EPRI



2025 White Paper

Dynamic Line Ratings Status, Applications and Opportunities

A GET SET White Paper



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FOREWORD

What is GET SET?

Energy companies are seeking options for increasing transmission capacity to support energy transition objectives and large demand increases from artificial intelligence (AI) and manufacturing growth [1]. EPRI's GET SET (Grid-Enhancing Technologies for a Smart Energy Transition) initiative aims to support the deployment of a subset of technologies to respond to the rapid load growth, changing generation mix, and extreme weather that energy companies are facing today. These solutions can potentially maximize the capacity of existing assets quickly while working to build new capacity in the long term. For example, one driver for increased grid congestion is the differing speed of construction for data centers as compared to transmission lines. The intermediate increased electrical loading can push transmission lines to or beyond their safe operating limits. While deploying grid-enhancing technologies (GET) is seen as a potential method to increase capacity from transmission lines and satisfy load growth, deployments must also ensure system stability, asset health, and public safety are maintained.

The GET SET initiative is committed to assimilating and disseminating existing GET knowledge to support utilities in assessing and deploying GET now, as well as leveraging those deployments and additional research to answer remaining questions and provide the tools that utilities need to evaluate and deploy more broadly.

GET SET White Paper Series

The GET SET white paper series is a collection of papers that describe four promising GET: Dynamic Line Ratings (DLR), Advanced Conductors, Advanced Power Flow Controllers (APFC), and Transmission Topology Optimization (TTO). This white paper series aims to document the current state of the science regarding GETs and their potential applications and identify opportunities for greater research and collaboration.

INTRODUCTION

The general benefits and limitations of dynamic line ratings (DLR) are presented in Table 1.

Table 1. *General benefits and limitations of DLR*

BENEFITS	LIMITIATIONS
Increases transmission capacity on existing circuits without physical changes (non-wires solution).	Can be costly to safely upgrade lines, particularly on lines with no clearance buffer, aged conductors, surge impedance loading (SIL) limits, stability limits, or limiting substation ratings.
Can increase capacity if weather is more favorable than static/seasonal assumptions.	May reduce ratings as often as 30–40% of the time.
There are many technology providers available.	Accuracy, reliability, and cost vary across technologies, complicating finding best-fit solutions.
Adoption of ambient adjusted rating (AAR) later simplifies adoption of DLR.	Adopting AAR reduces the return on investment of adopting DLR relative to using static ratings.
DLR technologies can provide insight into other system conditions.	There are presently no industry standards for specifying or validating DLR systems.
Capacity gains can loosely align with peak demand and peak renewable generation in some systems.	Capacity gains are not completely correlated to when transmission is limited.

DLR are a method for determining how much power can flow through overhead lines for a given allowable operating temperature. What differentiates DLR from other methods is the use of real-time data to account for local weather conditions that change every few minutes, such as wind speed and direction. [1] Because DLR can be relatively affordable and quickly deployed, interest in them has grown significantly in the last decade. While DLR have been around for many years, the performance of DLR technology has recently increased with the higher deployment rate of cell towers needed to carry data from the field to the processing server, allowing for an acceleration in adoption. This paper is aimed at industry professionals who are seeking to better understand the fundamentals of DLR, recent industry experiences, and the associated headwinds and tailwinds for adoption.

The aim of DLR is to develop more precise estimates of wind to be applied in ratings calculations. The capacity of a circuit is determined by the lowest thermal or stability limit across all assets in the circuit. Traditionally, static ratings are used which assume near worst-case conditions to reduce the risk of a circuit exceeding asset design limits. When conditions are favorable, such as a windy cool day, the DLR may unlock additional capacity. If the DLR is below the traditional ratings, a utility may improve its safety and reliability margins by reducing power flow, which helps ensure assets stay within their design limits.

Capacity Changes with DLR

Previous studies have demonstrated DLR can increase line utilization [2, 3]; however, there are situations where other upgrades are optimal. There are many metrics that determine what upgrade is optimal such as time to implement, costs (upfront, maintenance, life cycle, etc.), reliability, and cybersecurity requirements; a key decision factor is the amount of capacity DLR can unlock and what percentage of time capacity gains are available. DLR are a valuable tool in our toolbox, but not a “silver bullet” solution to all challenges.

Based on the analysis of a small number of spans, DLR could indicate a high theoretical benefit. However, there are several factors that can result in capacity gains below the theoretical limit such as the existence of wind-sheltered spans, ratings of terminal equipment, system stability, energy demand, etc. A 2024 survey of utilities with DLR experience indicated that annual average capacity gains are expected to be below 15% in many situations. In a case study presented at the 2024 GET SET workshop in Atlanta, average capacity gains ranged from 2–8% depending on evaluation criteria.

EPRI studies have found that when utilities have existing ratings that are less conservative, DLR could reduce capacity below a utility’s legacy ratings a significant amount of the time (30–45%) [4, 7]. In 2021, FERC Order 881 required the adoption of ambient adjusted ratings in the United States.

Many existing studies show capacity benefits of DLR relative to legacy rating methods that will no longer be utilized. To generalize, DLR capacity gains should be lower for a utility applying ambient adjusted ratings (AAR) than if it were using static ratings. Additional studies are needed to better understand what the real-world benefits will be as compared to theoretical gains.

DLR Compared to Other Ratings Methods

Because DLR benefits are relative to the legacy ratings methods, it is prudent to discuss the different rating practices used in the field today:

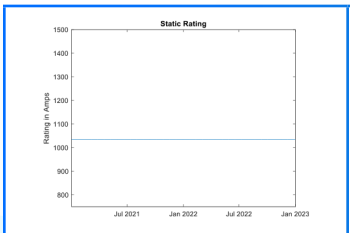
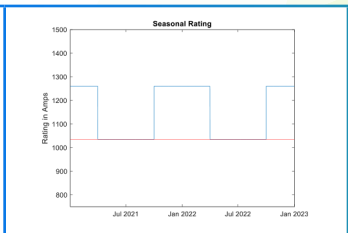
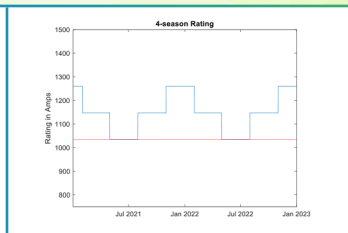
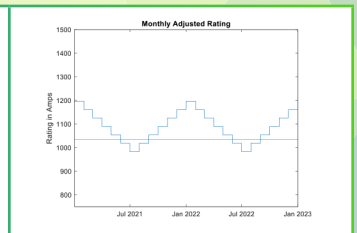
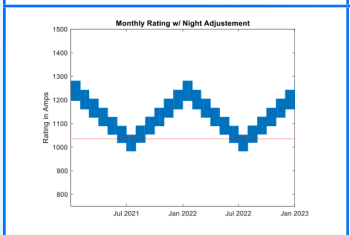
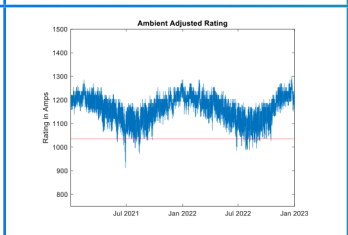
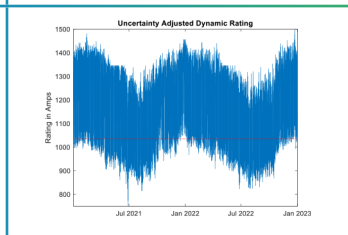
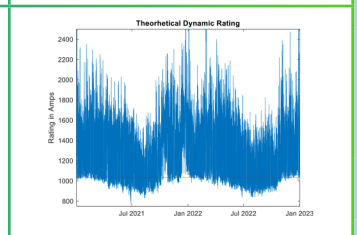
- **Static line ratings (SLR)** are a fixed single value that do not change with time. SLR are typically determined by estimating peak summer weather conditions and a moderate wind speed.
- **Variable line ratings (VLR)** adjust ratings for specific time intervals based on likely weather conditions within a specified time frame. VLR can include seasonal ratings, day/night ratings, or monthly adjustments. VLR still leverage fixed assumptions and do not change year over year.
- **Study-based ratings (SBR)** are similar to VLR, but the ratings are derived from a statistical analysis of recent local weather instead of following an industry guide.
- **Ambient adjusted ratings (AAR)** use either hourly or daily air temperatures to determine capacity. Solar heating values may be fixed, use day/night values, or be updated hourly.
  - FERC 881 specifies U.S. utilities to have hourly AAR with either day/night or hourly solar adjustments. The hours of daylight change monthly based on local conditions.
- **Dynamic line ratings (DLR)** are updated most frequently, every 5–30 minutes. DLR consider wind speed and direction changes along an entire circuit as well as temperature and solar heating. Rather than measure weather directly, some DLR vendors measure other properties and infer the weather parameters needed for a rating calculation instead.

A generic depiction of the rating methods over time is shown in Table 2.

DLR COMPARED TO CONVENTIONAL SOLUTIONS

Conventional upgrades such as reconductoring, retensioning, structure modifications, voltage upgrades, and direct current (DC) conversions could all increase average capacity (see Figure 1). These methods may be the best fit in scenarios where firm gains are needed or high ampacity gains are required. As discussed earlier, current research indicates DLR is well suited for situations where average transmission capacity needs are below 15%, where it is tolerable for capacity to decrease for periods of time, and/or where a constant known gain is not required. Alternatively, DLR may be used in combination with traditional upgrades to allow the combined smaller upgrades to unlock as much capacity as a larger effort. [12] Further studies may significantly improve our understanding of how to best pair or sequence upgrades.

Table 2. Generic examples of rating types (red line indicates relationship to static rating)

 Static	 2-season	 4-season	 Monthly
 Monthly and day-night	 AAR	 Risk-adjusted DLR	 DLR

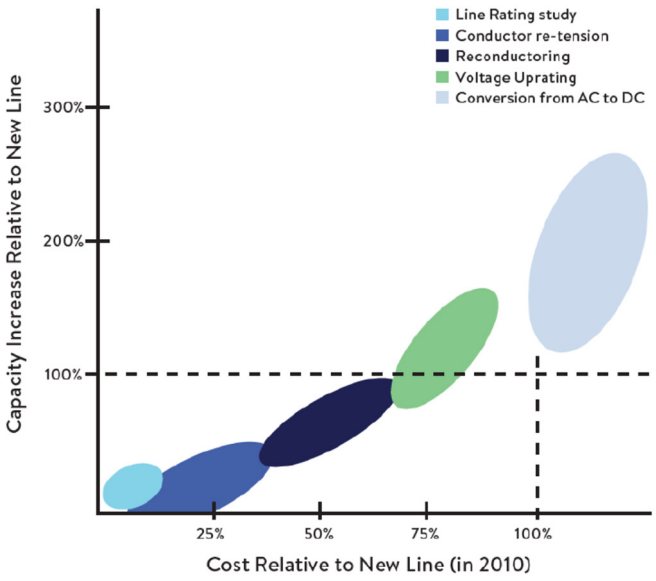


Figure 1. *Comparison of year-one costs for traditional upgrades*

One method to assess whether to deploy DLR or a conventional solution is a comparison of cost per mile for different solutions; it is also important to compare cost per megawatt (MW) and life-cycle costs. For example, retensioning a conductor is a one-time cost. Deploying DLR carries ongoing capital expenditures (CAP EX) and operations and maintenance (O&M) costs; increasing line current also increases losses. These factors naturally affect decision making and could be missed if only upfront costs are considered. In one study, DLR technology was found to be more cost-effective than a reconductoring effort [13]. While the initial cost for DLR was below the reconductoring, over a 40-year design life for new conductors, DLR could have been significantly more expensive than reconductoring considering lifetime costs [5, 13]. The cost difference varies based on site-specific conditions and depends on the DLR technology deployed. If energy management system (EMS) upgrades were required or load growth continued beyond what DLR provided, the scales would tip further in favor of conventional upgrades. In this specific hypothetical, DLR would be the lower-cost solution in the first few years, but perhaps not over the life cycle of the line. This may indicate that DLR offer a stronger use case when used as a "bridge technology" to reduce congestion during the design and buildout of traditional upgrades. In such a case, a utility should plan to recover its investment before the DLR technology needs significant maintenance or replacements to gain the most benefit.

The advantage of traditional upgrades is the existence of industry standards, best practices, specification documents, tests to validate performance, market integration methods, planning processes, and broad experience with the effects on system performance. Traditional upgrades also avoid concerns with communications issues and potential cybersecurity threat surfaces. The downside is that some traditional upgrades can take longer to implement and may require lengthy outages. When comparing DLR with traditional solutions to increase capacity, one critical aspect to consider is that DLR do not provide firm capacity. Therefore, planners must carefully consider the probability and inherent risks when the increased capacity is not available in real time. Developing an appropriate planning framework that considers these risks and mitigations for them is a key element of the GET SET initiative.

OVERVIEW OF AVAILABLE DLR APPROACHES

The equations within ratings standards are based on having accurate measurements of ambient temperature, solar irradiation, wind speed, wind direction, and physical conductor characteristics. These data can be directly input into ratings equations. The ratings equations follow the same general form whether they are used for static ratings, AAR, or DLR.

While there are several industry standards for calculating ratings (discussed later in this paper), they all follow the same general form:

$$Rating\ (Operating\ Temperature) = \sqrt{\frac{Wind\ Cooling + Emissive\ Cooling - Solar\ Heating}{Resistive\ Heating\ (Operating\ Temperature)}}$$

Some methods to obtain DLR measure other parameters, requiring the use of extra equations and models to establish the appropriate inputs for the rating equations. These intermediary calculations can provide added insights but also are an avenue for errors and uncertainty to be introduced or amplified. The key point is that when weather parameters are not measured or modeled, additional conversions must take place. Each method is nuanced, but DLR technologies can be placed in four general categories (see Table 3).

Table 3. *High-level overview of approaches to DLR (vendor agnostic)*

	CONDUCTOR MEASUREMENT	WEATHER MEASUREMENT	WEATHER MODELING	ENHANCED MODELING
	HARDWARE		SOFTWARE	
Definition	Hardware-based DLR that monitors physical properties of transmission assets (temperature, sag, etc.).	Hardware-based DLR that monitors weather conditions (i.e., weather stations).	Software-based DLR leveraging existing weather stations and models.	Software-based DLR that takes publicly available data and augments it using fluid dynamics or AI.
Potential Benefits	Can be most accurate DLR method when done correctly.	Weather data can be used for other needs. No calibration period. Robust supply chain. Many existing standards and guides.	Lower cost alternative that leverages existing public resources. No calibration period.	Is intended to be more accurate than public weather data.
Accuracy Drivers	Number of sites monitored. Quality of hardware and design. Fundamental approach and equations.	Distance of weather station from lines. Quality of hardware. Installation practices.	Number and quality of nearby weather stations. Weather model applied. Presence of wind sheltering objects.	Number and quality of nearby weather stations. Weather model applied. Presence of wind sheltering objects.
Challenges	Typically highest cost (CAP EX and O&M). Mixed experiences from the field. Continuous changes blur maturity level. Communication issues in many areas.	Added cost of hardware and hardware maintenance (unless coordinated with public weather network).	Expected to be lower accuracy, particularly in areas with dense vegetation.	Requires significantly more data, processing power, and resources to set up and correctly maintain models.

Note: This is a generalized example; there is no standardization of terms, definitions, etc. across the DLR space

Hardware-based methods can identify transmission capacity in near-real-time. *Software-based methods* are needed to forecast hours to weeks ahead, albeit with declining accuracy as the forecast extends into the future [8]. It is important to note that often DLR technologies blur these distinctions. For example, SentriSense has a DLR technology based on conductor measurement, but it can also be paired with a weather measurement to increase accuracy and redundancy. WindSim has an enhanced modeling approach, but if the local weather networks do not provide sufficient data, utilities may need to add weather measurements in a small number of locations to improve their models' accuracy and reliability.

DLR Landscape in 2024

In theory, DLR enable the use of less conservative assumptions while maintaining safe, reliable operation. Each technology and method will have some degree of uncertainty (potential error) in the rating based on the quality of the data, the methods and equations applied, and other factors.

There are many different DLR technology providers and methods available (see Figure 2). Understanding the strengths and limitations of all technologies can help ratings engineers select the best option for their systems based on a method's alignment with their existing practices, the expected performance, and their risk tolerance.

Ampacimon	Awesense	Bandweaver	DeAngeli OPGW	DeAngeli Smart
DOL	EGM – MSU	EMO (Micca)	Enline	Fibersense
FORM	GE Digi-DLR	GridGuard DLR	Grid Pulse	Grid Raven
Infravision	LakiPower	Lindsey	Line Ranger	Linescope
LineVision	Luna – LIOS	Multilin TNET	Neara	NEC SpectralWave
Neuron	PitchAero-DLR	Power Donut	Praetorian	Prisma Photonics
Prysmian OPGWatch	RED DLR	SentriSense	Sintella	Smartwires SUMO
Splight AI	Sumitomo DLR	Synapt	TopoloNet	Vaisala DLR
WindSim	Commercial Weather Models (>10)	Public Weather Models (>13)	Public Weather Nets (>80)	Utility Weather Stations
OPPC method	PMU method	SWING method	Cat-1	Gridwell
Levelwatch (Siemens)	Lineasens	Line IQ (Gridsense)	Ritherm	Sagometer
	Sentinel	TAM	ThermalRate	

Figure 2. *DLR technologies (blue), alternative methods (purple), and legacy systems (grey)*

DLR Coordination with GETs and Emerging Technologies

In addition to DLR, there are other technologies that can help unlock and better utilize transmission capacity. These may be referred to as advanced transmission solutions, emerging technologies, grid enhancing technologies, etc. Regardless of definition, there is a common understanding that there are many options that can be used in place of or in parallel with DLR in addition to traditional upgrade methods. Figure 3 shows technologies that could have strong synergies with DLR for specific line designs, network configurations, and/or load profiles.

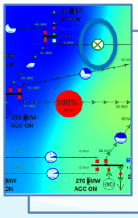
As an example, advanced conductors and virtual power plants (VPP) can be operated closer to their limits when combined with DLR, allowing a higher degree of utilization for an incremental cost. Technologies like advanced power flow controllers (APFC) and transmission topology optimization (TTO) can offer increased benefit alone or when paired with DLR. Pairing these tools with DLR allows power to be routed more effectively to lines with spare capacity available and away from those with constraints. This pairing also prevents APFC or TTO from sending power down a line that cannot handle additional loading due to unfavorable weather (such as during a period of low wind).



Advanced conductors: conductors designed to operate at higher temperatures than traditional conductors (i.e., above 100°C continuously) can allow higher capacity to be sent down rights-of-way on new or existing infrastructure.



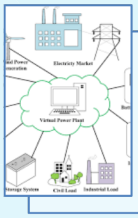
Advanced power-flow control: technologies like PFC and phase-shifting transformers can adjust line impedance to manage flows and improve stability during higher loads.



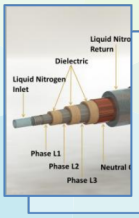
Transmission topology optimization: leverages software to control switchgear/breakers to route power around congested areas more efficiently.



Advanced storage: refers to a wide array of techniques and systems designed to store energy in various forms, including electrical, chemical, mechanical, and thermal storage solutions.



Virtual plant: Virtual power plants (VPP) are systems of distributed energy resources that work together to balance energy supply and demand on a large scale. These resources can include rooftop solar panels, electric vehicle chargers, smart water heaters, etc.



Superconductors: These lines use liquid nitrogen to cool superconducting materials, which can transmit up to 500% more electricity in a given right-of-way.

Figure 3. *Emerging technologies that can augment DLR deployments*

If DLR are high but there is no demand, a utility cannot fully leverage the value of the extra capacity. When advanced storage is in place, operators can utilize periods of high DLR to top off storage. Strategic release of storage can also smooth out the variability of DLR and help maintain power flow in key areas during periods of low DLR. When considered in conjunction, it is possible there will be more scenarios where storage is an acceptable solution/pairing.

While there are some circumstances where it is best to apply only one technology, in general, combining upgrades or other technologies with DLR can offer more flexibility, safer operation, and higher system utilization. For some technology pairings, the return on investment (ROI) from parallel deployments may be reduced [2, 13]. There is comparatively little research or guidance available to help the industry downselect grouped or sequential upgrades; this is an area for future work.

Examples of Rating Standards and Regulations

In the United States, FERC Order 881 mandates system operators to enable data exchange between relevant organizations for hourly updates with rating forecasts for the coming 10 days. Utilities are deploying changes to their EMS to simplify the management of rating data and automate the data exchange process with transmission owners. As identified in FERC Order 881, NOPR 22-5, and other federal and local proposals, requirements for AAR are intended to pave the way for easier DLR adoption [10, 11, 13]. To generalize, in the European Union and Australasia, DLR pilot/adoption rates are higher than in the United States.

Utilities may apply international or regional standards and guides to calculate their ratings. The most common overhead line rating calculation methods—published by IEEE and CIGRE—are broadly equivalent but will differ slightly (see Table 4) [2, 9]. The most common standards applied by DLR systems include:

- IEEE 738, "IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors"
- CIGRE TB207, "Thermal behaviour of overhead conductors"
- CIGRE TB601, "Guide for thermal rating calculations of overhead lines"

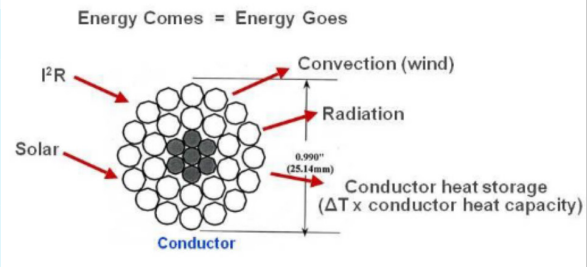
All existing bare overhead conductor thermal ratings standards leverage a heat balance equation. This couples the conductor temperature (which is limited by design factors) to the rated ampacity for a given set of weather conditions. The general relationship is shown in Figure 4.

While there are standards for the calculation of ratings and conductor temperatures, the industry presently lacks standards for the specification, selection, maintenance, or integration of DLR technologies. EPRI is presently working with member utilities (in coordinationwith DLR technology providers) to develop such specifications and best practices guidance [11]. New participants are welcome to engage, share learnings, and obtain access to these methods and guides.

Table 4. *Example comparison of ratings for a 425 mm² aluminum conductor steel-reinforced (ACSR) conductor*

Daytime ☼	Line Rating (MVA)		
Ambient Temperature (°C)	IEEE 738	Cigre TB207	Difference
0	229	213	**-7.0%**
5	223	206	**-7.6%**
10	216	199	**-7.9%**
15	208	191	**-8.2%**
20	201	182	**-9.5%**
25	193	176	**-8.8%**
30	184	163	**-11.4%**

Nighttime ☾	Line Rating (MVA)		
Ambient Temperature (°C)	IEEE 738	Cigre TB207	Difference
0	230	233	**1.3%**
5	223	226	**1.3%**
10	216	219	**1.4%**
15	209	212	**1.4%**
20	201	204	**1.5%**
25	194	196	**1.0%**
30	185	188	**1.6%**



Condition	Rating (Amps)
Air Temperature ↑	↓
Wind Speed ↑	↑↑
Sun Intensity ↑	↓
Conductor Emissivity ↑ (cooling in absence of wind)	↑
Conductor Absorptivity ↑ (rate of heating by the sun)	↓

Figure 4. *Depiction of the heat balance equation used in line ratings*

EXAMPLES OF DLR TECHNOLOGY DEPLOYMENTS

As part of ongoing research, EPRI engages with utilities to understand their industry needs, best practices, and lessons learned from overcoming challenges. While DLR adoption is increasing in the United States, several international utilities have also gained experience with DLR, including:

- **National Grid UK:** Provides updated line ratings based on weather measurements and forecasts upon request to the system operator through a manual process.
- **Elia Group:** Calculates day-ahead and intraday transmission capacity with conductor measurement sensors on 30 lines.
- **ELES:** Calculates ratings based on a weather model complemented with data from on-site weather measurement devices along the lines on over 30 lines.
- **Red Eléctrica:** Uses a combination of weather stations and conductor monitoring to establish DLR; plans through 2026 will increase DLR deployment to about 2% of the system.
- **Austria Power Grid:** Deployed weather stations for DLR at 16 locations across two circuits.
- **Transpower:** Applies a fixed rating that is based on time of day instead of static or seasonal methods; while not a true DLR, it provides similar benefits on 15 lines.
- **PPL:** Deployed conductor measurement-based DLR within two transmission corridors; these ratings are integrated into day-ahead markets.

Key Differences of a DLR Implementation from Pilots/Demos

DLR implementation requires strategic integration of technologies into established processes, operations, and market systems. System operator approaches to this work are specific to each organization, local regulations, and their corresponding market structure. A general flow of information is shown in Figure 5. To fully deploy DLR, a utility should consider:

- **System integration** – The industry does not provide standards for integrating DLR into established processes and software systems. In one EPRI survey, every participating utility reported the use of a customized method [8]. The methods vary widely, from fully manual processes for using DLR on an as-required basis, to fully automated DLR solutions integrated into the control room and EMS systems. In cases where transmission operator (TO) and system operator (SO) functions are unbundled, TOs and SOs can exchange ratings in different ways. For example, if an SO requests line ratings in response to grid conditions, the TO might submit ratings to the SO or simply provide look-up tables.
- **Operational implementation** – Experience with operational implementation varies. Utilities have reported implementations ranging from DLR applied on specific lines in response to outage-caused congestion to full integration of DLR into real-time, day-ahead, and intraday operations.

  Typically, the asset owner is responsible for calculating the DLRs and providing updated ratings to the SO, but data exchange methods vary between organizations. In regions where AAR have been applied, usually, the TO and SO use an agreed-upon process for updating look-up tables or choosing ratings based on weather measurements or forecasts. As FERC Order 881 takes force, the data exchange process is expected to become fully automated.

  Some organizations may opt to use “black box” line rating calculation models that feed the ratings directly into the EMS and/or supervisory control and data acquisition (SCADA) system. Fully integrating DLR into operations requires integrating raw measurement data into the EMS and/or SCADA system for internal rating calculations.
- **Market integration** – European utilities have reported varied experience integrating DLR into market systems. They also use different methods when integrating forecast ratings for use in intraday and day-ahead market calculations. The most common practice is to input updated line ratings into power flow simulation files because this approach requires few, if any, changes in the market system. Some SOs enable the EMS to automatically consider ratings used for market calculations. Others create rating files separately from the EMS and program the EMS to automatically update line ratings based on external inputs. Some use manual processes for updating rating files.

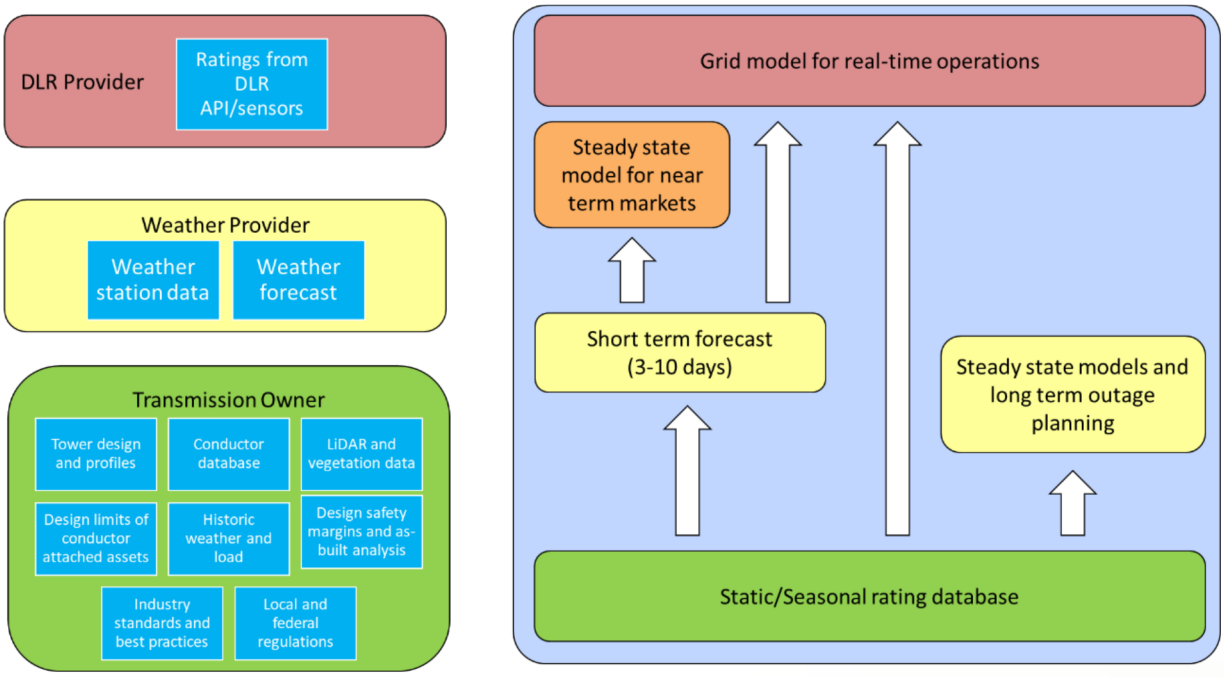


Figure 5. *DLR data flow for operations and planning*

Industry Experiences Shared from DLR Stakeholders

As part of efforts to document the experiences of utilities that have piloted or deployed DLR, EPRI developed a survey and specifically targeted responses from DLR stakeholders. This included existing EPRI members and non-members both within the United States and around the globe. Some of the key takeaways from the 34 respondents collected in 2024 include:

- There were many drivers for DLR adoption, including reducing renewable curtailment, post-contingency flow mitigation, increasing connection capacity, and others. The prevailing driver was reducing congestion costs.
- The majority of experience to date has come from limited pilots and limited deployments.
- Deployments were most common on lines in the 230–345 kV voltage class, closely followed by the 115–161 kV class.
  - There were a small number of sub-transmission deployments.
  - No ongoing deployments were noted at 400 kV or above.
- The overwhelming majority of respondents do not include DLR in planning or cost modeling.
  - A small number of utilities have developed methods for performing short-term planning.
- The majority of respondents saw an average capacity increase of 15% or less, with many seeing no average ampacity increase (as compared to their legacy ratings).
  - The largest increases are expected when legacy ratings were static and/or poorly optimized initially.
- Independent evaluations of the DLR technologies' performance were performed in less than 18% of pilots or deployments.
  - In several deployments the DLR technology provider performed the evaluation.
  - In the majority of cases no performance evaluation was reported.
- 26 of 34 respondents reported issues or concerns based on their experiences that could deter or slow their rate of DLR adoption, and, at a minimum, will require additional research to allow them to deploy DLR with confidence.

DLR IMPLEMENTATION BARRIERS AND SOLUTIONS

Improving the accuracy and reliability of DLR is critical to successful deployment and realization of peak benefits. As noted by the U.S. Department of Energy (DOE), inaccuracies can arise through both measurement and modeling errors [14]. Previous experiences with DLR in demonstrations that had accuracy and reliability challenges may reduce industry

confidence in the capability of DLR. Developing methodologies and solutions to address these concerns will be critical to accelerating broader DLR adoption.

Utilities participating in EPRI studies have described the main barriers their organizations encountered when implementing DLR for trials and deployments [4, 9, 15, 16, 21]. The barriers identified by utilities aligned with barriers identified in DLR publications by the DOE [14]. The reported barriers and suggested solutions include (but are not limited to) those shown in Table 5. These headwinds demonstrate the value of collaboration and research to ensure deployments are done safely and provide the desired benefits. EPRI is working with technology providers and DLR stakeholders to prioritize the issues and facilitate developing solutions with an independent and technology-agnostic technical basis.

There are several questions regarding multiple aspects of DLR technologies that we as an industry need to research. Needing more research does not mean we cannot deploy DLR for specific applications at present, particularly for strategic deployments where DLR implementation is staged, allowing utilities to adapt their practices as they gain experience.

Table 5. *DLR implementation barriers and potential solutions*

DLR IMPLEMENTATION BARRIERS AND SOLUTIONS	
BARRIERS	**STEPS TO RESOLVE**
Data accuracy/risk management	• Establish specification requirements and processes to validate accuracy including the required derisking algorithms (similar to those used in international deployments). • Performing non-biased laboratory and field testing of DLR can address knowledge gaps on accuracy, risk management, and life-cycle costing.
Communications and cybersecurity	• Continuing improvements in cellular and satellite networks will increase communication reliability. • The industry can collaborate to apply cybersecurity tests and black box testing to existing DLR technologies to ensure safe operation.
Costs of DLR technologies	• Data can be gathered on recent DLR, GET, and traditional upgrades to document the relative costs and capacity gains to guide selection of right-sized solutions.
Data availability	• Vendors can develop new tools that improve DLR integration in EMS solutions. • The industry can develop best practices on failover solutions, spares strategies, and increasing number of monitors deployed to provide redundancy.
Operational challenges with ratings-based technologies	• Workflows and training to manage variability and uncertainty in short- and long-term planning are needed. • Variable ratings cause conflicts with other operations requirements like relay coordination. • EMS systems require updates to enable full use of DLR. • How to handle DLR for different operation and planning studies such as economic analysis, outage planning, and reliability studies will differ; work is needed to define processes. • Tools are needed to adjust for uncertainty in DLR sitting between DLR and EMS systems.
Variability of DLR with distance and with time	• DLR can be derated to correct for errors from variation over distance; this is applied in existing implementations; data is needed to establish best practices. • Capping the rate of increase and considering worst-case forecasted conditions can reduce volatility of DLR over time; studies are needed to establish best practices. • Improve methods to locate critical spans (when vendors apply varying methods, it affects accuracy, cost, and risk).
Capacity decreased with DLR	• Capacity decreased from DLR indicates periods where DLR are reducing utility risk exposure; improved methods to compare risk tolerance with economic and reliability models can be developed to guide sequential upgrades that address the capacity gap.
Unknown maintenance requirements and life-cycle cost	• Develop specification document(s). • Apply accelerated aging tests. • Perform training on error detection and maintenance practices.

Table 5 (continued). *DLR implementation barriers and potential solutions*

DLR IMPLEMENTATION BARRIERS AND SOLUTIONS	
BARRIERS	**STEPS TO RESOLVE**
Site selection and quantity incorrectly defined	• New algorithms and tools can be developed to more accurately define the number and location for monitoring, including identification of at-risk spans. • New tools can be developed to flag potential circuits that would most benefit from DLR.
Moving the bottleneck	• Meshed grids may require different solutions or combinations of DLR with APFC and topology control. Control and operation approaches that maximize synergies between DLR and APFC can be developed. Studies can establish guidelines, design, and implementation. • Substation limits may cap DLR or become part of staged upgrades.
Insufficient maturity level	• Work is underway to develop a new maturity model to replace TRL score. • Require documentation on changes and recalibrations by technology providers.

Risk Management with DLR

All DLR measurements have imperfections, which will generate a risk for utilities adopting DLR. Internationally some DLR deployments include derating factors to manage risks, but it is not a universal practice. There is slightly varying guidance on an acceptable level of risk. CIGRE guides suggest that DLR (validated against a baseline) be allowed to go over the true capabilities of the line 1–5% of the time based on several factors. In the United States, a recent Advanced Notice of Proposed Rulemaking on DLR suggests DLR be allowed to exceed the true capacity of the system 2% of the time. Based on the available studies, many existing DLR technologies do not have risk corrections applied that meet these thresholds. To manage risks, the DLR data received from a technology could be derated/reduced. As an example (see Figure 6), the DLR can be simply multiplied by some value between zero and one to reduce the amount of time the provided DLR (red solid line in Figure 6) is above the true DLR (green line). This results in a lower rating from the DLR technology (red dashed line), but it is likely to be above legacy static ratings a high percentage of the time. Alternatively, caps may be placed on the DLR to limit the worst-case error. For example, if a DLR were capped at 30% above the old ratings, a large potential for unlocked capacity exists, but in a worst-case scenario the ratings error cannot be more than 30% (assuming the old ratings were correct). This is a greatly simplified alignment of DLR with line design and protection and control requirements.

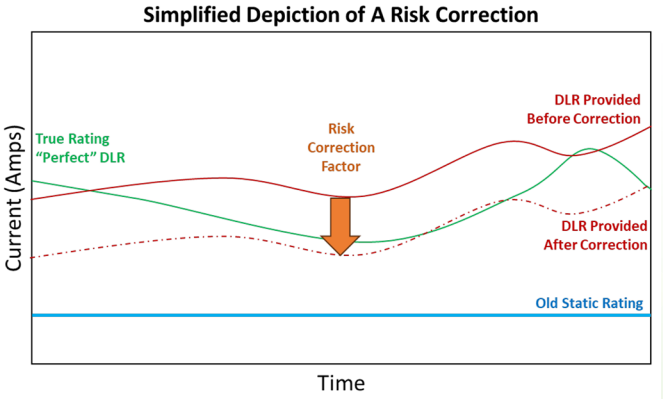


Figure 6. *Example of applying risk correction to DLR data*

In EPRI's DLR research, a risk-based approach is applied. A small error in the DLR of only a few amps does not pose a risk to asset health, system reliability, or public safety. These smaller errors would be considered negligible provided they do not happen continuously. The higher an error is, the higher the risks and consequences associated with it are. Using a risk-based approach, the amount of correction is focused on getting the system to function just inside its peak capabilities. In studies, we are able to achieve this by having multiple precise measurements of weather conditions and conductor conditions to establish the baseline data needed to develop the risk model. The tolerable risk level is derived using information about the line designs, system configuration, as-built condition, asset health, and other factors. If the risk drivers can be clearly identified, the derisking could be aligned with them so that small risks get small corrections and large risks get larger corrections (see Figure 7).

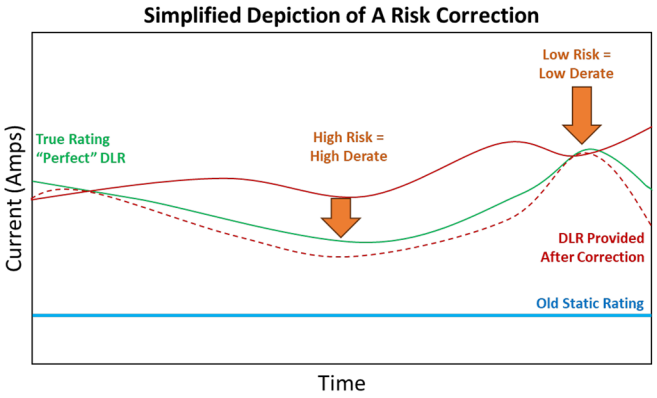


Figure 7. *Example of applying risk correction to DLR data if the risk drivers can be well-defined*

The Role of EPRI in Developing Solutions

EPRI is performing work across multiple topic areas to allow utilities to make decisions that are data-driven, have a transparent technical basis, are developed independently of stakeholder bias, and combine the valuable insights of utilities leading the transition to DLR.

As part of these efforts, EPRI is collaborating with utilities and technology providers to document the present capabilities and desired performance of DLR systems. This information is leveraged to develop technology specifications and identify methods to validate performance before DLR systems are tied to real-time operations or critical infrastructure. This will include all aspects of DLR performance including installation, maintenance, communications, accuracy, costing, etc.

To address areas where nonstandard tests are useful:

1. EPRI has expanded infrastructure in its outdoor lab in Lenox, MA.
2. EPRI has expanded test capabilities of the indoor lab in Charlotte, NC.
3. A significant number of field demonstrations are underway to gain experience with DLR in real-world conditions using a consistent evaluation method.
4. EPRI is evaluating methods for DLR specification and performance testing.

This establishes areas where utilities can learn rapidly without risks to their systems. The results of both lab and field tests are used to improve models that can be used to inform models and desktop studies (see Figure 8).

Field Evaluations Laboratory Testing Simulations and Modeling

Expanding on existing work [18, 19], EPRI is collaborating with utilities to improve methods and algorithms needed to identify where DLR technologies should be deployed and how many measurements are needed. While technology providers offer this service, the methods are often less transparent, difficult to scale, and can contain both false positives and false negatives [17].

EPRI is also collaborating on field evaluations with multiple U.S. utilities. This will provide insight into the performance of certain DLR technologies as well as provide learnings for improving workflows, line designs, aligning DLR with other stakeholder requirements, aligning DLR with emerging industry regulations, and facilitating knowledge sharing.

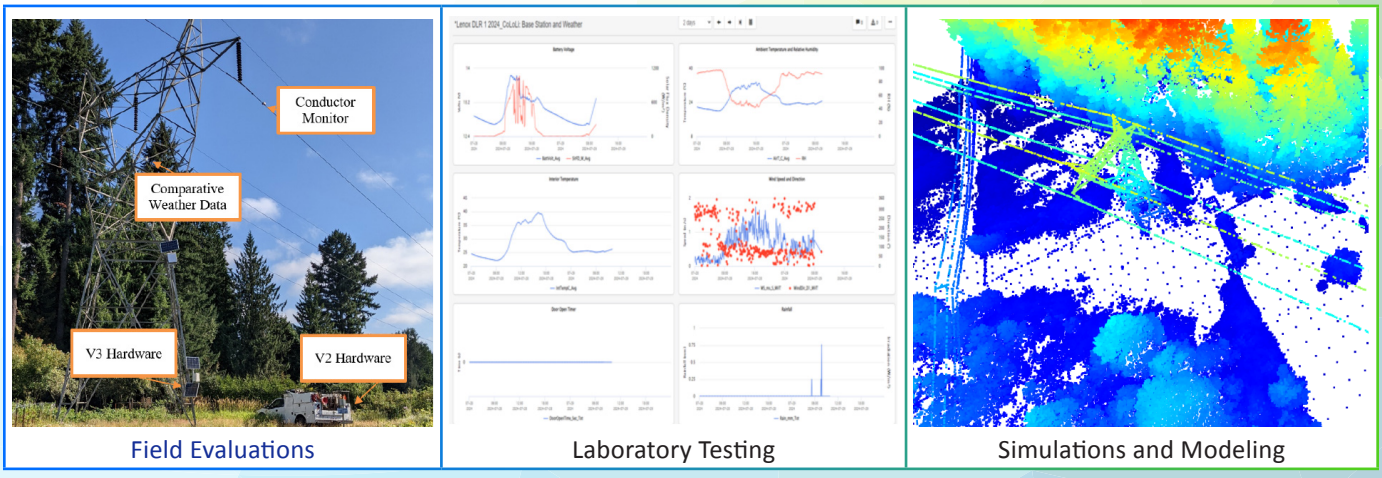


Figure 8. *Areas where EPRI is contributing to the acceleration of DLR adoption*

In parallel with these activities, EPRI continues to do research and help utilities apply other uprating methods such as building high-capacity advanced lines, the deployment of coated conductors [20], and performing traditional upgrades like reconductoring or voltage upgrades [3]. These efforts give meaningful scale to DLR as utilities can compare the cost, reliability, capacity gain, and time to implement multiple strategies including DLR when making decisions.

SUMMARY

The deployment of DLR is advancing quickly with growth in regulation, technology providers, and pilots. At the same time, common industry accepted methods to quantify the benefits in both planning and operations, compare against traditional or emerging technologies, and set ratings are under development.

One of the optimal use cases for DLR is as a bridge technology—a means to relieve congestion or remedial actions on heavily loaded lines while new lines are being built or to defer construction. There is also increased interest in DLR in areas where states or federal entities are planning to require the use of DLR. DLR have been more widely adopted in Europe than in the United States. One differentiator which may contribute to their successful implementation is the broader use of weather measurement-based ratings and robust derating factors to manage risks. The European utilities have reported using special protection systems (SPS) and topology optimization to maximize network utilization and prevent overloading lines during periods of low DLR. The ease of DLR integration depends on the transmission owner/system operator relationship, the data exchange mechanism employed, the EMS system's capabilities, cybersecurity regulations, and other organization-specific considerations.

Lessons Learned From Utility Implementations

Utilities participating in ratings studies have shared lessons learned from their implementations to help other organizations benefit from their experiences. They also shared recommendations other entities can follow when incorporating DLR into their operations and processes. However, there is no cookie-cutter approach to DLR implementation; the requirements, economics, risk tolerance, and best practices will be utility specific. Key findings include:

- In an ongoing industry survey (as of April 2024) only 17% of utilities that deployed or piloted DLR responded they have performed an independent evaluation of accuracy and performance.
  - While there are an increasing number of DLR projects, there is a vacuum of lessons learned because the deployments lack non-biased third-party evaluation.
- Average DLR capacity gains are likely to be in the range of 0–20%. When practices are implemented to manage risk and uncertainty, gains may be capped at around 30%.
  - As an example, if a utility is adding a small wind farm to an area, DLR could give it just enough capacity increase to avoid new line construction. However, if a utility is building a 500 MW solar plant, DLR alone is not able to prevent a traditional upgrade.
  - DLR benefits are subject to the rating limits of substation components, voltage drop, and system stability. [6]
  - Less complex ratings (seasonal, day/night, etc.) can often yield benefits more quickly with less effort than applying DLR; however, gains may be slightly lower during certain times.
- When performing cost-benefit analyses to determine which uprating method to deploy for each line, consider the lifetime cost and losses as opposed to only year-one cost.
  - Less accurate DLR methods require derating factors to manage risk; while this reduces gains these options may be lower cost and still provide suitable ROI.
- Identify skills needed for DLR and build internal knowledge prior to the deployment to ease the transition to integrated operational DLR.
  - Develop a hiring or training plan to build internal knowledge prior to implementation.
- Utilities that have had DLR success employ a gradual, phased approach for implementing line rating technologies and integrating the technologies with the EMS.
  - This allows time to compare technologies and prepare systems, processes, and procurement.

- Identify technology alternatives and potential vendors to start the procurement process. In some cases a mixture of DLR technologies/technology providers may be needed to achieve desired results and have protection from issues with sole sourcing the solution.
- Weather forecasts are needed to make DLR actionable; hours- to days-ahead ratings are needed for both operations, planning, and marketing.
  - Capacity gains and short-term forecasts will be highly variable. Utilities need to derive strategies to manage both economic risks and the risks to asset health, public safety, and reliability.
- Determine whether any mandates for improving line ratings pertain to your organization and if any regulations impose barriers to deployment.

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