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An Empirical Analysis of the Operational Efficiencies and Risks Associated with Static, Ambient Adjusted, and Dynamic Line Rating Methodologies

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SUMMARY

Advanced transmission line ratings are currently under consideration at many utilities for a multitude of reasons including a pending Federal Energy Regulatory Commission (FERC) notice of proposed rulemaking published in November 2020. Operating the grid with Static Line Ratings (SLR) based on conservative assumptions of temperature and wind speeds can leave additional existing capacity unaccounted for and in transmission-constrained areas, can cause market binding events, redispatch, curtailment, and roadblocks for renewable energy projects. Alternatively, overstated ratings during periods with low or no wind present can put National Electrical Safety Code (NESC) mandated line clearances and conductor health in jeopardy, risking the safety and reliability of the grid.

Several line rating methodologies exist in practice across the US grid operators, each utilizing a different approach based on fixed assumptions or variable inputs for the properties that make up the IEEE 738 [1] heat balance equations for line ratings. Ambient Adjusted Ratings (AAR) can offer limited extra capacity over Static Line Ratings (SLR), however at times they will overestimate capacity because assumed wind speeds are not available, but cooler temperatures would indicate that higher ratings should be used. This combination of assumptions will put system reliability at risk for a significant portion of time. Dynamic Line Ratings (DLR) take into account real-time and forecasted field measurements to determine conductor ampacity, eliminating assumptions around wind speed, the most influential variable driving conductor ratings.

This paper examined and compared the three rating methodologies through a statistical data analysis approach to understand the operational efficiencies that can be realized from each methodology. It also highlights the risks associated with incorrect static assumptions. The AAR often indicated that increased capacity over SLR was available, however both utilize the fixed wind speed assumption which is not always present. DLR provided significant capacity increases above both SLR and AAR as it accounts for the fluid dynamics effects of wind flowing across a conductor which provides significant convective cooling. DLR occasionally was shown to be below the AAR which indicates that the AAR would have incorrectly indicated that additional capacity was available. The DLR provided even greater additional capacity over AAR and mitigated the risk of an overstated

static wind speed assumption. Since DLR values are determined by field-based sensors, the rating methodology allows for many input assumptions to be eliminated. This methodology provided the greatest increase in usable capacity as compared to SLR and AAR, in terms of aggregate capacity over time. DLR also minimized risks to operational reliability and increased safety as the sensor-based values would have prevented unnecessary risk from being introduced into the system during times when AAR and SLR would have overestimated line capacity.

On average, DLR provides 33.8% greater capacity in summer and 19.3% greater capacity in winter than SLR while mitigating the risk of exceeding maximum operating temperature. AAR provides 15.1% greater capacity in summer and 2.7% greater capacity in winter, with a risk of overstating ratings. DLR provides 16.3% greater capacity in the summer over AAR and 16.2% greater capacity over AAR in the winter.

DLR dips below AAR 22% of the time in the summer and 27% of the time in the winter, a consequence of occurrences when AAR's static wind speed assumption overestimates actual wind speeds. This most often happens at night when wind speeds are lower, and temperatures cooler. AAR, which considers only variations in temperature, would indicate that additional capacity is available. During these periods, operating the line at the rating determined by AAR would put the line at risk of exceeding its maximum operating temperature if the line were loaded at AAR capacity in post-contingency operations.

KEYWORDS

Dynamic Line Ratings, DLR, Ambient Adjusted Ratings, AAR, Transmission Line Monitoring

1. Introduction

Advanced transmission line ratings are currently under consideration at many utilities for a multitude of reasons including the operational efficiencies that can be gained by implementing advanced methodologies. Advanced line ratings typically include Ambient Adjusted Ratings (AAR) and Dynamic Line Ratings (DLR), while the most commonly used methodology is a Static Line Rating (SLR). Operating the grid with SLR based on conservative assumptions of temperature and wind speeds can leave additional existing capacity unaccounted for and in transmission-constrained areas, can cause market binding events, redispatch, curtailment, and roadblocks for renewable energy projects. Alternatively, overstated ratings during periods with low or no wind present can put National Electrical Safety Code (NESC) mandated line clearances and conductor health in jeopardy, risking the safety and reliability of the grid.

Traditionally, additional capacity has been added to our grid through construction of new transmission lines, which is an important component of any grid planning process. Complementing this approach, advanced line ratings have been shown to enable additional capacity with existing infrastructure at a fraction of the cost of traditional transmission line construction projects and without requiring a time-consuming permitting process. A recent study [2] analyzing the impact of Grid Enhancing Technologies (GETs) showed that grid congestion can be reduced and the generation interconnection process can be accelerated by utilizing the additional capacity unlocked by operationalizing advanced line ratings.

To study the operational efficiencies and risks associated with the different types of line ratings, National Grid and LineVision performed an analysis comparing the sets of ratings that would be generated for the same transmission line using the different methodologies. The study was conducted on a 115 kV transmission line in Massachusetts owned and operated by National Grid and it was equipped with LineVision V3 non-contact line monitors in July of 2019. The monitoring system was mounted directly to the tower structure and consists of a combination of LiDAR and EMF (electromagnetic field) sensors. The system is able to measure and determine key conductor parameters for all individual phases monitored such as sag, horizontal motion (blowout), conductor temperature, DLR, and provided operators with alerts on anomalous operating conditions such as galloping, ice build-up, or excessive motion.

The analysis was conducted over a one-year period from April 2020 to March 2021 and all ratings were determined for the steady-state, normal condition and are in units of megavolt-amperes (MVA). Short-term and long-term emergency ratings were not analyzed in this paper.

When considering applying advanced line ratings such as AAR and DLR to transmission circuits, it is important to consider that their ability to increase capacity applies to thermally-limited lines where the conductor is the limiting element. If a circuit is voltage- or stability-limited, or limited by substation terminal equipment such as a wavetrap or circuit breaker, that constraint must first be alleviated before advanced line ratings would be able to provide increases in usable network capacity. The scope of this analysis is limited to the rating of the overhead conductor and was performed as if there were no down-stream next limiting elements in the system which would have resulted in a ratings ceiling.

2. Line Rating Methodologies

Several line rating methodologies exist in practice across the US grid operators, each utilizing a different approach based on fixed assumptions or variable inputs for the properties that make up the IEEE 738 [1] heat balance equations for line ratings. SLR utilizes a fixed set of assumptions that do not change, or change once per year for a Winter and Summer Rating. With AAR the rating calculation is based upon a varying ambient temperature and can offer limited extra capacity over SLR. However, at times AAR can overestimate capacity because the assumed wind speeds are not available but cooler temperatures would indicate that higher ratings should be used. DLR takes into account real-time field measurements of conductor properties to determine the conductor ampacity (rating), removing the reliance on assumptions about wind speed, which is the most influential variable driving conductor ratings. DLR thus optimizes capacity utilization while minimizing risks to operational reliability and safety as assumptions are not used.

In this study, the seasonal SLR utilized fixed assumptions of wind speed, ambient temperature, and global horizontal irradiance (GHI). The conductor type for the studied line is 477 (18/1) ACSR "Pelican". The fixed assumptions are:

	Months	Ambient Temperature	Wind Speed	GHI
Summer	May-November	37.8 °C (100 °F)	0.914 m/s (3.0 ft/s)	1097 [W/m^2]
Winter	December-April	10.0 °C (50 °F)	0.914 m/s (3.0 ft/s)	644 [W/ m^2]

Table 1. Weather assumptions for the SLR by season.

Conductor Type	Emissivity / Absorptivity	Conductor Maximum Operating Temperature
477 (18/1) ACSR "Pelican"	0.8 / 0.8	100 °C (212 °F)

Table 2. Conductor properties.

AAR used in this study applied the same assumptions of wind speed and GHI, but ambient temperature was adjusted on an hourly basis. Temperatures were rounded up to the nearest increment of 2.8 °C (5 °F). Ambient adjusted ratings of the overhead lines were calculated once per hour based on the ambient temperature at the first minute of the hour, then held constant for the entire hour.

DLR values were determined by the LineVision system's data. Ambient temperature and GHI were measured in the field or determined by a location-specific real-time weather model. Perpendicular wind speed, a key parameter in calculating DLR, was determined by solving the IEEE 738 steady-state heat balance equations for its effective value in convective cooling of the conductor, when all other variables are known or measured. With the Maximum Operating Temperature of the conductor also known, the IEEE 738 equations can be again used to determine the maximum allowable current under the steady-state conditions, which is the DLR.

3. Static Ratings

Based on the assumptions and properties in Table 1 and Table 2, normal steady-state SLR values for the overhead conductors are shown in Table 3.

Summer SLR	160 MVA
Winter SLR	199 MVA

Table 3. Seasonal SLR values.

4. Ambient Adjusted Ratings

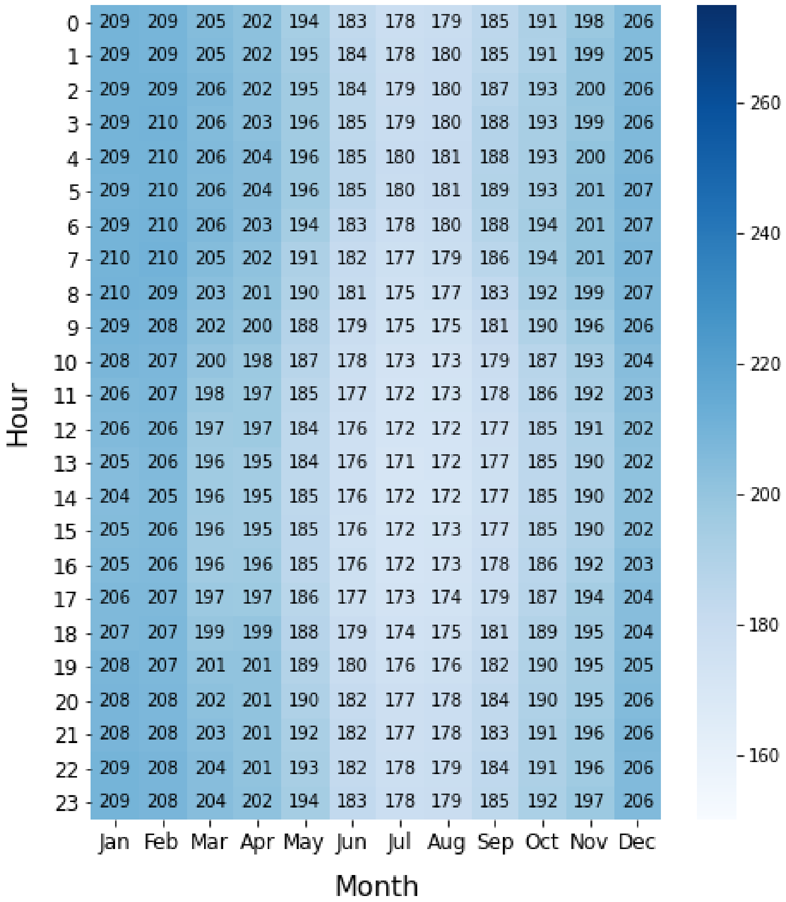


Figure 1 (Top Right). Average AAR by month and hour of day.

The average AAR for summer months was 184 MVA and for winter months was 204 MVA. The heat map in Figure 1 depicts monthly trends by hour of day in AARs throughout the year. AARs are typically highest during cool-weather months as their variation is driven by the changing temperature.

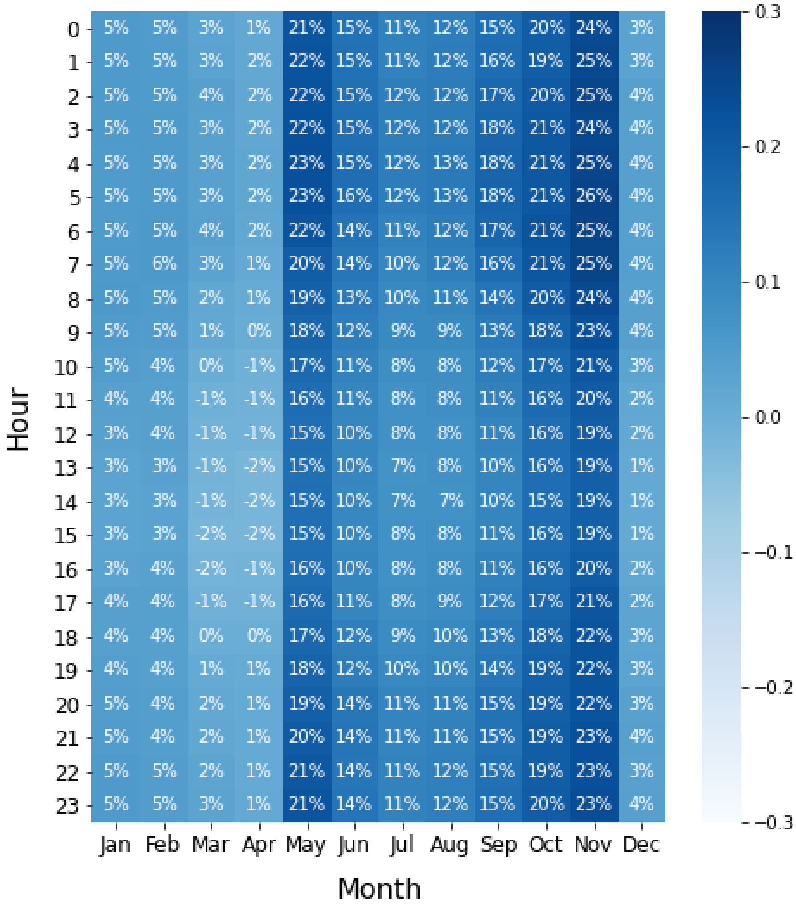


Figure 2 (Bottom Right). Comparison of AAR and SLR. Average percentage change in rating as determined by AAR compared to SLR.

The average absolute increase in capacity provided by AAR as compared to SLR in the summer was 24 MVA and winter was 5 MVA.

On average, AAR is 15.1% higher than SLR in summer, and 2.7% higher than SLR in winter.

The noticeable difference between the percentage increases seen in May and December are driven by the seasonal switching of the SLR from the Summer to Winter as May is the start of the summer rating and December is the start of the winter rating.

Generally, modest capacity increases are shown to be available if AAR were to be utilized as opposed to SLR. However, notably during the mid-day hours of March and April, the AAR presented as slightly lower than SLR. This was driven by unseasonably warmer average ambient temperatures than historical weather.

5. Dynamic Line Ratings

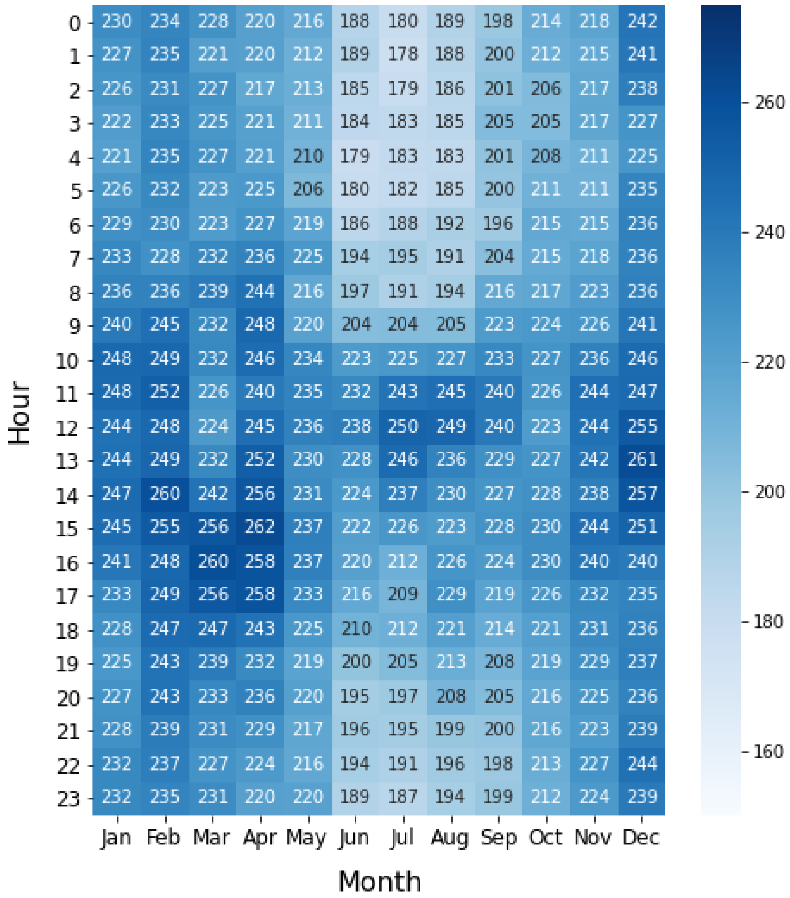


Figure 3 (Left). Average DLR by month and hour of day.

The average DLR as determined by the LineVision system for summer months was 214 MVA and for winter months was 237 MVA, significantly above the SLR and the average for the AAR.

DLRs are greatest in the winter months due to lower ambient temperatures. Greater wind speeds during the midday hours also lead to increased DLRs due to convective cooling.

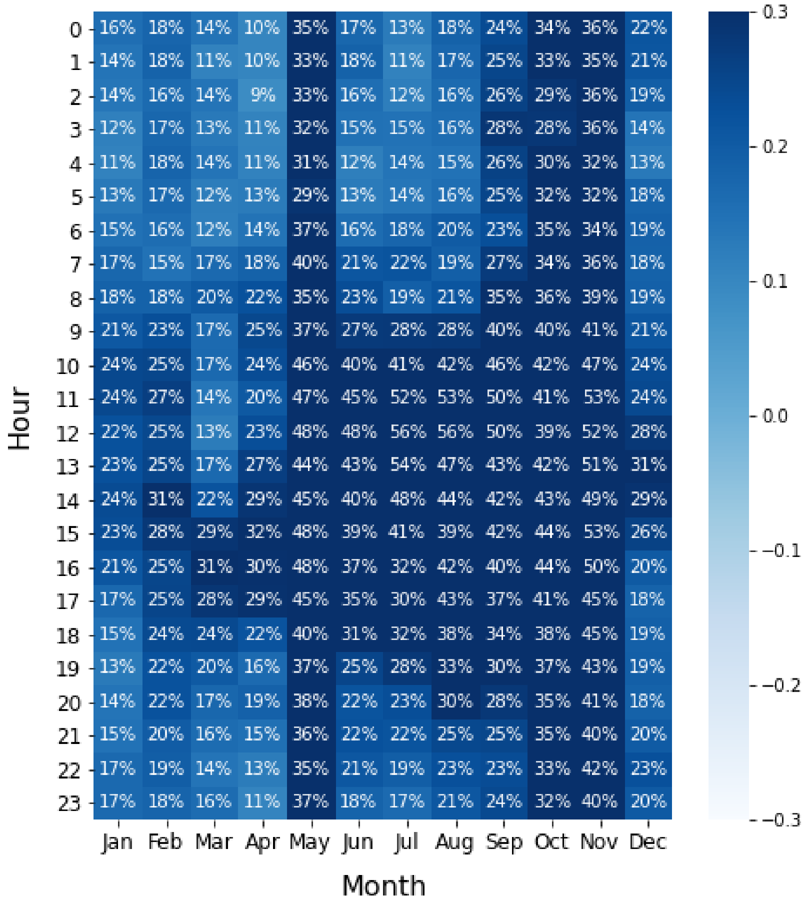


Figure 4 (Left). Comparison of DLR and SLR. Average percentage increase in rating as determined by DLR compared to SLR.

The average absolute increase in capacity provided by DLR as compared to SLR in the summer was 54 MVA and winter was 38 MVA.

On average, DLR is 33.8% higher than SLR in summer, and 19.3% higher than SLR in winter.

The noticeable difference between the percentage increases seen in May and December are driven by the seasonal switching of the SLR from the Summer to Winter

Figure 5 (Right). Comparison of DLR and AAR absolute values. Average difference between DLR and AAR by month and hour of day.

The heatmap in Figure 5 was generated by subtracting the AAR value from the DLR, resulting in the absolute average change in the rating that is provided by DLR as compared to AAR. The DLR shows significant capacity upside that would be available.

The average absolute increase in capacity provided by DLR over AAR in the summer was 30 MVA and in the winter was 33 MVA.

It is important to note that occasionally certain hourly averages showed a negative value, which indicates periods where AAR overestimated the true capacity that was available on the conductor.

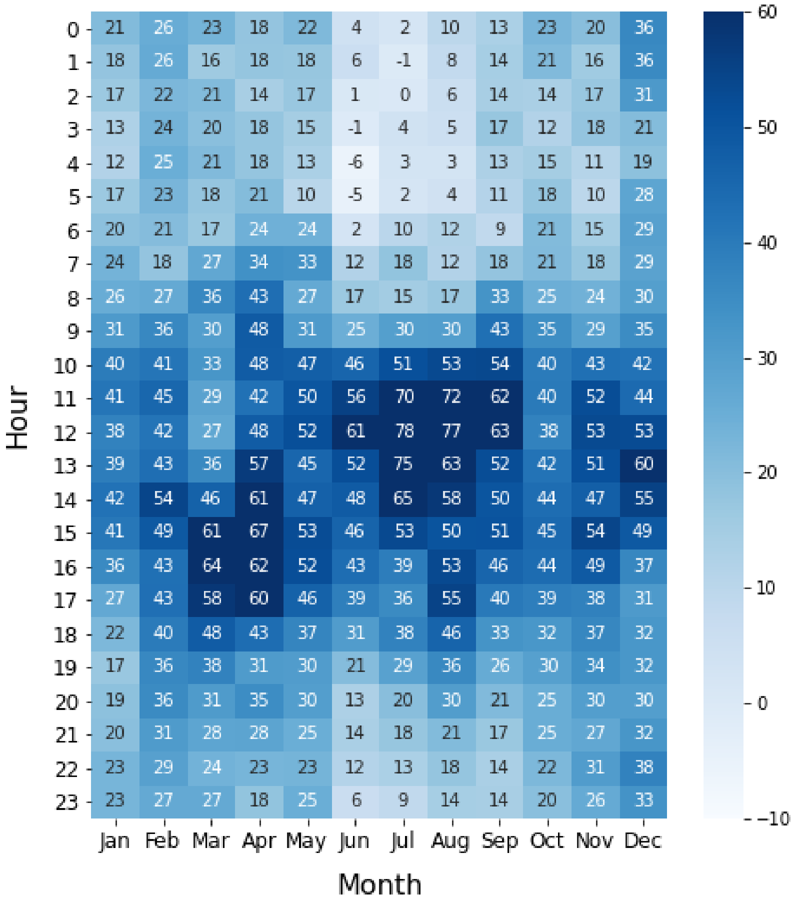
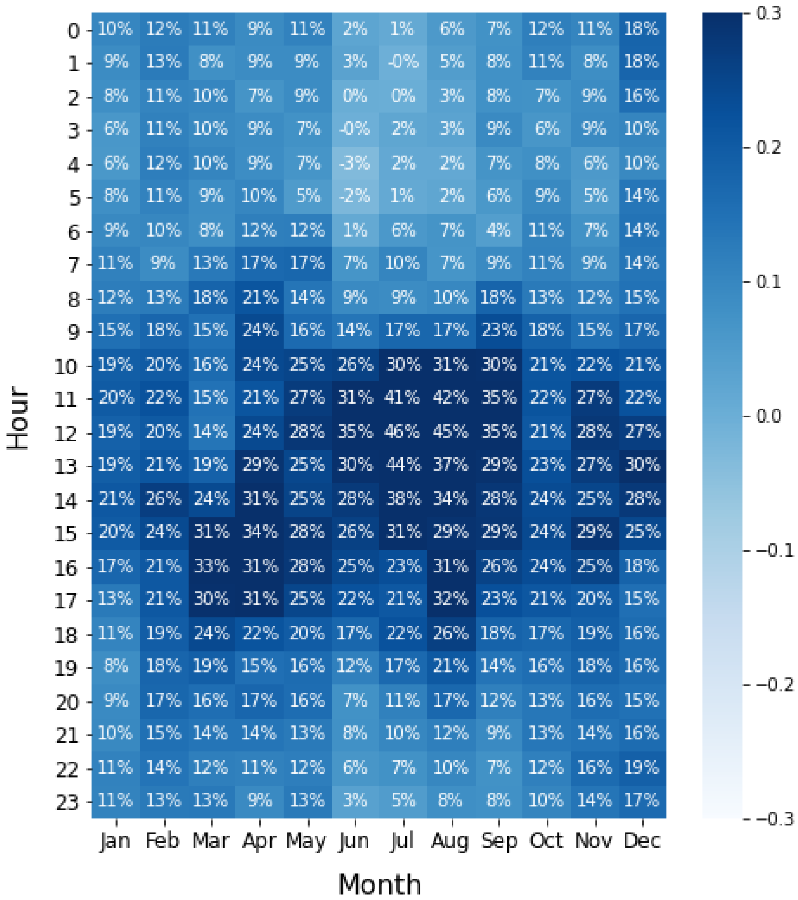


Figure 6 (Right). Comparison of DLR and AAR. Average percentage increase in rating as determined by DLR compared to AAR.

DLR provides a noticeable pattern of increasing ratings above AAR in midday hours. This is because DLR takes into account the cooling effects of wind flowing across a conductor while AAR does not. These winds are strongest during the midday hours which typically coincide with peak demand, providing additional line capacity when it is most needed.

The few instances of negative percentages in Figure 6 indicate that DLR is on average less than AAR for the given hour and month, indicating AAR would have incorrectly indicated additional capacity was available.



6. Conclusion

SLR relies on fixed assumptions of both wind speed and ambient temperature. AAR frequently indicates additional capacity is available during periods of cooler ambient temperatures in the winter months and overnight hours but often overstates available capacity due to a fixed assumption of wind speed. DLR provides extra capacity during cooler weather in addition to midday peak demand hours when wind speeds are strong. DLR, as a field sensor-based technology, mitigates the risk of exceeding the conductor maximum operating temperature by utilizing real time measurements of all input parameters.

Since wind speeds greatly affect a conductor's true ampacity, DLR based ratings that take into account the varying wind speeds show that additional capacity is available when wind speeds are strongest. This same wind that is cooling the conductors might also be powering wind turbines and thus line ratings are at their highest when wind generation is also occurring. This correlation has the potential to reduce wind-driven congestion. DLR can therefore help renewable projects stalled in the interconnection queue or facing curtailment because the transmission system operated under SLR or AAR methodologies indicate that capacity is not available.

Average capacity determined by each rating methodology on the line in this study is summarized in Table 4.

Rating Methodology	Summer	Winter
Static Rating [MVA]	160	199
Average AAR [MVA]	184	204
Average DLR [MVA]	214	237

Table 4. SLR, AAR, and DLR averages by season.

DLR dips below AAR 22% of the time in the summer and 27% of the time in the winter, indicating the AAR's static wind speed assumption frequently overestimates actual wind speeds. This most often occurs at night when wind speeds are lower, yet cooler temperatures would indicate additional capacity is available, compounding the negative effect. During these periods when DLR is less than AAR, operating the line at the rating determined by AAR would put the line at risk by possibly exceeding the maximum operating temperature.

Summary of Key Findings	Summer	Winter
% of Time AAR is above SLR	100%	78%
% of Time DLR is above SLR	93%	77%
% of Time DLR is above AAR	78%	73%
Average % Capacity Increase, AAR over SLR	15.1%	2.7%
Average % Capacity Increase, DLR over SLR	33.8%	19.3%
Average % Capacity Increase, DLR over AAR	16.3%	16.2%

Table 5. SLR, AAR, and DLR comparisons by season.

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[2] "The WATT Coalition: Unlocking the Queue." 2021 https://watt-transmission.org/wp-content/uploads/2021/02/Brattle__Unlocking-the-Queue-with-Grid-Enhancing-Technologies__Final-Report_Public-Version.pdf90.pdf.