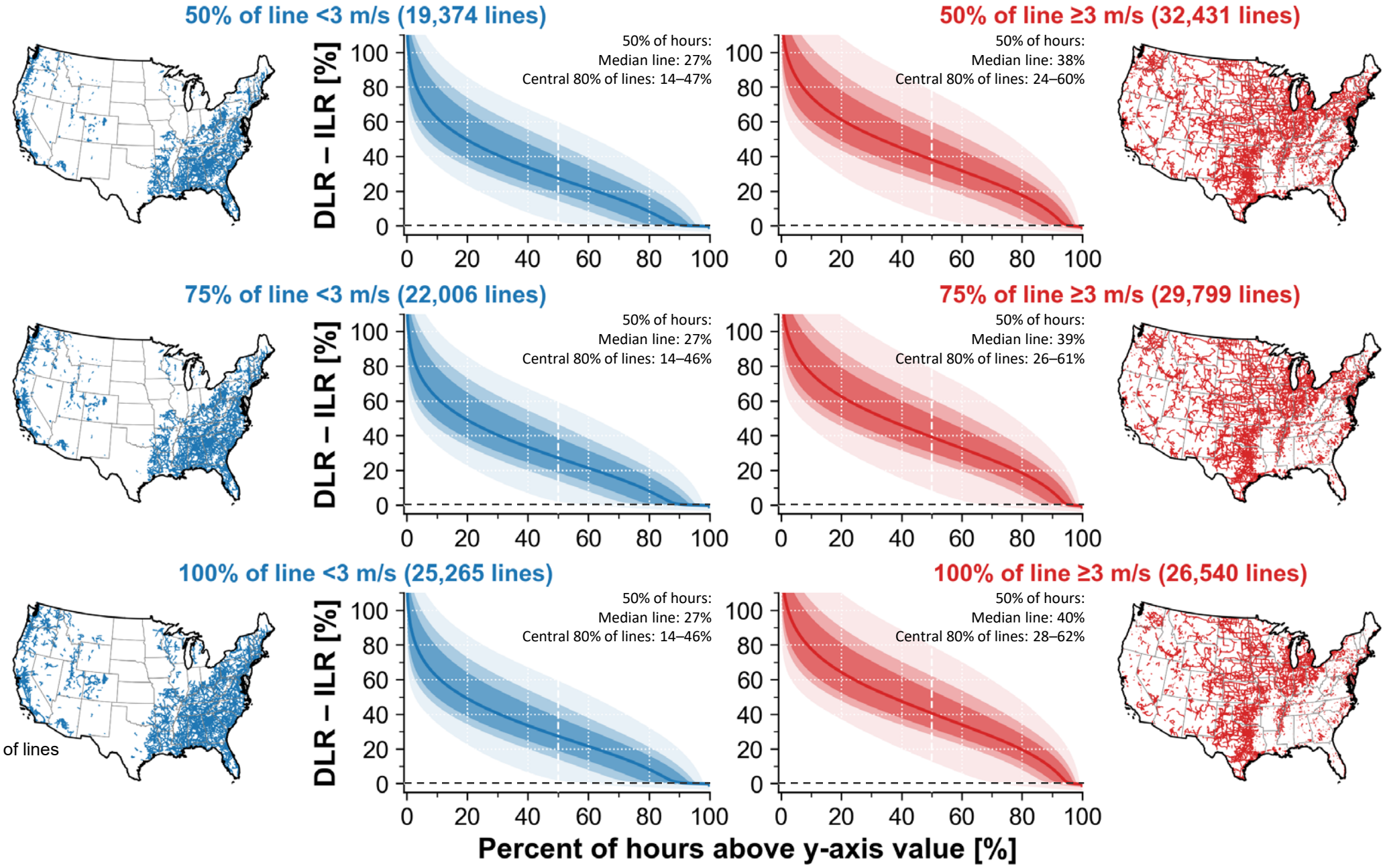
ILR: zero windspeed



Preliminary results

Exploring an average-windspeed threshold

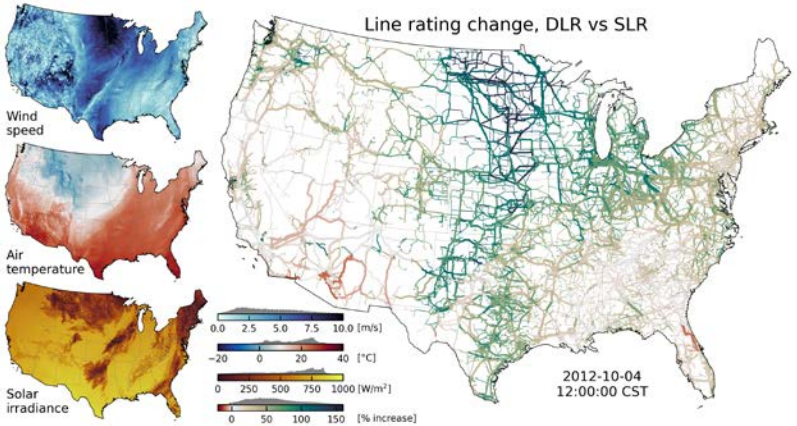
ILR: zero windspeed



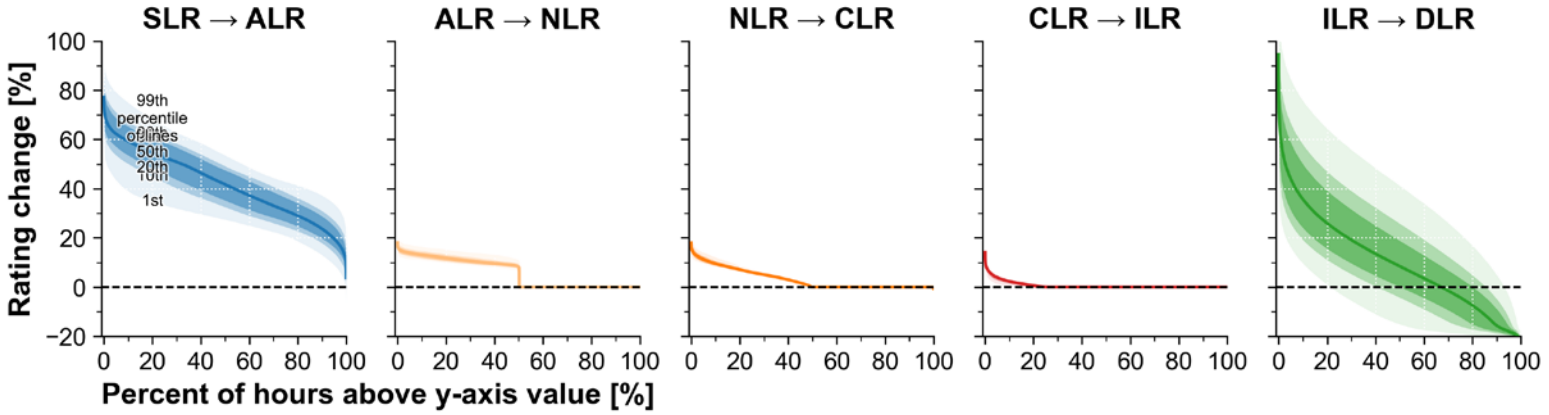
Preliminary results

Some observations

1. Hourly line ratings can be quickly approximated for tens of thousands of lines using **publicly available historical weather data** for use in planning and cost/benefit studies

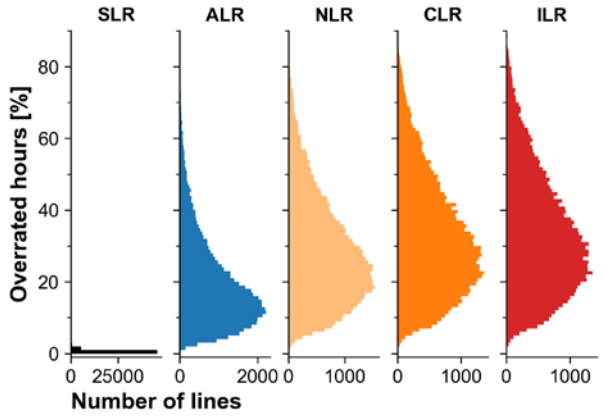


2. Moving from **nighttime**-adjusted ratings to **clear-sky**-adjusted ratings provides more benefit than moving from **clear-sky**-adjusted ratings to **actual-irradiance**-adjusted ratings



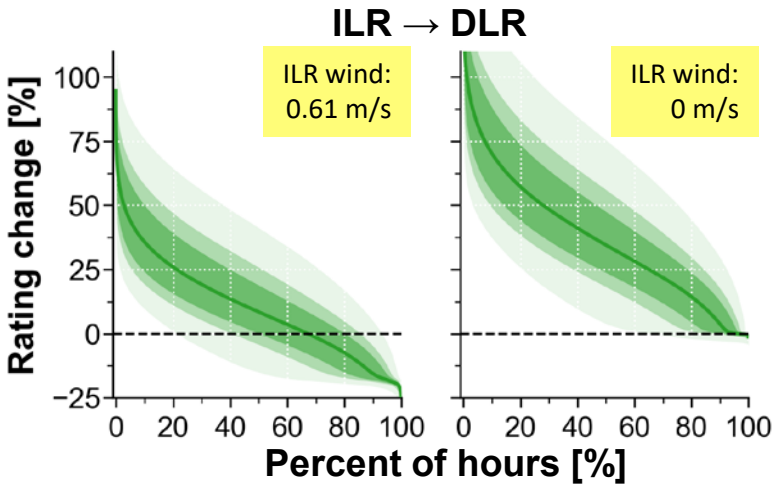
3. If using real-time temperature and irradiance **without** adjusting the assumed static windspeed, the **incidence of "overrated" hours increases** (≤0.61 m/s wind alone is more common than ≥40°C temperature, ≥1000 W/m² irradiance, and ≤0.61 m/s windspeed together)

0.61 m/s perpendicular windspeed for SLR, ALR, NLR, CLR, ILR:

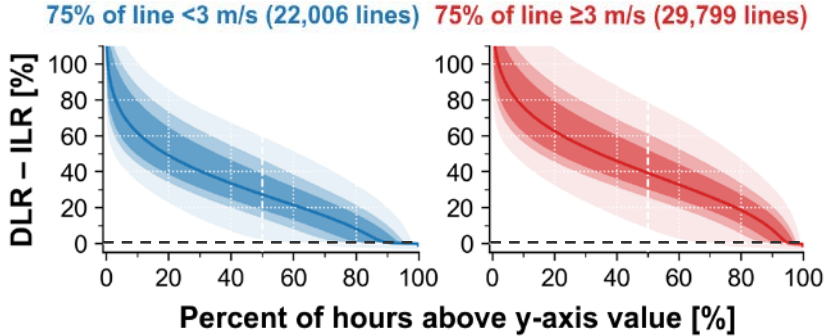


Preliminary results

4. DLR provides substantially more detail than ILR; the nature of benefits (higher ratings vs avoided "overrating") is **sensitive to counterfactual assumptions and line-specific weather patterns**



5. Lines with ≥75% of their length above 3 m/s tend to demonstrate larger increases in ratings with DLR than lines below the threshold, but there is **significant variability across lines**, and many lines below the threshold still show large benefits from DLR; full calculations including hourly wind speed and direction provide more information than heuristics based on average wind speed



Contact information and computer code:

patrick.brown@nrel.gov

https://github.com/NREL/DynamicLineRatings

www.nrel.gov

NREL/PR-6A40-91599

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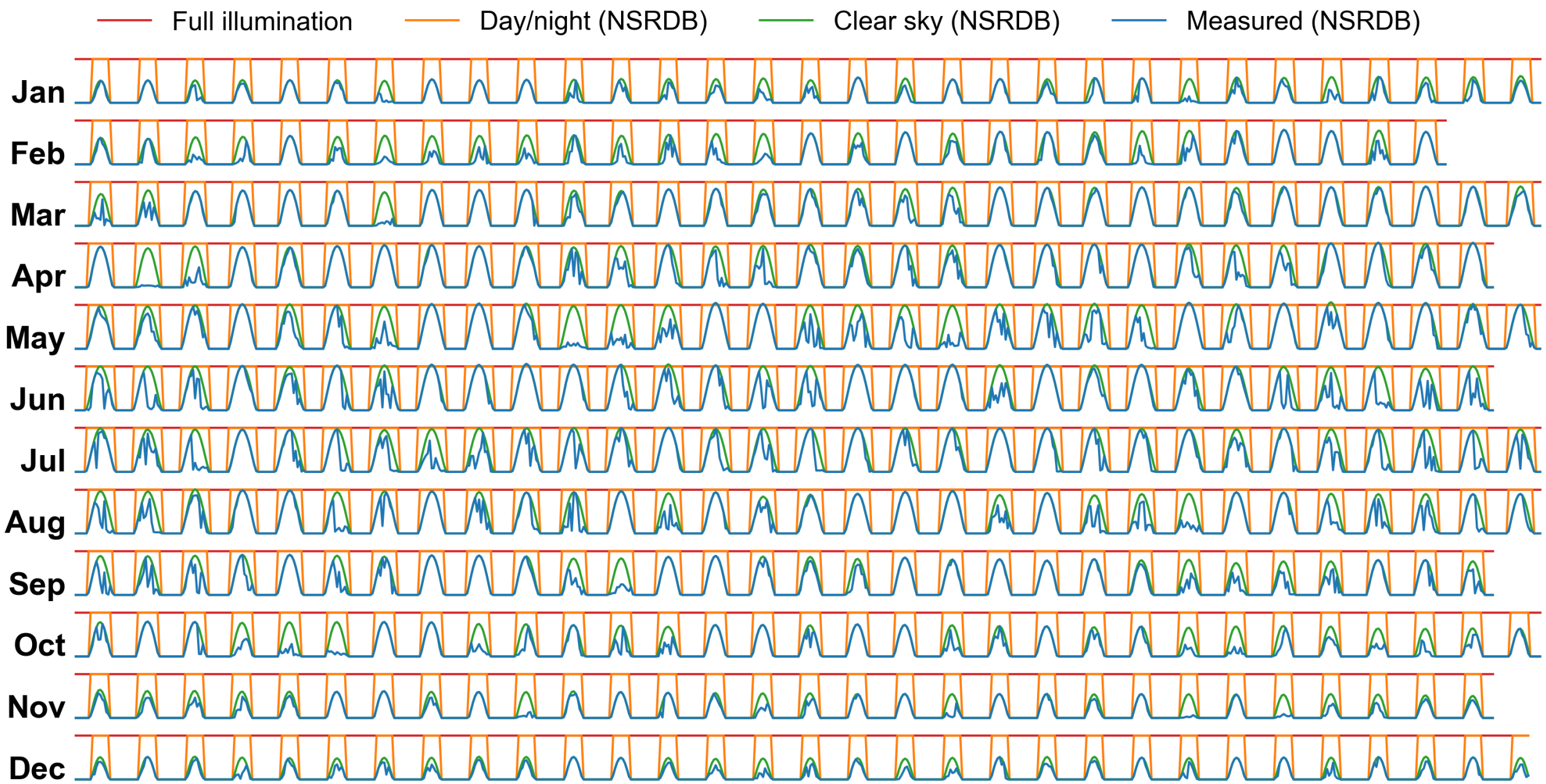
Supplementary Information

Abbreviations

ACSR	aluminum conductor, steel reinforced
ALR	ambient-temperature-adjusted line rating
ANOPR	Advanced Notice of Proposed Rulemaking
CIGRE	International Council on Large Electric Systems
CLR	clear-sky-irradiance-adjusted line rating
DLR	dynamic line rating (including wind speed and direction)
FERC	Federal Energy Regulatory Commission
GHI	global horizonal irradiance
HIFLD	Homeland Infrastructure Foundation Level Dataset
IEEE	Institute of Electrical and Electronics Engineers
ILR	measured-irradiance-adjusted line rating
kV	kilovolts
m/s	meters per second
NLR	nighttime-adjusted line rating
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Database
SLR	static line rating
W/m^2	watts per square meter
WTK	Wind Integration National Dataset (WIND) Toolkit
ZLR	seasonal line rating

Irradiance options

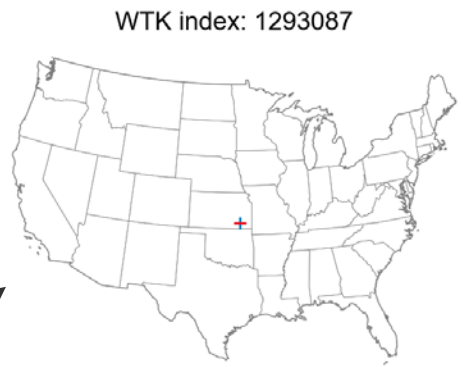


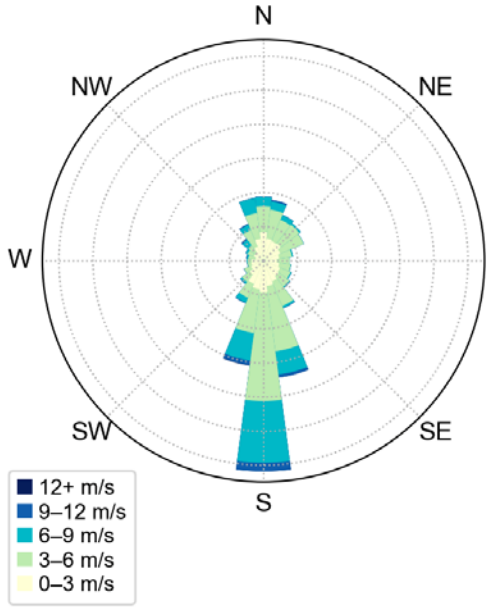
Validation: Wind angle

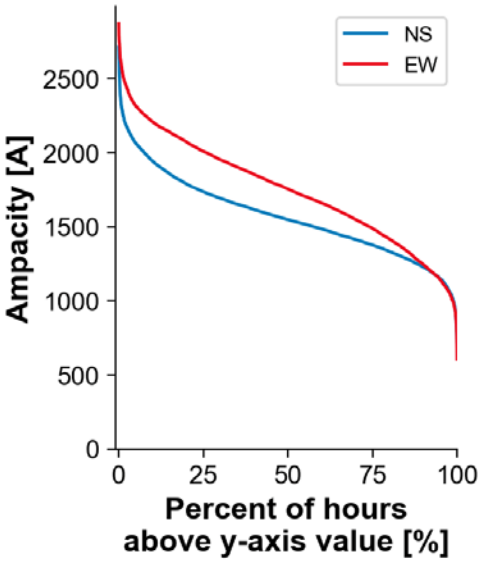
Convective cooling is strongest when the wind blows perpendicular to the conductor.

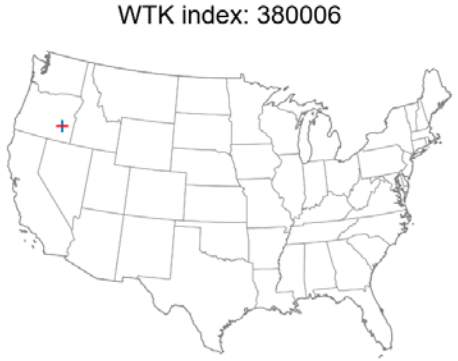
These tests show that the line ratings behave as expected:

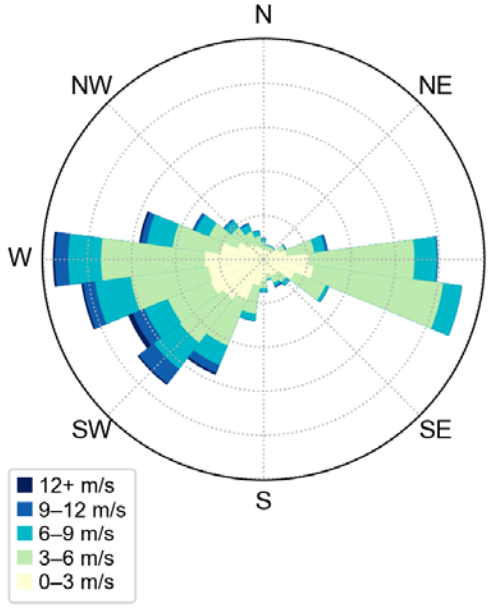
- In a location where the prevailing wind is from the **north and south**, an **east-west line has a higher rating** than a north-south line
- In a location where the prevailing wind is from the **east and west**, a **north-south line has the higher rating**

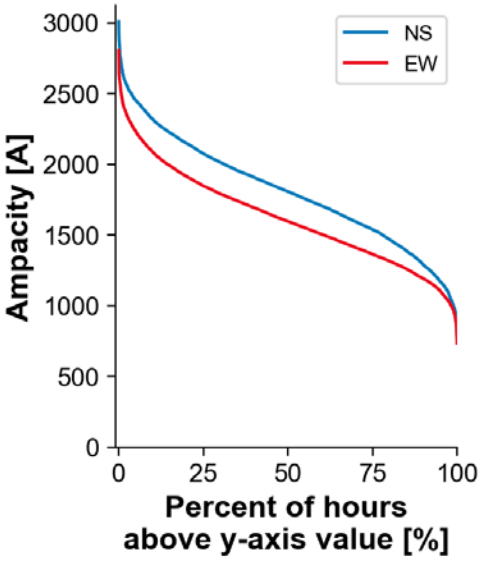






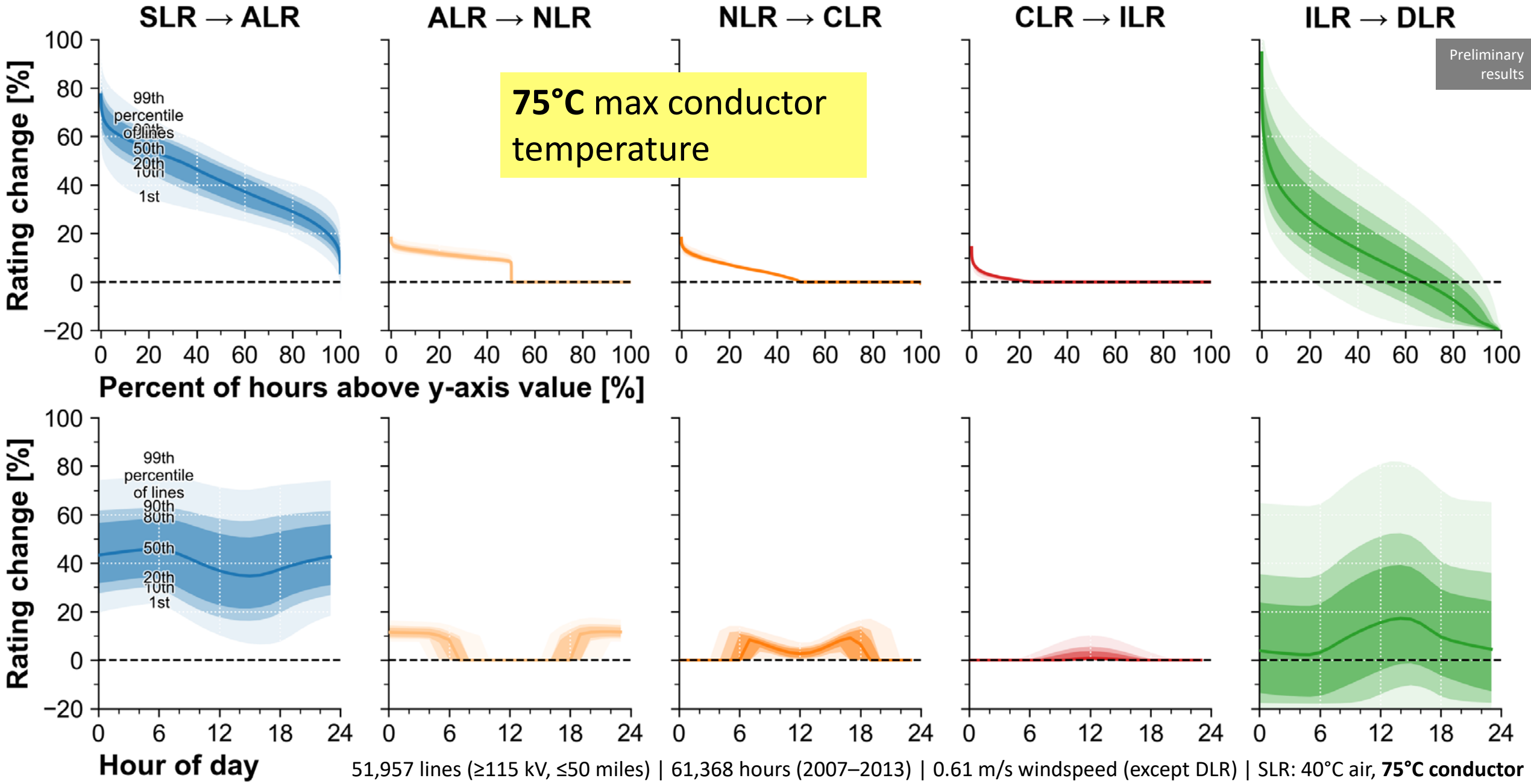






Preliminary results

What if we change the assumed conductor temperature?



51,957 lines (≥115 kV, ≤50 miles) | 61,368 hours (2007–2013) | 0.61 m/s windspeed (except DLR) | SLR: 40°C air, **75°C conductor**

What if we change the assumed conductor temperature?