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Dynamic Line Rating Systems for Transmission Lines

Topical Report

Smart Grid Demonstration Program

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Abstract

Through the U.S. Department of Energy's Smart Grid Demonstration Program (SGDP), the New York Power Authority (NYPA) and Oncor Electric Delivery Company (Oncor) demonstrated dynamic line rating (DLR) technologies to increase the efficient use of the existing transmission network, mitigate transmission congestion, and develop best practices for applying DLR systems. Both demonstration projects confirmed the presence of real-time capacity above the static rating, in most instances, with up to 25% additional usable capacity made available for system operations. NYPA worked with the Electric Power Research Institute (EPRI) using technologies and approaches that EPRI developed, while Oncor deployed Nexans' commercially available conductor tension-monitoring CAT-1 System. Key outcomes of the two SGDP projects include NYPA's assessment of the benefits and disadvantages of DLR technologies and Oncor's demonstration that dynamic ratings can be automatically applied in real-time system operations. The projects revealed opportunities to enhance future DLR deployments by ensuring the reliability of DLR data, preemptively addressing cybersecurity concerns, integrating dynamic ratings into system operations, and verifying the financial benefits of DLR systems.

Keywords: transmission, DLR, dynamic line rating, dynamic capability rating, real-time rating, thermal rating, rating, dynamic capability rating system, transmission line monitoring system, congestion, transmission constraint, EPRI, Nexans, NYPA, Oncor, Smart Grid Demonstration Program

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Executive Summary

This report examines two projects funded by the U.S. Department of Energy's (DOE's) Smart Grid Demonstration Program (SGDP) that demonstrated dynamic line rating (DLR) technologies for transmission lines. The New York Power Authority (NYPA) and Oncor Electric Delivery Company LLC (Oncor) were the recipients of these two projects. This report addresses the following objectives:

- Educate readers on the fundamental technical aspects and potential benefits of DLR technologies
- Summarize the purpose and scope of the NYPA and Oncor DLR demonstration projects, including the types of devices and software being demonstrated
- Summarize the technical performance of the field-deployed DLR technologies from the NYPA and Oncor demonstration projects
- Synthesize the results and lessons learned from the NYPA and Oncor demonstration projects to help guide future deployments
- Provide insights into other current and planned deployments of DLR technologies

Fundamentals and Potential Benefits of DLR Technologies

Transmission systems are constrained by the capacities of their transmission lines. All transmission owners and operators calculate static ratings for their transmission lines for normal, long-term emergency (LTE), and short-term emergency (STE) conditions. The static rating indicates the maximum amount of current that the line's conductors can carry (under a set of assumed weather conditions) without violating safety codes or damaging the conductor. Static ratings are adjusted infrequently, so they are usually conservatively based on "worst-case scenario" conditions (i.e., low wind speed, high ambient temperature, and high solar radiation). When static ratings are adjusted daily, hourly, or even more frequently to account for different ambient temperatures, they are called ambient-adjusted ratings.[1]

DLR technologies enable transmission owners to determine capacity and apply line ratings in real time. This enables system operators to take advantage of additional capacity when it is available. Unlike static ratings, dynamic ratings are calculated in real time based on the

[1] Although some transmission owners consider ambient-adjusted ratings to be "dynamic," ambient-adjusted ratings are not considered true dynamic ratings for the purposes of this report. This is because ambient air temperature measurements are the only time-sensitive data that ambient-adjusted ratings consider.

transmission line's actual operating conditions at specific moments, rather than on fixed assumptions. Dynamic ratings are often, but not always, greater than static ratings.

DLR systems are composed of DLR technologies and the communications and control systems needed to implement dynamic ratings in an operations environment. DLR technologies include two primary components: (1) sensors and supporting communications devices located on or near a transmission line and (2) software colocated with the transmission owner's energy management system (EMS). DLR technologies deploy weather sensors for wind speed, ambient temperature, and solar radiation and/or gather data from line temperature, tension, sag, or clearance sensors. Communications technologies transfer data to DLR software on a server colocated with the EMS that determines the maximum dynamic rating for the specific conductor and environmental conditions. These ratings can be incorporated into a control system, such as a Supervisory Control and Data Acquisition (SCADA) system or EMS, to make them accessible in the transmission owner's and/or system operator's control room. Transmission owners and system operators can use this information to make informed decisions about transmission line capacity while maintaining the safety and reliability of the overall system. The primary benefits of a DLR system include the following:

- Increased transmission system efficiency
- Decreased or deferred capital costs through improved utilization of existing assets
- Decreased system congestion costs
- Reduced greenhouse gas emissions through the facilitated integration of renewable energy generation into the transmission system
- Increased situational awareness and operational flexibility of the transmission system

The financial benefits of DLR systems are twofold. First, DLR systems enable transmission owners to follow an optimized and least-regrets transmission capital spending strategy. A DLR system's relatively low cost and its abilities to be rapidly deployed and relocated make it ideal for projects facing the uncertainty of changing generation and load topologies. DLR systems can provide additional transmission capacity where it is much needed, especially when the cost of traditional construction represents a significant capital drain to the transmission owner. The additional capital that DLR systems release can be redirected to projects where capital is most needed. Second, DLR systems can enable a transmission owner to mitigate or avoid the costs associated with transmission system congestion. Congestion occurs when actual or scheduled power flows across a line or piece of equipment are restricted below desired levels, either by the capacity of the line or by the operational restrictions created and enforced to protect the security and reliability of the grid. (1) In systems in which locational marginal pricing is in effect, users of congested transmission paths often must pay a congestion charge. Although trends in transmission system congestion and its associated costs vary from region to region, congestion and congestion costs are generally becoming more widespread and volatile as demand increases and excess generation capacity shrinks. (2) Furthermore, the number of Level 5 transmission loading relief (TLR) events, which indicate system congestion, has increased substantially in recent years. (3) These trends make DLR technologies an increasingly valuable addition to the grid.

The SGDP DLR Demonstrations

NYPA and Oncor undertook DLR projects to mitigate transmission constraints, particularly during contingencies (i.e., unexpected failures or outages of transmission system components), and to increase the efficient use of the existing transmission network. They aimed to develop best practices for applying DLR systems, including communicating between the field back to the control center, integrating data with real-time operating systems, and improving Wide-Area Situational Awareness (WASA). (4), (5) NYPA's SGDP project assessed a wider array of DLR technologies, but Oncor's was larger in scale and aimed for a higher degree of integration with utility and Independent System Operator (ISO) operations. Table ES 1 highlights the objectives and outcomes of both projects.

	NYPA's DLR Project	Oncor's DLR Project
Project objectives	♦ Assess a variety of prototype and commercially available DLR technologies ♦ Demonstrate how DLR technologies could be used in transmission system engineering, operations, and planning at NYPA ♦ Determine a correlation between increased real-time capacity and increased wind generation	♦ Demonstrate the commercial viability of mature DLR technologies, with a focus on Nexans' technology ♦ Automatically utilize dynamic ratings in real-time system operations ♦ Develop a "best practices" guide to facilitate future DLR deployments
Key outcomes	♦ Calculated dynamic ratings and confirmed excess real-time capacity above static ratings ♦ Confirmed positive correlations between dynamic rating and wind farm output, as well as wind farm output and line loading ♦ Identified DLR systems' potential to facilitate the integration of	♦ Calculated dynamic ratings and confirmed excess real-time capacity above ambient-adjusted ratings ♦ Integrated dynamic ratings into the system operator's economic dispatch tool for automatic utilization in real-time operations ♦ Confirmed that a fully integrated DLR system is commercially

	NYPA's DLR Project	Oncor's DLR Project
	wind generation, define more effective static line rating methodologies, and support transmission planning studies	viable ♦ Determined that DLR systems are economically valuable, even though the financial benefits may be difficult to quantify ♦ Identified DLR systems' potential to facilitate the integration of wind generation, mitigate congestion, and improve grid reliability ♦ Developed a "best practices" guide to facilitate future DLR deployments
Conclusions	There is a wide variety of DLR technologies, each with its own set of advantages and disadvantages. Transmission owners should consider the potential challenges to DLR deployments carefully and be mindful of them from the project planning phase through execution.	Mature DLR technologies have significant value and are ready for wide-scale commercial implementation, provided that the transmission owner plans their deployment carefully.

Source: Navigant Consulting, Inc. (Navigant) analysis; data from (4), (5)

Table ES 1. Objectives and Outcomes of the SGDP DLR Demonstrations

NYPA partnered with the Electric Power Research Institute (EPRI), an independent, nonprofit organization that conducts research, development, and demonstration (RD&D) projects related to electricity generation, delivery, and use. NYPA demonstrated EPRI's conductor temperature sensors, along with three other varieties of DLR instrumentation (two technologies to measure weather conditions and one to measure conductor sag). NYPA installed these devices on three 230 kilovolt (kV) transmission line sections in upstate New York. EPRI provided technical support throughout the project. NYPA's SGDP project was launched in January 2010 and concluded in January 2013. (4)

Oncor partnered with Nexans, an international leader in transmission line cables and cabling solutions for power production, transmission, and distribution. Oncor demonstrated Nexans' CAT-1 conductor tension-monitoring system,[2] along with two other DLR technologies (devices

[2] The CAT-1 System was developed by The Valley Group, which is now a Nexans company.

to measure conductor sag and clearance) for validation and verification purposes. Oncor installed these devices on eight transmission circuits (138 kV and 345 kV lines) in Texas. Oncor received support from several parties, such as Nexans and the Electric Reliability Council of Texas (ERCOT). Oncor's SGDP project was launched in January 2010 and concluded in May 2013. (5)

Technical Performance of DLR Technologies

The SGDP projects revealed that DLR devices are reliable but require certain conditions to be met in order to operate accurately. The primary difficulties encountered during the two projects were recognizing that many DLR devices cannot gather accurate data when lines are lightly loaded and reconciling the lines' "as-built" characteristics with their design. (4), (5) Although DLR systems are technically challenging, both NYPA and Oncor learned to successfully implement DLR technologies and were able to gather accurate data on their DLR systems.

NYPA encountered several reliability issues with its DLR system, but Oncor encountered fewer complications. Oncor's DLR system calculated valid ratings more consistently than NYPA's DLR system for two reasons. Oncor's study lines were generally more heavily loaded, and Oncor structured its DLR system so that the system automatically selected the best available rating methodology (static, ambient-adjusted, or dynamic), based on line conditions and data availability, ensuring that ratings were constantly available.

For DLR devices measuring conductor temperature, sag, or tension, line loading determines whether the effective wind speed—and, by extension, the dynamic rating—can be accurately determined. If a line is lightly loaded (i.e., below 20%-30% of the static rating), the conductor temperature will not be sufficiently elevated above the temperature it would reach due to the impacts of ambient temperature and net solar radiation. (5) In these operating conditions, changes in conductor temperature, sag, or tension are small and are subject to prohibitively large measurement errors. The effective wind speed on the line section cannot be determined in these situations; therefore, the projection of the full real-time capacity of the line is less accurate. (4)

Key Results and Lessons Learned

It is somewhat difficult to compare the results of the two projects because of substantial differences in project execution and overall objective. NYPA monitored the effects of DLR technologies on a few transmission line spans, whereas Oncor observed the systemic impacts of instrumenting entire transmission lines with DLR technologies. The general purposes of the projects were also significantly different. NYPA sought to explore and compare a wide variety of technologies, while Oncor focused on demonstrating repeatable, real-world applications for the most mature DLR technologies. (4), (5)

Although NYPA and Oncor demonstrated different DLR technologies and set different project scopes and objectives, both utilities concluded that DLR systems indicate excess real-time capacity above the static rating in most instances. Based on calculations from the NYPA field data, real-time capacities showed increases of 30%-44% above the static rating, although NYPA's final Technology Performance Report (TPR) does not provide aggregate percentages for increased capacity at the study sites. (4) Oncor's study lines experienced increases of up to 200% in capacity, but Oncor capped the increment at 125% of static rating to accommodate the capacities of the "next limiting elements" on the lines and in consideration of the relay settings for the system protection schemes. From a practical perspective, Oncor observed increased real-time capacities between 6% and 14%, which were available over 83% of the time. Relative to static ratings, the DLR system released, on average, 30%-70% greater real-time capacity. (5) As the results of DLR deployment depend heavily on the specific location of the transmission line, these particular observations may not translate to transmission lines in other systems or at other voltage levels, even on the same grid.

Both of these SGDP projects revealed that DLR systems can facilitate the integration of wind generation into the transmission system. NYPA found positive correlations between wind farm output and dynamic rating, as well as between wind farm output and line loading. These relationships are not surprising. Increased wind speed is the primary driver of both increased wind farm output and increased real-time capacity (particularly when the wind blows at a right angle to the line). Transmission lines connected to wind farms would be more heavily loaded when the wind farms are generating more power (i.e., when the wind is blowing), assuming the lines and wind farms experience similar wind conditions. (4) Oncor observed a relative increase in wind generation when DLR systems increased the study lines' capacities. (5)

A significant outcome of Oncor's SGDP project was integrating the DLR system with ERCOT's control room. Dynamic ratings have been integrated into transmission owners' communication and control systems before. However, Oncor's SGDP project represents the first time that dynamic ratings were automatically incorporated directly into a system operator's state estimator tool. This incorporation eliminated the need for the operator to manually view, interpret, and apply the dynamic rating. This represents a breakthrough in the DLR industry, which has historically struggled to seamlessly integrate dynamic ratings into the system operator's control room, and demonstrates significant progress toward the commercial readiness of DLR systems.

These SGDP projects revealed key opportunities associated with DLR technologies, including potential applications for enabling a least-regrets capital investment strategy, calculating ratings for terminal equipment in substations based on real-time ambient temperature data, forecasting day-ahead dynamic ratings, improving transmission line rating methodologies at an operational level, and facilitating the integration of remotely sited wind generation. Additionally, the SGDP projects revealed several potential challenges to the wide-scale implementation of DLR systems, such as ensuring the reliability of DLR data, preemptively addressing cybersecurity concerns, integrating dynamic ratings into system operations, and verifying the financial benefits of DLR systems to system operators and transmission owners. Oncor's project overcame most of these challenges, but NYPA's project faced significant complications because of them.

Current and Planned DLR Deployments

NYPA and Oncor are undertaking two follow-on DLR deployments. NYPA's new DLR project, which is examining the potential coupling of DLR technologies with phasor measurement unit (PMU) sensor data, will be operational in mid-2014, while installation of Oncor's latest DLR project was completed in June 2013. These projects are both deploying Nexans' CAT-1 tension-monitoring system. (6), (7)

Future developments in DLR technologies may involve calculating dynamic ratings for terminal equipment in substations and forecasting line ratings. EPRI is currently exploring the possibilities of calculating ratings based on real-time temperature data for terminal substation equipment and forecasting dynamic ratings for transmission lines using statistical observations of wind conditions. (8) Nexans has already developed a transmission line capacity forecast engine, although it has not yet demonstrated this methodology in the United States. (2)

1. Introduction

The U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability (DOE-OE), is implementing the Smart Grid Demonstration Program (SGDP) under the American Recovery and Reinvestment Act of 2009. The SGDP involves 32 projects that demonstrate how suites of existing and emerging smart grid technologies can be applied and integrated to validate their technical, operational, and business feasibility. The projects are segmented into two areas, Smart Grid Regional Demonstrations (16 projects) and Energy Storage Demonstrations (16 projects), with a total budget of about $1.6 billion, including a Federal share of about $600 million. The Smart Grid Regional Demonstrations are intended to quantify smart grid costs and benefits and validate business models at scales that can be readily replicated across the country. The Energy Storage Demonstrations include demonstrating the viability of advanced batteries, flywheels, and compressed air energy storage systems for load shifting, ramping control, frequency regulation, distributed applications, and integration of variable renewable resources, such as wind and solar power.

DOE-OE is analyzing the impacts, costs, and benefits of the SGDP projects and is presenting the results through interim and final Technology Performance Reports (TPRs) for each project. Additionally, DOE-OE is presenting a series of topical reports, which analyze data and results from multiple projects that demonstrate the same or similar technologies and applications. These reports cover a variety of technologies and applications, including the following:

- Dynamic line rating (DLR) technologies
- Conservation voltage reduction (CVR)
- Microgrids
- Distributed energy resources (DER) integration
- Smart grid communications systems

1.1 Purpose and Scope

This report examines two SGDP projects that demonstrated DLR technologies. The New York Power Authority (NYPA) and Oncor Electric Delivery Company LLC (Oncor) were the recipients of these two projects. NYPA and Oncor are both pursuing additional projects related to DLR deployment, which are discussed in this report. Key benefits of DLR technologies include monitoring line capacity in real time, improving system safety and reliability, optimizing the use of existing grid assets, optimizing transmission capital expenditures by deferring the rebuild of existing or addition of new transmission circuits, increasing the market value of additional transmission capacity, and maximizing the options available to system operators to handle contingency conditions (i.e., unexpected failures or outages of transmission system components, such as generators, transmission lines, circuit breakers or switches, or other elements).

This report presents information on the SGDP DLR projects, including the types of devices and software being demonstrated, as well as the projects' benefits and results. It also examines the lessons learned from these projects and the future outlook for DLR technologies.

1.2 Overview of Dynamic Line Ratings

This section provides an overview of several key concepts associated with DLR technologies. The concepts discussed here include transmission line capacity and transmission line ratings, including static, ambient-adjusted, and dynamic ratings.

1.2.1 Transmission Line Capacity

Electric transmission lines are essential to deliver electricity to consumers. A transmission line is constrained by its capacity. The capacity of a long, extra-high-voltage (EHV) line is determined by the line's surge impedance loading (SIL) or voltage drop limits. The capacities of shorter, high-voltage (HV) lines are more commonly limited by thermal considerations. (9) A line's thermal capacity indicates the upper limit of power (or current at a specific voltage) that the line's conductors can carry without violating safety codes or damaging the conductor. (4) For the purposes of this report, "capacity" refers to thermal capacity.

There is a fundamental relationship between capacity, conductor temperature, and conductor sag. Capacity is inversely related to the temperature of a transmission line's conductors. Conductor temperature can increase because of a variety of factors—increased line current, warmer ambient temperatures, increased solar radiation, or decreased wind speeds, to name a few causes. As the conductor temperature increases, the conductors elongate and sag, further decreasing the clearance between the conductors and the ground. Conductor-to-ground clearance is one of the design parameters for a transmission line in order to maintain safe clearances from vegetation, buildings, and other electric power components. Conductor temperature and sag limit capacity because of clearance-related safety codes.[3]

With the installation of new generation and increased loads, transmission infrastructure has experienced unforeseen demand, which may result in congestion. Congestion occurs when

[3] Very high conductor temperatures may result in significant annealing, which damages the conductor; therefore, annealing concerns also limit capacity. However, conductors seldom reach temperatures at which annealing might occur. In practice, safety codes regarding conductor-to-ground clearance are typically the limiting factor of capacity. (9)

actual or scheduled power flows across a line or piece of equipment are restricted below desired levels, either by the capacity of the line or by the operational restrictions created and enforced to protect the security and reliability of the grid. (1) System operators manage anticipated congestion through locational marginal pricing, which requires users of constrained transmission paths to pay a congestion charge. Congestion charges cause the cost of delivered energy to rise, resulting in substantial increased costs for customers within that region. (4) Furthermore, heavy line loadings strain the operational margins required for contingencies, which raises both reliability and safety concerns. The thermal capacity of transmission lines, particularly overhead lines, is often the limiting circuit component for many transmission systems. In the current operating environment, transmission owners have the ability to accurately measure real-time load, but they have limited ability to measure the real-time rating or capacity margin of the transmission grid, one of their most valuable assets. (5)

Trends in transmission system congestion and its associated costs vary from region to region. However, the overall trend across the United States is that congestion and congestion costs are becoming increasingly widespread and volatile. (2) DLR systems can enable a transmission owner to mitigate congestion or avoid it altogether, making DLR technologies an increasingly valuable addition to the grid.

1.2.2 Static, Ambient-Adjusted, and Dynamic Line Ratings

A transmission line's rating indicates the highest current that the line can safely transfer without violating safety codes, damaging transmission components, or jeopardizing network reliability. The rating may be determined by the conductor's maximum operating temperature (which the transmission owner typically sets at levels such as 75 degrees Celsius, 90 degrees Celsius, or 125 degrees Celsius) or, more typically, by the minimum allowable conductor-to-ground clearance (which is determined by safety codes). (5) A line's rating is governed by several variables. (10) These include the following:

- Conductor size and resistance
- Conductor clearance to the ground
- Ambient weather conditions
    - Temperature
    - Wind speed and direction
    - Solar radiation

The rating is calculated from a steady-state heat-balance equation, which balances the thermal energy input and the thermal energy output of the line (i.e., the heat energy that the conductor gains must equal the heat that the conductor gives off to maintain a constant temperature). The conductor gains heat from the sun and from power lost because of line resistance. The conductor loses heat to the line's surroundings through radiation, cooling by rain, and convection by wind. (4) Ratings may be static (i.e., constant), ambient-adjusted (i.e., adjusted periodically), or dynamic (i.e., calculated using real-time data). Ratings are not set by manufacturers or standards groups but rather are left to the discretion of the transmission owner's engineers. (9)

All transmission owners and operators calculate static ratings for their transmission lines. Static ratings are based on fixed thermal and operating condition assumptions. The assumptions must be conservative to allow for unexpected contingencies. Typically, these assumptions are based on 98% of the expected worse-case values for key environmental parameters, such as wind speed, ambient temperature, and solar radiation. Furthermore, the assumptions suppose that adverse operating conditions (i.e., low wind, high solar radiation, and high temperature) all occur at the same time. Under these conservative assumptions, the owner would be at risk of exceeding safety margins about 2% of the time when operating at maximum capacity. (4) A line's real-time capacity is often, but not always, higher than its calculated static rating. This effect is especially pronounced during midday, when load requirements are greatest. In the afternoon, minimum wind speeds are higher than during the rest of the day; static ratings often suggest a transmission system may be constrained during this timeframe, but there may actually be a comfortable capacity available on the transmission line's margin. (8) However, in certain operating conditions, such as when winds are lighter than the assumed wind speed for the calculated static ratings (normally 2 feet per second), a line's capacity may be lower than its static rating. (11)

Contingency conditions may require high power flows that exceed a transmission line's normal static rating. To accommodate these short-term overload events, static ratings are also calculated for long-term emergency (LTE) periods lasting up to four hours and short-term emergency (STE) periods lasting up to 15 minutes. These ratings are higher than static ratings for normal (i.e., 24/7) conditions to reflect increased power flow requirements on the grid. The system operator will only dispatch the transmission system to these ratings for a relatively short period of time until the grid can resume normal operations. (4)

In many power systems, static ratings are adjusted to account for significant differences in maximum ambient temperature. Line ratings may be adjusted daily, hourly, or even more frequently to reflect the maximum ambient temperature predicted during a particular period of time. The method of periodically adjusting a line's rating based on ambient air temperature is called ambient-adjusted rating. For example, in New York, transmission lines receive a summer seasonal line rating assuming an ambient temperature of 35 degrees Celsius. If the maximum ambient temperature predicted for the next 24 hours is only 25 degrees Celsius, the ambient-adjusted rating can be increased by approximately 10% for the next 24 hours. However, ambient-adjusted ratings may not be perfectly accurate; although the ambient-adjusted rating reflects actual ambient temperature, it assumes a constant wind speed and solar radiation. (4) Some transmission owners consider ambient-adjusted ratings to be “dynamic,” but for the purposes of this report, ambient-adjusted ratings are not considered true dynamic ratings. This is because ambient air temperature measurements are the only time-sensitive data that ambient-adjusted ratings consider.

In contrast, dynamic ratings enable system operators to determine capacity and apply line ratings in real time, based on actual operating conditions. Dynamic ratings acknowledge that the assumed conditions on which static ratings are based are conservative and not likely to occur during peak load periods. Furthermore, dynamic ratings recognize that certain weather conditions (sometimes localized to only a portion of the line), such as wind speed and direction, ambient temperature, solar radiation, rainfall, and ice loading on a line, can impact conductor temperature and cause a line’s capacity to change along the line and throughout the day. Dynamic ratings provide a more accurate assessment of transmission line ratings and operating margins than static ratings or ambient-adjusted ratings, allowing operators to optimize the utilization of the transmission grid. A DLR system does not itself increase line capacity; rather, it reveals the line’s real-time capability. Although dynamic ratings are often greater than static ratings, in a minority of cases, DLR technologies reveal that a line’s dynamic rating is less than the static rating.

DLR technologies deploy weather sensors for wind speed, ambient temperature, and solar radiation and/or gather data from conductor temperature, tension, or sag sensors. Communication technologies transfer this data to DLR software that determines the maximum line capacity and calculates the dynamic rating based on real-time conditions for the specific installation. The system operators can use this information to make informed and real-time decisions to perform switching and load transfer operations, as network conditions require, in an effort to maintain a safe and reliable grid.

1.3 Organization of This Report

Section 2 provides information on the types of DLR technologies that were demonstrated in the NYPA and Oncor SGDP projects and their expected benefits. Section 3 highlights the key attributes and specific objectives of both projects. Section 4 provides a summary of the projects’ results. Finally, Section 5 explains the lessons learned from both projects and examines the future of DLR technologies by discussing ongoing challenges to and potential opportunities for DLR deployment.

This report also contains three appendices. Appendix A lists the sources referenced in the report. Appendix B provides detailed data and results from the two SGDP projects. Finally, Appendix C provides a “best practices” guide, which is adapted from Oncor’s final TPR, to facilitate future DLR deployments.

2. DLR Methodologies and Value Proposition

This section provides a brief history of DLR technologies and an overview of the technical approach to calculating dynamic ratings. It also discusses the various types of DLR devices and software and the expected benefits that may be realized through the deployment of a DLR system.

2.1 History of DLR Technologies

The concept of dynamic transmission line rating has been known by several names, including real-time rating, real-time thermal rating (RTTR), dynamic thermal conductor rating (DTCR), and dynamic cable rating (DCR). DLR technologies have been commercially available for approximately 25 years. Real-time monitoring technology for underground transmission lines, initially called the Cable Monitoring and Rating System (CMARS), was developed in the late 1970s through U.S. Department of Energy (DOE) sponsorship. The first CMARS demonstration project was implemented on Public Service Electric and Gas's (PSE&G) transmission system in New Jersey in 1975, with Underground Systems Incorporated (USi) providing support and technical evaluation. (11)

In the mid-1980s, USi developed a commercial, real-time monitoring and dynamic rating system for transmission cables, called UPRATE™. Companies such as Boston Edison, the Long Island Lighting Company (LILCO, now the Long Island Power Authority [LIPA]), PSE&G, Consolidated Edison of New York (ConEd), and NYPA installed UPRATE™ in their transmission systems. (11) In the early 1990s, The Valley Group developed its own DLR technology for overhead transmission lines, which it called the CAT-1 Transmission Line Monitoring System (CAT-1 System). (12) In 1998, the Electric Power Research Institute (EPRI) assembled a task force to develop its own DLR technology, the Video Sagometer, which would not require line outages during installation. (8) The Valley Group (now a Nexans company) and EPRI remain key players in the development and deployment of DLR technologies today, along with several smaller players, such as EDM International, Inc. (through which EPRI markets some of its technology), Promethean Devices, and Pike Electric Corporation.

2.2 Technical Approach

Dynamic ratings are determined by understanding the thermal relationship between the conductor, power flow, and ambient conditions. This relationship is defined and applied by the Institute of Electrical and Electronics Engineers (IEEE) and the Council on Large Electric Systems

(CIGRÉ) standards, which provide the mathematical equations defining the thermal behavior of the conductor (i.e., the heat balance equation described in Section 1.2.2):

- IEEE Standard 738-2012, "IEEE Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors," 2012. (IEEE 738) (13)
- CIGRÉ Technical Brochure 207, "Thermal Behavior of Overhead Conductors, Working Group 22.12," 2002. (CIGRÉ 207) (14)

DLR technologies collect transmission line data at prescribed locations (some of them remote) on the lines; calculate the dynamic rating based on the equivalent conductor temperature, ambient temperature, and influence of weather conditions on the line; and transmit the data to the transmission owner's and/or system operator's Supervisory Control and Data Acquisition (SCADA) system or energy management system (EMS). DLR technologies are executed through several essential elements. (11) These elements are described below:

- Sensors and devices to measure key parameters, such as load, wind speed, ambient temperature, conductor temperature, sag, and tension, on a continuous, real-time basis
- Parameter identification algorithms, which must continually evaluate and update key, uncertain thermal parameters, such as wind direction
- Accurate dynamic thermal models of transmission equipment, operating in real time, to accurately describe the equipment's performance in normal and emergency situations and quantify its capacity

The challenge of DLR systems is to determine where and how many devices are needed to ensure all spans of the line are monitored, measure the line's actual operating conditions, automatically gather data on these conditions, integrate the information to calculate dynamic ratings, and train the system operators on the use of dynamic ratings. Meeting this challenge allows the system to be operated safely and most effectively up to its full dynamic rating, system conditions permitting, since it bases capacity calculations on real-time data, rather than on static assumptions. (11) Historically, another key challenge has been how to introduce DLR data into the control rooms of system operators (i.e., the Independent System Operator [ISO], Regional Transmission Organization [RTO], or other system operators). This may involve the integration of a new terminal at the system operations center and additional training for grid operators. Oncor was able to integrate the dynamic ratings directly into the Electric Reliability Council of Texas's (ERCOT's) Security Constrained Economic Dispatch model, which meant that dynamic ratings could be implemented in real-time operations to automatically optimize the system without requiring the system operator to decide whether to use them. Oncor is the first transmission owner to incorporate dynamic ratings into the control room in this way. (5)

2.3 DLR Devices and Software

DLR systems are composed of the DLR technologies themselves and the communications and control systems needed to evaluate and/or implement dynamic ratings in an operations environment. DLR technologies include two primary components: sensors located on or near a transmission line, which monitor changing operating conditions, and communications devices and software, which transmit field data, interpret the data, and quantify the line's capacity. Existing control systems, such as SCADA or EMS, transmit dynamic ratings to transmission owners and system operators.

2.3.1 DLR Devices

DLR technologies can monitor the line's external environment or the line itself to determine the real-time capacity of the line. These devices continuously record field data, which is paired with time-of-day information (timestamp and/or Global Positioning System [GPS] location) to show when the data was collected. Some DLR devices are point sensors that gather information at only a specific location on the transmission line; when these devices are deployed, they are often installed in groups so that data can be gathered from several positions along a transmission line. Others are position sensors, which gather data about the characteristics of an entire line section. There are five types of DLR devices, which are differentiated by what they measure:

1. Direct weather measurements
2. Direct conductor temperature measurements
3. Conductor sag measurements
4. Conductor tension measurements
5. Conductor clearance measurements

Regardless of what a particular DLR device measures, all devices share a common goal. The goal is to measure specific parameters to calculate the dynamic rating and capacity margin. This goal is accomplished by measuring key operating conditions that affect the line's capacity in real time: (1) weather conditions—such as ambient temperature, solar radiation, wind speed, wind direction, and rainfall—and (2) the characteristics of the line itself, such as conductor temperature, clearance, sag, and tension. Effective wind speed is the biggest driver of capacity, but it can be difficult to determine unless it is measured directly. See Table 1 below for a description of how changing operating conditions affect capacity.

Operating Conditions	Change in Conditions	Impact on Capacity
Ambient temperature	2 °C decrease	+ 2%
	10 °C decrease	+ 11%
Solar radiation	Cloud shadowing	+/- a few percent
	Total eclipse	+ 18%
Wind	3 ft./s increase, 45° angle	+ 35%
	3 ft./s increase, 90° angle	+ 44%

Source: Navigant Consulting, Inc. (Navigant) analysis; data from (7)

Table 1. Impacts of Changing Operating Conditions on Transmission Line Capacity

Devices that make direct weather measurements are the least expensive and are highly reliable. They are also the simplest to implement because they do not need to be installed on the line itself, their components are more reliable, and they provide data that is easy to interpret. (4) However, these devices are point sensors, so they may not accurately reflect average operating conditions along the entire length of the line. Installation sites must be carefully considered, especially for collecting data from remote sections of a transmission line.

The other four types of devices measure conductor temperature, either directly or indirectly. Conductor sag or tension measurements are related to conductor temperature through a state-change equation, although this equation can be difficult to calculate. Conductor temperature can be used to determine effective wind speed, which is used to calculate dynamic ratings. As with weather measurement devices, direct conductor temperature measurements are point sensors that only describe the conditions at the point of installation and may not accurately represent average operating conditions along the entire length of the line unless multiple devices are installed. In contrast, conductor tension and sag measurements, which operate as position sensors, can be used to determine the line segment's average conductor temperature.

For DLR devices measuring conductor temperature, sag, or tension, line loading determines whether the effective wind speed—and, by extension, the dynamic rating—can be accurately calculated. Effective wind speed can only be determined when the line is loaded heavily enough to increase the conductor temperature several degrees Celsius above the temperature it would reach due to the impacts of ambient temperature and net solar radiation (dead-end to dead-end, which may be up to several miles). (5) Generally, the line must be carrying a minimum load of 20%-30% of its static rating or have a minimum current density of 0.5 amps per thousand circular mils (kcmil). This condition is often unmet, especially for 69 kilovolt (kV) to 230 kV lines. When the effective wind speed cannot be determined, the DLR software conservatively approximates the impact of wind on the line. The resulting dynamic rating is correspondingly conservative. For lightly loaded lines, transmission owners may need to rely on other DLR technologies or direct wind speed measurements if they wish to take full advantage of the available real-time capacity. (4) The devices themselves are reliable, but transmission owners must be aware of their potential limitations.

The fifth type of DLR device, which measures conductor clearance, is unique among conductor temperature-measuring devices in that it has no contact with the transmission line itself. Promethean Devices' Real-Time Transmission Line Monitoring System (RT-TLMS is an example of this technology. (5) Rather than measuring conductor temperature directly, the RT-TLMS utilizes three ground-based sensors to measure the magnetic field around the conductor. The magnetic field strength is proportional to the amount of current flowing through the line. By monitoring the phase currents of a transmission line and performing calculations of the installation geometry, the conductor height (i.e., clearance) and the conductor temperature may be calculated and therefore monitored. Additional technologies, such as Lindsey Manufacturing's Transmission Line Monitor (TLM), measure the natural frequency and/or inclination of the conductor to characterize its catenary curve, as well as conductor temperature and clearance. (5)

NYPA selected four sets of devices for testing: Campbell Scientific's weather stations; Pike Electric Corporation's ThermalRate Systems, which measures weather conditions by mimicking how the line behaves under those conditions; EDM International, Inc.'s Video Sagometers,[4] which measure conductor sag; and EPRI's Backscatter Conductor Temperature and Load Sensors (EPRI Sensors), which directly measure conductor temperature. In contrast, Oncor primarily deployed Nexans' CAT-1 System, which measures conductor tension. Oncor also deployed Video Sagometers and the RT-TLMS, which measures conductor-to-ground clearance. Thus, all five types of DLR devices are represented in the SGDP projects discussed in this report. Sections 3.2.1 and 3.2.2, respectively, describe how NYPA and Oncor deployed these devices in their DLR projects.

2.3.2 DLR Software

DLR devices are installed with auxiliary equipment, such as power supplies (e.g., solar panels and batteries), various types of communication technologies to transfer sensor data to a management system (such as a SCADA system or EMS), and other supporting electronics and hardware. From the SCADA system or EMS, data is collected and transmitted to a server, either within or outside the transmission owner's firewall, where dynamic ratings are calculated using

[4] EPRI originally developed the Video Sagometer, which EDM International, Inc. now markets. (6)

proprietary DLR software. In some cases, the DLR software may be built into the device itself, as is the case with the ThermalRate System. (4)

DLR software analyzes the field data gathered by DLR devices and provides real-time information to the transmission owner or system operator on the estimated temperature and capacity of the transmission line. This information reveals the maximum current that can be safely and reliably carried on the transmission line, based on real-time conditions. Data from the DLR system can be integrated into the transmission owner or system operator's SCADA system or EMS for further analysis. Oncor demonstrated that it is also possible to integrate DLR data directly into the system operator's state estimator application; as previously stated, Oncor is the first transmission owner to achieve this type of integration. (5)

Software used in DLR systems includes data logger software packages and software that calculates dynamic ratings for transmission lines. Data logger software packages, such as the Campbell Scientific LoggerNet software deployed in NYPA's SGDP project, support programming, communication, and data retrieval between onsite data loggers and an offsite server. EPRI's and Nexans' proprietary software was used to calculate dynamic ratings, respectively, in NYPA's and Oncor's SGDP projects. NYPA utilized EPRI's Dynamic Thermal Circuit Rating (DTCR) software,[5] which uses real-time or historical weather and electrical load data to calculate real-time capacity based on actual load and weather conditions. (4) Oncor utilized Nexans' IntelliCAT™ software, which calculates dynamic ratings based on conductor tension measurements. (5)

Once the software calculates the dynamic rating, the rating is transmitted back to the transmission owner's SCADA system or EMS, where its integrity is validated. Dynamic ratings can then be passed on to the system operators, which may include ISOs or RTOs that control many transmission lines within a region.

2.4 Expected Benefits of DLR Systems

Accurate dynamic ratings enable a transmission owner to know the true transfer capacity of transmission grid elements in real time. (5) While increased situational awareness of the transmission system is intrinsically valuable, this awareness translates into other, more concrete benefits. The primary benefits of a DLR system are increasing transmission grid efficiency, optimizing the allocation of transmission capital investment by improving the

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[5] Note that EPRI's Dynamic Thermal Circuit Rating (DTCR) software should not be confused with dynamic thermal conductor rating (DTCR), which is another term for the general concept of DLR.

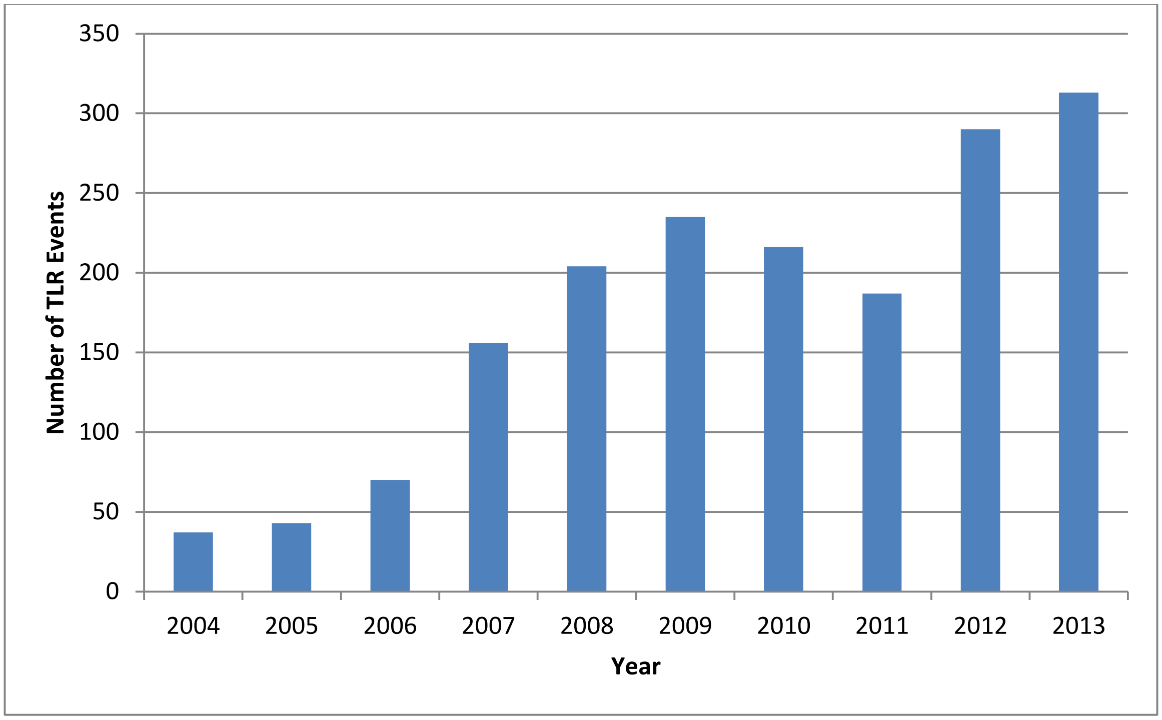
utilization of existing transmission assets, decreasing congestion costs, and reducing greenhouse gas emissions by facilitating the integration of renewable energy generation into the transmission system. These benefits can accrue to transmission owners, system operators, and customers. (5)

When the transmission system operates optimally, the system operator is better able to maintain safe and reliable operation of the grid. DLR systems increase reliability and efficiency by optimizing the use of the transmission network and maximizing the capacity of transmission paths. As a result, DLR systems help mitigate transmission congestion and reduce the probability of direct operator intervention to resolve real-time congestion. (5) Monitoring operating conditions enables the transmission owner to respond to changing weather and contingencies in real time, minimizing the impact of adverse system conditions. For example, consider the impact DLR systems can have on a transmission system experiencing an operating contingency. The operation of the transmission network must be able to withstand loss of its most critical element and still operate reliably (i.e., it must operate under a North American Electric Reliability Corporation [NERC] category N-1 contingency). (5) Under these conditions, the power flow on higher-voltage transmission lines could be constrained by the capacity rating of lower-voltage transmission lines. The ability to use DLR systems to apply real-time and higher-capacity ratings to lower-voltage transmission lines would mitigate power flow constraints throughout the entire transmission network in emergency situations, thereby improving the utilization of existing grid assets and reducing the cost of delivered energy for customers within that region.

DLR systems enable a transmission owner to ensure that transmission system reliability and safety standards are met. Since DLR systems can help mitigate congestion, they may enable a transmission owner to reduce or eliminate transmission loading relief (TLR) events. TLR events reflect bulk transmission system congestion. (15) During TLR events, scheduled transactions are curtailed to modify power flows that might otherwise lead to violations of reliability criteria. They are often associated with storms or equipment maintenance events that can cause scheduling inconsistencies and/or unplanned outages. (1) The Southwest Power Pool (SPP) Reliability Coordinator issues a Level 5 TLR event every time its market footprint experiences congestion. Other markets (such as the New York Independent System Operator [NYISO] and ERCOT) do not issue TLR events and instead redispatch constrained markets in real time. (15) TLR events do not indicate the commercial value of curtailed transactions. (1)

TLR events are classified according to their severity, with Level 5 and higher being the most severe. (3) Although the total number of TLR events has decreased since 2009, the number of Level 5 events (i.e., curtailments of firm transmission service) has increased. As shown in Figure

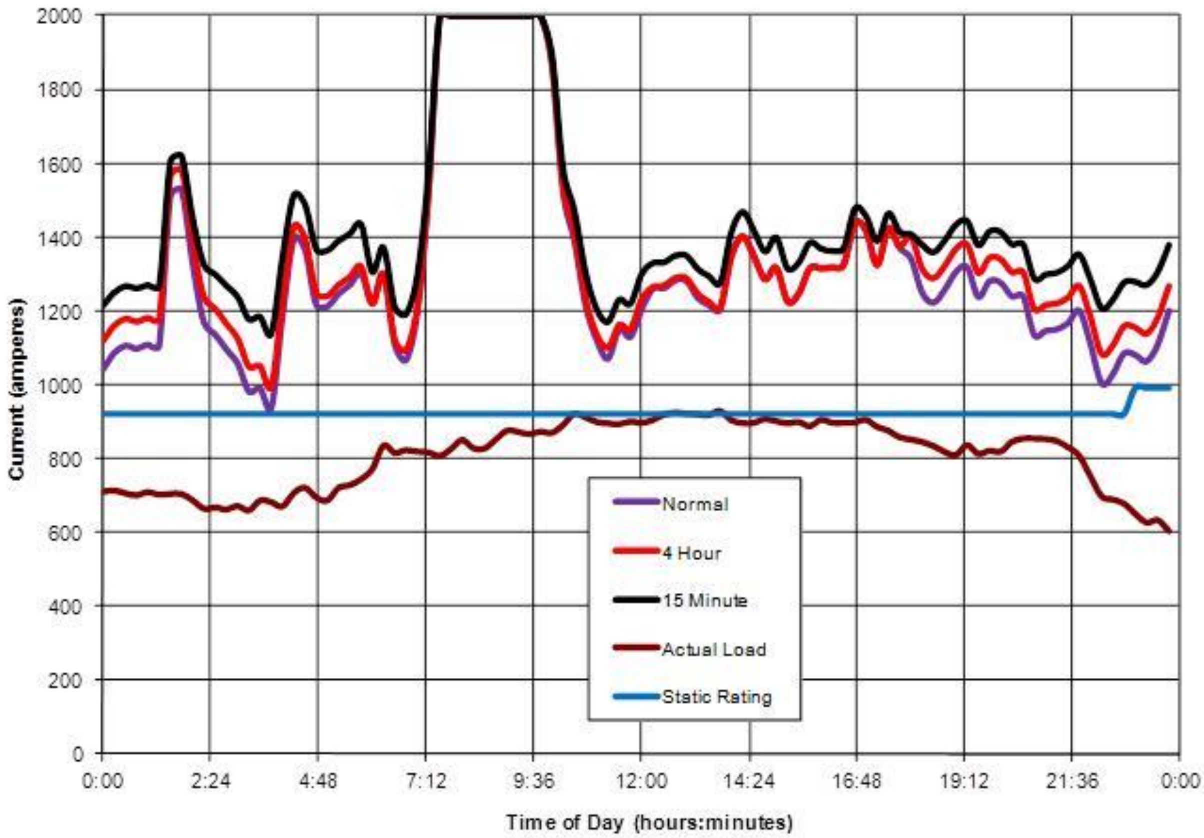
1, there were more Level 5 TLR events in 2012 and 2013 than in any previous year. (3) By reducing congestion, DLR systems may reduce the need for operators to curtail scheduled transmission service and thereby reduce the incidence of TLR events.



Source: Navigant analysis; data from (3)

Figure 1. Number of Level 5 TLR Events

DLR systems may even help a transmission owner avoid contingency violations altogether. Figure 2 shows a line that experiences increased current loading above the static rating several times between 9:36 AM and 4:48 PM. Without a DLR system in place, these events must be reported as violations, and the system operator would have to shift the grid to sub-optimal dispatch. However, the dynamic rating reveals that the line was actually operating safely and that no violations occurred. Thus, DLR systems may reduce the need for operator intervention. Real-time monitoring of line temperature ensures that reliability standards are maintained and that lines are not damaged by overheating, while real-time monitoring of line sag ensures that safety clearances are met.



Source: Used with permission from NYPA (4)

Figure 2. Use of DLR Systems to Avoid Contingencies

DLR systems help a transmission owner to maximize capital efficiency while reducing transmission congestion costs. DLR systems enable a transmission owner to add incremental capacity to existing transmission lines at a low cost and redirect the released capital to major grid enhancements. Costs compared to static line ratings are further reduced by decreasing or eliminating transmission congestion costs, thereby avoiding false thermal violation alarms and improving reliability indices.

It is difficult to quantify the exact economic value of DLR systems, since future meteorological conditions and load flows cannot be known with certainty until they occur. However, a sound estimate can be made by examining the economic impact of congestion events, which can be high. For example, over the past two years within the Oncor transmission system, 180 different lines (out of approximately 1,500 total lines) experienced congestion, and the associated congestion charges totaled more than $349 million. The daily average congestion cost totaled almost $250,000 per line. Several lines experienced congestion costs in excess of $1 million for a given day, with maximum costs as high as $6 million. (5) Since DLR technologies can help a load owner to avoid congestion costs, DLR systems clearly offer substantial economic benefits to transmission owners. Because DLR systems reduce system costs, their integration may result in lower prices for customers within that region. (10)

Finally, DLR systems have the potential to reduce greenhouse gas emissions by facilitating the integration of generation from renewable resources into the transmission system, especially those that are sited in remote locations. This is because increased line capacity enables more power to be transmitted from remote generation sources, which can be substituted for generation from less clean resources. In a situation involving solar generation, DLR systems would enable a transmission owner to determine whether solar radiation on the line decreased the line's actual rating below the static rating at any given time, while for situations involving wind generation, DLR systems would enable a system owner to determine whether wind speed and direction increased the line's dynamic rating above the static rating. In both the NYPA and Oncor DLR projects, significant power from wind generation was located in remote parts of each utility's transmission system. In the case of Oncor's SGDP project, the energy generated by wind needed to be delivered across half the width of Texas to reach load centers. (5) While neither project generated definitive data on the role of DLR systems in wind production, both observed increased line capacity when DLR systems and wind generation were combined. (4), (5) Furthermore, Oncor observed that ERCOT's Security Constrained Economic Dispatch tool appeared to utilize the increased line capacity to recommend generation shifts to more wind production. (5)

In addition to these general benefits of DLR systems, NYPA identified several benefits unique to its particular DLR project. (16) NYPA summarizes the benefits of its DLR project as follows:

- Higher power capacities of existing transmission assets during high wind farm output periods, which led to a greater understanding of the transmission system's capabilities
- More effective current planning practices, including an ability to seasonally change static ratings of transmission lines based on the knowledge and experience gained through the project
- Reduced system operations and maintenance (O&M) cost, which was achieved by tracking equipment thermal state and avoiding potential damage through timely action

Oncor also identified unique benefits of its SGDP project. (5) These include the following:

- Improved management of the transmission grid (i.e., increased transfer capacity of the line based on real-time conditions rather than static contingent parameters and increased system awareness of the status of the transmission system)

- More efficient methods for the future deployment of DLR technologies, facilitated by the creation of a "best practices" guide, which will enable other utilities to develop and deploy their own DLR systems more smoothly
- Increased stakeholder interest and involvement
- Enhanced interoperability and security of smart grid data

3. DLR Demonstration Projects

Two of the SGDP regional demonstration projects involved DLR systems. As discussed in Section 1.1, NYPA and Oncor were the recipients of these two projects. Table 2 lists key attributes of both SGDP DLR demonstrations.

Key Elements of DLR Demonstrations	DLR Demonstration Projects	
	NYPA	**Oncor**
DLR system developer	EPRI	Nexans
Other partners	♦ EDM International, Inc. ♦ Pike Electric Corporation ♦ NYISO ♦ New York State Energy Research & Development Authority (NYSERDA)	♦ Promethean Devices ♦ EDM International, Inc. ♦ SwRI ♦ Siemens Energy Inc. ♦ Chapman Construction Company ♦ ERCOT
Total installed cost	$481,000	$4,833,000
Total project budget	$1,440,000	$7,279,166
Project duration	1/1/10 – 1/31/13	1/1/10 – 5/4/13
Project location	Three 230 kV transmission line sections in New York	Five 345 kV and three 138 kV transmission circuits in Texas
DLR equipment	♦ 3 Video Sagometer systems ♦ 3 ThermalRate Systems ♦ 9 EPRI Sensors ♦ Weather stations	♦ 27 Nexans CAT-1 units ♦ 5 Video Sagometer systems ♦ 2 RT-TLMS
Communications equipment	♦ Backscatter data loggers, LoggerNet data logging software, and Remote Terminal Units (RTUs) ♦ Ethernet cables connecting data loggers to cell modems ♦ RF Link (to transmit load data to ThermalRate systems) Data was transmitted via Virtual Private Network (VPN)	♦ CATMaster radio/RTU interface ♦ RTUs Data was transmitted via radio frequency to substations, where it was imported to the SCADA system and EMS

Key Elements of DLR Demonstrations	DLR Demonstration Projects	
	NYPA	**Oncor**
DLR software	EPRI's proprietary DTCR software	Nexans' proprietary IntelliCAT™ software
Average increased real-time capacity	30%-44% above static rating based on available field data[6]	8%-12% above ambient-adjusted rating (138 kV lines) 6%-14% above ambient-adjusted rating (345 kV lines)[7]

Source: Navigant analysis; data from (4)*,* (5)

Table 2. Key Attributes of DLR Demonstrations

3.1 DLR Project Objectives

NYPA and Oncor undertook their respective DLR projects in an effort to relieve congestion and increase power flow through the transmission network. They also aimed to develop best practices for applying DLR systems, including the integration of data into communication and control systems (SCADA or EMS) and the improvement of Wide-Area Situational Awareness (WASA).

NYPA identified several specific objectives for its DLR demonstration. (16) These objectives include the following:

- Use DLR technologies to determine a correlation between high wind generation and increased transmission capacity
- Perform side-by-side field trials and evaluations of DLR devices that will consider cost, ease of installation, accuracy, maintenance issues, reliability, and ease of use
- Set up DLR software for real-time operation, first on a server in an engineering environment, separate from NYPA's operations environment, for initial tests and evaluations; then in an operations environment but not fully integrated into operational

[6] NYPA does not provide aggregate percentages for increased capacity at the study sites in its final TPR. The calculated average increased real-time capacity across NYPA's three study sites ranged from 25.3%-52.3%. (4) The figure presented in this table excludes the extreme low-end and extreme high-end values of this range.

[7] Oncor frequently experienced increased capacities greater than these (sometimes as much as approximately 200% of ambient-adjusted ratings), but it limited the capacity available to ERCOT to 125% of static ratings. Capacity increases between 6% and 14% were available 94%-91% of the time, while higher capacities were available less frequently.

procedures; and finally integrated into operational procedures so that results can be shared with the NYISO system operators

- Estimate the benefits of using DLR systems to help DOE perform cost-benefit analysis of the technology and encourage other utilities to replicate the project
- Help revise the transmission circuit procedures that will likely be impacted due to varying equipment ratings by clarifying the necessary changes with maximum benefit and minimal disruption
- Improve current planning practices and demonstrate the effectiveness of seasonally changing static ratings based on the knowledge gained through this project

Oncor identified various project objectives in the categories of congestion reduction objectives, economic objectives, operational objectives, and demonstration objectives. (5) These objectives are outlined below:

- Congestion reduction objectives
    - Demonstrate that DLR technologies are reliable by using dynamic ratings in real-time system operations over the course of several critical peak operating seasons
    - Quantify the increased line capacity to improve the efficiency of system planning and operations
    - Establish interoperability and transparency with Oncor's EMS and ensure the integrity and accuracy of the data through a cybersecurity assessment
- Economic objectives
    - Quantify the economic value of increased capacity released by the DLR system
    - Estimate the savings associated with the deferral of rebuilding, reconductoring, or building new circuits to meet transmission requirements
    - Quantify the total costs of implementing an effective DLR program
- Operational objectives
    - Relieve congestion and transmission constraints
    - Gain operational knowledge of DLR systems and develop a "best practices" guide to facilitate wide-scale deployment of DLR systems
    - Ensure that safety code clearances are not impacted
    - Demonstrate that multiple monitoring units can be integrated into operations
    - Identify/quantify other operational limits that may impact the ability to raise transmission line ratings
- Demonstration objectives

- Extrapolate the impact of DLR systems on the study's transfer path to the entire ERCOT region
- Determine a methodology to release day-ahead line ratings
- Develop user-friendly tools for the operator to manage improved WASA

3.2 Demonstrations of DLR Systems

This section provides an overview of NYPA's and Oncor's DLR demonstrations. A high-level overview of each project provides information about the study sites and the technologies that each project assessed. This overview is followed by a description of project implementation, such as major tasks and milestones. NYPA's SGDP project assessed a wider array of DLR technologies, as its primary objective was to explore, evaluate, and demonstrate how these technologies could be used in NYPA's transmission system engineering, operations, and planning. Oncor's project was larger in scale and aimed for a higher degree of integration with utility and ISO operations, as it sought to demonstrate the commercial viability of implementing a DLR system in real-time system operations.

3.2.1 NYPA's DLR Demonstration

NYPA partnered with EPRI, an independent, nonprofit organization that conducts research, development, and demonstration (RD&D) projects related to electricity generation, delivery, and use. NYPA demonstrated EPRI's conductor temperature sensors, along with three other varieties of DLR instrumentation. NYPA's SGDP project was launched in January 2010 and concluded in January 2013. (4)

3.2.1.1 Project Overview

NYPA initiated its DLR demonstration in 2010 through a partnership with DOE to evaluate EPRI's DLR technologies and instrumentation. NYPA was interested in studying DLR technologies because the utility must transfer significant power—particularly power generated by hydroelectric plants in northern New York and wind farms in western and northern New York—across great distances to the southeastern New York population centers within a historically constrained transmission system. NYPA hoped to use DLR technologies to confront a growing problem in New York—the trend that wind generation is coming online faster than the existing transmission system can be upgraded to integrate it. Therefore, NYPA aimed to determine the correlation between wind farm output and transmission line capacity, which could be observed through a DLR system. NYPA used dynamic ratings to correlate increased wind generation and increased transmission capacity, a relationship that could defer millions of dollars in capital expenditures on transmission projects. (4)

The project included the installation and maintenance of DLR instruments along three 230 kV line sites in northern New York. These lines included the Moses–Willis line (Site 1), which spans 710 feet and is surrounded by inactive agricultural land and low hayfields near the town of Massena; the Willis–Ryan line (Site 2), which spans 580 feet and is surrounded by cultivated cropland close to Chateaugay; and the Moses–Adirondack line (Site 3), which spans 545 feet and is surrounded by permanent pasture in Massena. (16) All three sites are located in mostly open, level terrain with minimal wind shielding from trees and other objects. These sites were chosen because of their close proximity to wind generation, which would help determine a correlation between wind farm output and transmission line capacity. (4)

NYPA sought DLR technologies that could be quickly installed, preferably with few or no required outages. NYPA selected four sets of devices for testing: weather stations; ThermalRate Systems, which measure weather conditions; Video Sagometers, which measure conductor sag; and EPRI Sensors, which measure conductor temperature and current. EPRI Sensors are a prototype system, while the ThermalRate System and Video Sagometers are commercially available from Pike Electric Corporation and EDM International, Inc., respectively. NYPA also utilized offsite weather service data as a backup for its own meteorological measurements. A summary of NYPA's monitoring methods is shown in Table 3.

Monitoring Method	Minimum Current Density	Location	Parameters Measured	Power Source
Onsite weather station	N/A	Local	Wind, ambient temperature, solar intensity	Solar
ThermalRate System	N/A	Local	Wind, ambient temperature, solar temperature	Solar
EPRI Sensors	0.5 amps/kcmil	Multi-local	Conductor temperature, current	Battery
Video Sagometers	0.5 amps/kcmil	Line section	Sag	Solar
Offsite weather service	N/A	Remote	Wind, ambient temperature, solar intensity	N/A

Source: Navigant analysis; data from (4)

Table 3. Summary of NYPA's Monitoring Methods

EPRI's DTCR software was used to calculate dynamic ratings at ten-minute intervals. When the EPRI Sensors and/or Video Sagometers could not gather data accurate enough for the DTCR software, dynamic rating calculations were performed using an alternate model, DynAmp, which is based on a 1988 EPRI research study. The DLR software resided on a remote server at the EPRI High Voltage Laboratory in Lenox, Massachusetts, until the end of the demonstration. (4)

NYPA aimed to transmit dynamic ratings to the NYISO control room in real time; however, it was unable to do so, for reasons discussed in Section 4.

3.2.1.2 Project Implementation

The project was launched in 2010 and concluded at the end of January 2013. The project consisted of ten main tasks:

1. Review lines and sites for study
2. Design instrumentation mounting, integration, power, and communications
3. Purchase, configure, test, and install field instrumentation
4. Maintain field instrumentation
5. Conduct initial DLR system setup and verifications
6. Develop physical modeling of lines and sag-temperature equations
7. Execute the DLR system, with EPRI to provide training and continued support
8. Train NYPA personnel on the operation of the DTCR server
9. Analyze instrumentation, rating, and weather data
10. Conduct meetings and develop reports

Each installation site contained the following devices:

- Weather instruments to measure wind speed and direction, temperature, solar intensity, and rain
- ThermalRate sensor (1) and supporting solar electronics
- Video Sagometer cameras and targets (1)
- EPRI Sensors (3)

EPRI provided technical support throughout the project, as field instrumentation often required troubleshooting or maintenance. NYPA provided bucket trucks and line crew support. Dynamic rating calculations were performed between December 2010 and October 2012. The DTCR server was shipped to a NYPA location in January 2013, at which point a training program took place to facilitate the server's transfer, operation, and integration at NYPA. A timeline of project milestones is provided in Table 4.

Date	Milestone
January 2010	Agreement awarded
July 2010	Project kickoff
November 2010	Installation training Instruments installed
December 2010	Initial calibrations
August 2011	Interim report
August 2012	Project update meeting
January 2013	Transfer of DTCR server
February 2013	DOE report submitted NYPA report submitted
April 2013	Project closeout

Source: Navigant analysis; data from (4)

Table 4. NYPA DLR Project Milestones

3.2.2 Oncor's DLR Demonstration

Oncor partnered with Nexans, an international leader in transmission line cables and cabling solutions for power production, transmission, and distribution. Oncor demonstrated Nexans' CAT-1 conductor tension-monitoring system, along with two other DLR technologies for validation and verification purposes. Oncor's SGDP project was launched in January 2010 and concluded in May 2013. (5)

3.2.2.1 Project Overview

Oncor and its partners launched a DLR project in 2010 through a partnership with DOE. The project aimed to conduct studies to remove the constraints that prevent utilities from using DLR technologies and to demonstrate the effective use of dynamic ratings to reduce grid congestion. Oncor was interested in implementing a DLR system because many of its transmission paths, including those selected for this project, are believed to face significant transmission constraints. (5)

Oncor deployed DLR technologies at 27 locations along eight transmission circuits. These circuits included five 345 kV lines and three 138 kV lines, which were located in Bell, Bosque, Falls, Hill, McLennan, and Williamson Counties in central Texas. Oncor selected these sites because ERCOT has included these circuits in its Commercially Significant Constrained Path, which identifies them as significantly constrained. ERCOT forecasted that these circuits would become an even greater constraint in the near future. (5)

Oncor primarily deployed Nexans' CAT-1 System, which measures conductor tension, in its DLR demonstration. The CAT-1 System includes load cells and CAT-1 units. Load cells are tension-measuring devices attached to the conductor. CAT-1 units are composed of various power sources, communications equipment, and data logging equipment. Up to two load cells can be connected to each CAT-1 unit to record and transmit tension data. The CAT-1 System features sensors to gather net radiation temperature (NRT) data, which is used to calculate the solar radiation component of dynamic ratings. (7) Oncor selected the CAT-1 System because it provided the flexibility to move DLR sensors as needed. Oncor believed that the CAT-1 System could be adapted to transmit a live data feed of dynamic ratings to ERCOT's control room, as Nexans has been successfully integrating dynamic ratings into transmission owners' EMSs for approximately ten years. Oncor also deployed the RT-TLMS and Video Sagometers as validation and verification for the ratings calculated with the CAT-1 System. (5)

At each location, CAT-1 Systems were attached to transmission structures. CATMaster radio receivers were installed inside ten substations. The remaining DLR components, including the server on which the DLR software resided, were housed at Oncor's system control center in Dallas. (5)

Oncor collaborated with several key partners during this project. Nexans provided technical support for the CAT-1 System, while EDM International, Inc. and Promethean Devices provided technical support for, respectively, the Video Sagometers and RT-TLMS. Chapman Construction Company facilitated construction[8] and installation. SwRI assisted in data reduction and validation and conducted independent analyses in tandem with the SGDP project. Siemens helped Oncor modify its EMS to validate incoming DLR data, which enabled Oncor to stream dynamic ratings to ERCOT's control room. Finally, Oncor collaborated with ERCOT to facilitate the integration of dynamic ratings into real-time system operations. (5)

3.2.2.2 Project Implementation

The project included two major phases. First, DLR instrumentation and validation hardware were installed in the field, and the system was calibrated to go online to stream DLR data to the operating environment. Second, Oncor conducted relevant studies to assess the application of

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[8] Nexans recommends that the CAT-1 System be installed on dead-end structures. A dead-end is a location on the transmission line where the conductors are terminated. Several of the 345 kV lines that Oncor studied in its SGDP project had no dead-end structures between substations, so "floating dead-ends" needed to be constructed. (5)

the DLR data in the operating environment and the impact of DLR technologies on the availability of transmission line capacity, the accuracy and optimization of the DLR deployment protocol, interoperability and cybersecurity capabilities, and the economic and environmental impact on congestion relief. The project was initiated in early 2010, and project operations concluded in December 2012. Studies associated with the project were completed by March 2013. (5)

Oncor installed the following devices as part of its DLR project:

- Load cells (19 load cells on 345 kV lines and 26 load cells on 138 kV lines), which measure conductor tension
- CAT-1 units (11 installed on 345 kV lines and 16 installed on 138 kV lines), which receive tension data from load cells
- CATMaster data aggregators (eight installed in substations to route the data into the Oncor SCADA system)
- IntelliCAT™ server (one installed in Dallas)
- Video Sagometers (five) and Promethean Devices’ RT-TLMS (one for monitoring 138 kV lines and one for monitoring 345 kV lines) for technology validation tasks

A timeline of Oncor’s project milestones is shown in Table 5 below.

Date	Milestone
April 2010	Initial DLR installation
September 2010	Design installation plan/material procurement
January 2011	Terminal upgrades
March 2011	Completed DLR installation Installation of sag monitors
May 2012	Began streaming DLR data to ERCOT
March 2013	Project studies: reported quarterly ♦ Analysis of DLR real-time constraint release ♦ Sag studies – alternative DLR technology confirmation ♦ *Economic Trade Space Analysis* ♦ *Interoperability and Cybersecurity Assessment* ♦ Technology deployment protocol
June 2013	Completed project documentation

Source: Navigant analysis; data from (5)

Table 5. Oncor DLR Project Milestones

Oncor took a "total-system" approach to its SGDP project. Oncor did not seek to explore and evaluate DLR technologies; rather, it sought full-scale, real-time integration with its own operations and ERCOT's wholesale electricity market. (5) Oncor's project implementation was unlike any other DLR deployment and is perhaps the most significant take-away from the project. See Section 4.2 for a discussion of the outcomes enabled by Oncor's project implementation.

DLR systems have most often been deployed for transmission system planning purposes or research and development (R&D) tasks. These deployments generally monitor only the "critical spans" of transmission lines—the span(s) that have minimal clearances or the sections of the line that are most shielded from the wind and therefore have lower capacities than other spans. Oncor realized that the location of the critical span is not static because the wind along a line is volatile. Oncor undertook a full and complete deployment on eight transmission lines, monitoring the entire line, rather than a few spans. (5)

DLR technologies face several inherent challenges, which can complicate efforts to integrate them into real-time operations. Depending on project objectives, these issues may or may not significantly undermine the success of a DLR deployment. For exploratory or R&D-focused deployments, failure to address these challenges will not necessarily render a project unsuccessful. However, if left unaddressed, these issues can potentially cripple deployments that aspire to real-time integration with system operations. Oncor structured its SGDP project to successfully overcome these challenges, as shown in Table 6.

Challenge	Oncor's Solution
Point-sensor DLR technologies can only monitor discrete "points" along a transmission line, rather than the entire line. If too few devices are used, dynamic ratings may be inaccurate.	Oncor deployed position-sensor DLR technologies, which gather spatial data, not point data. Oncor determined the optimal number of monitors needed to accurately characterize the study lines.
As discussed in Section 2.3.1, most DLR technologies cannot gather accurate data or perform DLR calculations when lines are lightly loaded. Light loads can create "gaps" in DLR data.	Oncor selected technology (Nexans' CAT-1 System) that could calculate ratings under light loads using alternative data. The DLR system automatically selected a rating based on best-available rating, so ratings were always available, regardless of load conditions.
Dynamic ratings may release more additional capacity on transmission lines than the rest of the transmission system can safely accommodate.	In consideration for the next limiting element on the line being monitored, Oncor limited the additional capacity available to ERCOT operators to 125% of the lines' static ratings.[9]
System operators may be reluctant to embrace the steep learning curve inherent in a DLR system, and they may question whether the dynamic ratings are satisfactorily reliable.	Oncor automated the validation of DLR data and its incorporation into ERCOT's real-time operations, ensuring data reliability and minimizing the efforts required from grid operators.

Source: Navigant analysis; data from (5)

Table 6. Oncor's Solutions to DLR Challenges

Oncor strove to observe the systemic effects of the DLR system by determining the impact of dynamic ratings on the entire ERCOT system. In particular, Oncor analyzed the impacts on wind generation and system congestion relief. (5) The outcomes of these studies are discussed in Section 5.

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[9] Oncor selected a 125% cap to maintain a small "buffer" for the next limiting elements of the system, whose capacities were approximately 133% of the static rating. This ensured that the next limiting element would not become constrained when dynamic ratings were utilized.

4. Analysis of Results

This section examines the results of the NYPA and Oncor DLR demonstrations. For each project, a high-level overview of the data gathered throughout the project is provided before the specific results of the project are summarized. Detailed project results can be found in Appendix B. Although NYPA and Oncor gathered different data and obtained different results, both utilities concluded that DLR systems demonstrate excess capacity on transmission lines above the static rating in most instances.

4.1 Results of NYPA's DLR Demonstration

Through its DLR demonstration, NYPA determined that DLR systems are valuable because dynamic ratings can provide a "better knowledge" of a line's actual capacity than using static ratings. (4) Furthermore, in most cases, the dynamic ratings of the circuits studied were significantly greater than the static ratings. Although NYPA determined that the real-time capacity of these transmission lines is often higher than the static rating, the utility did not subsequently adjust its line ratings at an operational level as a result of this project. The data gathered throughout the project indicate that the current static ratings and the assumptions on which these ratings are based are justified. (4)

NYPA identified many successes and challenges of DLR technologies through its demonstration, with individual conclusions discussed in Section 5. The main conclusion is that, despite the steep learning curve inherent in implementing a DLR system, DLR technologies are successful in integrating additional transmission capacity in real time, most of the time. For the specific lines studied this project, that is particularly true during periods of high wind farm output (i.e., when the wind is blowing). However, NYPA believes that some DLR technologies need improvements before they could be reliably utilized throughout the transmission system, and it would be a challenge for a transmission owner to implement a DLR system without "significant effort" upfront and regularly thereafter. (4) The challenges and limitations NYPA encountered with its selected DLR technologies are discussed in Section 5.

4.1.1 Data Gathered

NYPA organized the data gathered during its DLR project into four categories: raw field data, calculated data, statistical distributions of data, and instrument performance statistics. Raw field data was directly measured onsite using the DLR devices (e.g., wind speed was measured using anemometers). Calculated data used raw field data as an input (e.g., line rating was calculated using raw data on wind speed). Table 7 summarizes the types of raw field data and calculated data associated with each DLR device NYPA deployed.

DLR Device	Raw Field Data	Calculated Data
Weather station	Ambient temperature Solar intensity Wind speed Wind direction Rain rate	Effective perpendicular wind speed Conductor temperature Dynamic ratings
Video Sagometer	Sag	Effective perpendicular wind speed Conductor temperature Dynamic ratings
ThermalRate System	Effective perpendicular wind speed	Dynamic ratings
EPRI Sensors	Conductor temperature Current	Effective perpendicular wind speed Dynamic ratings

Source: Navigant analysis; data from (4)

Table 7. Summary of Data Collected by NYPA

4.1.2 Key Results

One of NYPA's goals was to perform an assessment of the DLR equipment installation process. NYPA's line crews do not normally have experience with the specialized instruments required for DLR systems, so they received comprehensive training from EPRI. The NYPA line crew continued to improve and learn with each onsite equipment installation. In addition to becoming familiar with the installation process, the installation process itself was improved and streamlined. Overall, NYPA determined that certain types of DLR instruments can be successfully installed without outages by a well-versed line crew. NYPA estimates that it would take four hours to install one set of instruments for future DLR needs. (4)

NYPA considered whether weather data provided by online weather services, such as the National Oceanic and Atmospheric Administration (NOAA), could be utilized in a DLR system in lieu of onsite direct weather measurements. NYPA determined that such resources are not likely viable. Weather data from such services are usually not obtained from the same geographical areas in which transmission lines are likely to be found. While such weather data may provide useful measurements of ambient temperature or solar radiation, wind measurements will not be satisfactorily accurate to determine dynamic ratings. (4)

NYPA found that dynamic ratings can provide a better knowledge of the actual line rating than that provided by static ratings. Furthermore, in most cases, dynamic ratings are significantly greater than static ratings. Table 8, Table 9, and Table 10 compare the static ratings of each circuit to the median dynamic ratings calculated with DLR technologies, categorized by normal periods (for 24/7 operation), LTE periods lasting up to four hours, and STE periods lasting up to 15 minutes. For the purposes of comparison, the dynamic ratings presented are Level 50 (L50) ratings, meaning that they represent the median magnitude of dynamic rating for the line. Although NYPA's installation sites experienced minimal shielding, it is possible that there are sections of these lines that are sheltered from the wind by trees or local geological factors, such as valleys or hills, which would minimize the wind speed's impact on increasing the transmission line's real-time capability above static ratings. Ideally, a monitoring site used to determine the rating of the line would be chosen in the most wind-sheltered area of the corridor. (4)

Time Period	Static Rating (Amps)		Median Dynamic Rating (Amps)		Average Capacity Increase (%)	
	Summer	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**
Normal	1,089	1,331	1,659	1,853	52.3%	39.2%
LTE	1,256	1,460	1,763	1,939	40.4%	32.8%
STE	1,410	1,593	2,030	2,370	44.0%	48.7%

Source: Navigant analysis; data from (4)

Table 8. Summary of NYPA Site 1 Static and Dynamic Ratings

Time Period	Static Rating (Amps)		Median Dynamic Rating (Amps)		Average Capacity Increase (%)	
	Summer	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**
Normal	1,087	1,331	1,535	1,837	41.2%	38.0%
LTE	1,256	1,460	1,652	1,922	31.6%	31.6%
STE	1,410	1,593	1,940	2,186	37.6%	37.2%

Source: Navigant analysis; data from (4)

Table 9. Summary of NYPA Site 2 Static and Dynamic Ratings

Time Period	Static Rating (Amps)		Median Dynamic Rating (Amps)		Average Capacity Increase (%)	
	Summer	**Winter**	**Summer**	**Winter**	**Summer**	**Winter**
Normal	1,087	1,331	1,500	1,748	38.0%	31.4%
LTE	1,256	1,460	1,615	1,830	28.6%	25.3%
STE	1,410	1,593	1,883	2,241	33.6%	40.7%

Source: Navigant analysis; data from (4)

Table 10. Summary of NYPA Site 3 Static and Dynamic Ratings

These results reinforce the observation that weather conditions, especially high winds, can create substantially greater real-time capacity. Detailed data concerning NYPA's static and dynamic ratings can be found in Appendix B.

Another goal of the project was to observe any correlation between the potential power output of nearby wind farms and real-time capacity. NYPA found that wind speed is the single most influential weather factor in both wind farm output and dynamic ratings. NYPA observed a positive correlation between wind generation and line rating. In the region NYPA sited its project, both the wind farms and transmission lines are in flat, open terrain, so wind speeds encountered by the wind farms are closely correlated with the wind speeds at the transmission lines. Consequently, NYPA believes wind farm curtailment could be mitigated using dynamic ratings on relevant transmission lines. (4)

The last goal of the project was to transfer knowledge and the DLR technologies themselves to the NYPA control center. In January 2013, the fully operational DTCR server was transferred to NYPA, in conjunction with a live demonstration of the NYPA line ratings with hands-on training for NYPA personnel. Today, NYPA retains possession of the server, modems, field instruments, ratings software, and all project data. (4)

4.2 Results of Oncor's DLR Demonstration

Oncor determined that, for most transmission lines, the dynamic rating typically delivers an increased real-time capacity above the ambient-adjusted rating 80%-95% of the time and above the static rating 97%-99% of the time. As NYPA also discovered, Oncor determined that even greater capacity gains can be safely utilized in STE (15-minute exposure) situations. Oncor considers this project a "complete success." (5) The SGDP project demonstrated that dynamic ratings are a valuable and successful tool to increase the real-time capacity of a transmission line, enabling transmission owners and system operators to mitigate congestion, increase system reliability, and follow a "least-regrets" strategy for capital spending. Conclusions drawn from Oncor's project are discussed in Section 5.

4.2.1 Data Gathered

Oncor compared the DLR capacity calculated throughout the project to the existing ambient-adjusted ratings and static ratings for each month for each transmission line segment at two-minute intervals. Oncor chose this comparison to identify the added benefit of DLR systems beyond what is provided by ambient-adjusted ratings, rather than strictly focusing on the benefits of dynamic over static ratings. (5) To visualize the benefits, the comparisons between DLR and ambient-adjusted and static ratings were processed in the following ways:

- Charts tracking DLR and ambient-adjusted ratings on a monthly basis as a timeline
- Charts illustrating the difference between DLR and ambient-adjusted or static ratings on a monthly basis as a percent-of-time probability distribution
- Charts illustrating the difference between DLR and ambient-adjusted or static ratings on a monthly basis as a daily distribution

Oncor developed time series of ratings by recording data every two minutes and then plotting the ratings for each two-minute interval. Cumulative distributions were developed in a similar way by recording data every two minutes, subtracting the ambient-adjusted or static rating from the dynamic rating for each two-minute interval, and plotting the difference as a standard cumulative probability chart. (5)

At the end of each month, log files containing all segment ratings for the month were extracted from the server located in Oncor's Transmission Management System's control center. A Visual Basic program was developed to extract raw data from the log files, perform comparison calculations, organize data and results into time-stamped Microsoft Excel files, and generate the charts described above. (5)

4.2.2 Key Results

This project demonstrated that DLR technologies identify significant additional capacity above static ratings or ambient-adjusted ratings. While quarterly results varied, the average increased real-time capacity delivered by dynamic ratings was 6%-14% greater than the ambient-adjusted rating for 345 kV lines and 8%-12% greater than the ambient-adjusted rating for 138 kV lines. Note that Oncor compared increased capacity to the ambient-adjusted rating, not the static rating. Oncor's current rating methodology is ambient-adjusted rating, so comparisons to static ratings would not have provided a meaningful assessment of increased capacity. The availability of the added capacity ranged from 83.5% of the time under all operating conditions to 90.5% of the time when outages and anomalies were excluded from the data. Table 11 provides a statistical summary of the additional capacity above ambient-adjusted ratings identified by the DLR system for 345 kV lines. (5) The results of Oncor's DLR project are presented in detail in Appendix B.

	Median	Max	Min	Average
Months free of data anomalies	92.2%	97.7%	73.5%	90.5%
Months with up to 10% of data missing or DLR defaulted to the static rating because of data anomalies	90.5%	97.7%	65.9%	89.1%
All months	89.1%	97.7%	6.5%	83.5%

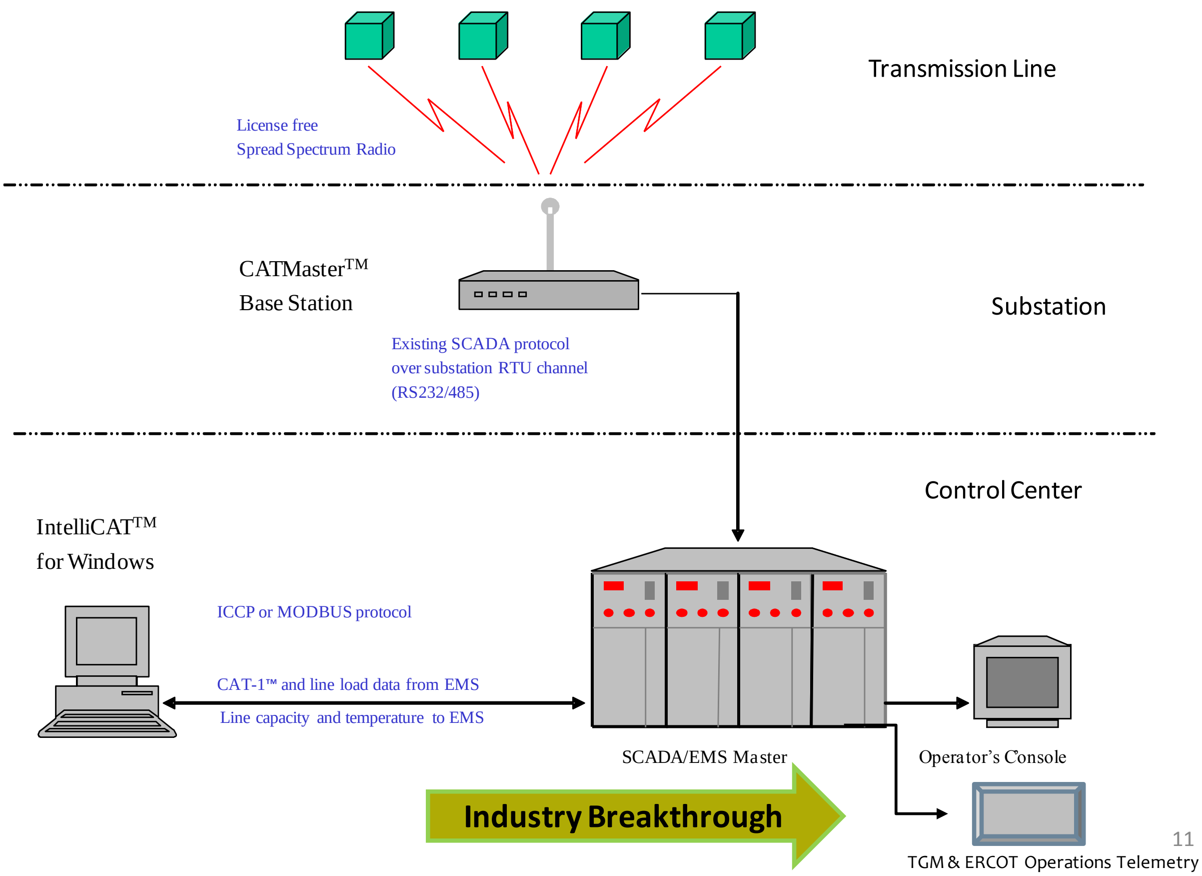
Source: Navigant analysis; data from (5)

Table 11. Percent of Time Dynamic Rating Exceeded Ambient-Adjusted Rating (All 345 kV Lines)

Oncor showed that multiple DLR technologies can be deployed to monitor real-time capacity. Overall, Oncor found the DLR system to be highly reliable and accurate, providing 24/7 functionality and measuring average conductor temperature accurate to 1-2 degrees Celsius. Oncor discovered that the CAT-1 system could not calculate dynamic ratings when lines were loaded at less than 20% of the static rating. On a monthly average, Oncor found that lines were too lightly loaded to calculate dynamic ratings with the CAT-1 system 21%-70% of the time. When this occurred, a variant of dynamic rating, designated as a net radiation temperature-based (NRT-based) rating, was calculated and used for real-time operations. The NRT-based rating was based on actual ambient temperature, actual solar radiation, and an assumed low wind speed. (5) Further information on NRT-based ratings can be found in Appendix B.

As NYPA also discovered, Oncor found that increased real-time capacity with dynamic ratings was even more pronounced under STE (15-minute exposure) conditions. The study demonstrated that, for short-term emergencies, capacity of at least 10% above the ambient-adjusted rating was available 93% of the time under all load conditions and 98% of the time under moderate load conditions (for load greater than 20% of the static rating). Those increased capacities can be safely deployed within a market structure while ensuring lines will always be operated within their safety limits.

Another significant outcome of Oncor's project was that Oncor successfully transmitted dynamic ratings directly to ERCOT (starting in May 2012) by streaming data into ERCOT through Oncor's EMS. This represents an industry breakthrough, as a real-time data feed of dynamic ratings to a system operator's Security Constrained Economic Dispatch tool had never been implemented before. With Siemens' assistance, Oncor built data validation tools into the EMS so that only valid dynamic ratings were communicated to ERCOT. If the calculated ratings appeared invalid or suspicious, the EMS reverted to ambient-adjusted ratings (or static ratings in the absence of ambient-adjusted ratings) and transmitted those ratings to ERCOT instead. This eliminated the need for ERCOT to interpret dynamic ratings, which facilitated the integration of dynamic ratings at the system operator level. Because the dynamic ratings were integrated into real-time system operations, Oncor refers to its DLR system as an integrated DLR (iDLR) system in its final TPR. (5) Figure 3 illustrates the flow of data between the installation sites, Oncor operations, and ERCOT's Security Constrained Economic Dispatch tool.



Source: Used with permission from Oncor (5)

Figure 3. Oncor's Integrated DLR System

Oncor demonstrated and documented the following key parameters to ensure easier and wider deployment of DLR systems at the regional and national level:

- Demonstrating how installation procedures can be streamlined, including potential improvements on the assembly itself or the installation practices and methodology
- Optimizing the number of monitors required to accurately rate the transmission line, depending on dead-end and insulator type

- Training installation crews on effective installation practices
- Establishing guidelines for the introduction of DLR systems into the grid operations environment and facilitating the real-time streaming of the data to the grid management system, maintaining reliability, security, and economic dispatch
- Evaluating current calibration techniques with a view to improve productivity while maintaining and improving accuracy
- Developing a “best practices” manual for future installations (see Appendix C)

4.3 Observations and Analysis

Generally, dynamic ratings are found to be 5%-25% greater than the static rating. (8) However, the increased real-time capacity observed with dynamic ratings varies tremendously at different locations on the same circuit and on different lines across the service territory. This is due to variations both in the particular line’s characteristics and operating conditions and in the assumptions on which the static ratings are based. Furthermore, Oncor has noted that a transmission owner typically only requires 5%-10% additional capability above the static rating to address most congestion issues. (5)

As previously discussed, Oncor observed capacity increases between 6% and 14% above ambient-adjusted ratings at least 83% of the time. NYPA observed real-time capacity increases between approximately 30% and 44% above the static rating in its demonstration data. It is somewhat difficult to compare the results of the two projects because Oncor monitored entire transmission lines, whereas NYPA monitored transmission line spans. Because Oncor’s dynamic ratings were applied to entire lines, the ratings were “rounded down” to accommodate the span along the line with the lowest real-time capacity. (5) In contrast, NYPA’s dynamic ratings considered the real-time capacities of only one span at a time. (4) Sections along Oncor’s study lines also saw increased real-time capacities as substantial as NYPA’s, but shielding or other factors elsewhere on the line decreased the overall dynamic rating. (7) In addition, Oncor limited its study lines’ real-time capacities to 25% above the static rating due to considerations for the next limiting element in the system, even though greater capacities were sometimes observed (see Appendix B for detailed project data). (5)

Compared with the most commonly observed capacity impacts of DLR deployments, the results of NYPA’s DLR project are atypical and prompt further explanation. The circuits NYPA studied were ideally located in flat, open terrain with minimal shielding and steady, high winds. For instance, although the NYISO’s guidelines for static ratings assume wind speeds of 3 feet per second, the median wind speed at Site 1 was 12.1 feet per second, with winds occasionally reaching more than 23 feet per second. (4) Since wind is the single most influential environmental factor for capacity, these high winds likely contributed significantly to the increased real-time capacity that NYPA observed after the installation of its DLR system.

While the increased real-time capacity noted above is available most of the time, it is not always available. For instance, a line with an average increased real-time capacity of 30% may not have any excess capacity on an especially hot, humid, windless day. These lines did not experience congestion during the study, but even if they had, NYPA may not have been able to fully utilize the excess capacity, as considerations for the next limiting element on the grid likely would have prevented it from doing so. (4)

These results highlight the impact that location has on the outcomes of DLR studies. Both NYPA's and Oncor's test sites were located in relatively open terrain, and all test sites had considerable wind exposure. Had the test sites been shielded from crosswinds—for instance, for a corridor going through a heavily forested area—the results of the projects would have been different. Clearance would have been a more important factor for these two projects, had the study sites been located in more heavily vegetated or more populous areas. Although the general conclusion to be drawn from these projects is that dynamic ratings are associated with greater real-time capacity than static ratings, the outcomes of these projects would not necessarily translate perfectly to other locations throughout the country, or even to other locations along NYPA's or Oncor's respective transmission systems.

While both utilities aimed to transmit dynamic ratings to the system operator in real time, only Oncor was ultimately able to do so. NYPA found that its lines were often too lightly loaded to calculate consistently accurate ratings, so the project was unable to "go live" with the NYISO. However, since Oncor's lines were sufficiently loaded and because Siemens helped Oncor build data validation tools into its EMS, Oncor was able to establish a live data feed directly into ERCOT's Security Constrained Economic Dispatch tool, which automated the integration of dynamic ratings with real-time operations. Thus, heavily utilized lines and automatic validation of DLR calculations can make the real-time integration of dynamic ratings into the operator's control room substantially easier for both the transmission owner and system operators.

5. Lessons Learned

As NYPA's and Oncor's DLR projects were demonstration projects, both projects involved significant learning, and their respective challenges and outcomes were uncertain when the projects were initiated. This section describes the takeaways from NYPA's and Oncor's DLR projects. It highlights ongoing challenges to DLR deployment, including DLR data reliability, cybersecurity, integration into system operations, and verifying DLR systems' financial benefits. This section describes opportunities for DLR technologies and similar methods of monitoring transmission system capacity, such as dynamic ratings for terminal equipment in substations, day-ahead line rating forecasts, improved static rating methodologies, and wind energy integration. Finally, this section briefly describes two projects at NYPA and Oncor that continue to study DLR systems.

5.1. Lessons Learned from NYPA's DLR Demonstration

NYPA discovered that, while dynamic ratings can offer significant benefits to transmission owners, DLR systems are challenging to implement. DLR technologies are reliable, but the learning curve to implement them is significant. A detailed analysis must be performed to determine if a particular line is a good candidate for increased real-time capacity, and the proper instruments must be procured, installed, and maintained. Communication links from the field must be established. NYPA performed an intensive cybersecurity assessment at the outset of the project, which impacted project scheduling and increased overall project costs. Some instruments needed special analysis and modifications to meet NYPA's security criteria. One of the biggest challenges recognized during the project was that the DLR system required an engaged technical team to implement and oversee the entire project. If a transmission owner has a shortage of skilled staff, implementing a DLR project would be challenging. The system requires dedicated effort to ensure that it is providing accurate information to fully utilize the additional real-time capacity identified by the dynamic ratings. (4)

Many of the lessons learned from NYPA's project concern the performance and reliability of the studied DLR devices. Most of NYPA's reliability issues concerned its own communications devices, but all of the DLR devices also experienced reliability issues, especially the EPRI Sensors and Video Sagometers. In most cases, these issues were related to the significant learning curve inherent in deploying a DLR system, rather than to the design or quality of the technologies. The DLR vendors typically responded quickly to reliability issues and resolved them. The availability of the DLR devices throughout the project is shown in Table 12.

Instrument	% Available	% Available Real Time*
Weather station thermometer	99.4	91.6
Weather station anemometer	93.7	90.5
Video Sagometer camera	79.3	69.4
EPRI Sensor	71.9**	69.5
ThermalRate System	85.0	75.9
NYPA SCADA RF Link	75.1	69.5
All data logger communications	N/A	90.3

**   Accounts for availability of communications systems, software, and DTCR server*
*** Available and conductor temperature above 1 °C*

Source: Navigant analysis; data from (4)

Table 12. Availability of NYPA's DLR Devices (All Sites)

NYPA’s data logger communications were available 90.3 percent of the time, on average. However, NYPA experienced a few communications issues, resulting in gaps in the data. Sometimes, these communications issues could be traced to the installation sites, while in other instances, the DTCR server itself caused data interruptions. A DTCR server outage in January 2012 contributed to poor communications availability during that timeframe. Since the DTCR server was not continuously monitored, there was a delay before the server was restarted. The server also went down in June 2012 due to overloaded memory, although future outages were prevented by simply closing and reopening the graphical user interface (GUI) every few days to “clean” the server’s memory. If communications between the DTCR server and the data loggers were interrupted, the data loggers stored the data until communications were restored, at which point they transmitted the data to the server. However, the data loggers overwrote the oldest data, so some data could have been permanently lost during prolonged communications losses. Most of the data affected by communications losses was delayed rather than lost. Most communications losses were short, although there were some prolonged interruptions. (4)

A secondary reliability issue concerns the devices that provide power to the DLR equipment. NYPA employed photovoltaics (PV) to power its DLR devices, but these power sources encountered many difficulties. Wind and snow, which commonly impacted NYPA’s installation sites, were particularly detrimental to the PV panels, and the mounting brackets for the panels broke numerous times. (6) Sometimes, the PV panels were simply not large enough to provide adequate power to the DLR equipment. (8) The PV panels’ backup batteries had short lives, which made emergency site visits to inspect damaged PV panels especially time-sensitive. Although NYPA evaluated alternative power sources, it could not identify a better option than PV panels for remote locations. Thus, the potential reliability concerns associated with using PV panels to power DLR devices remain unresolved. (6) EPRI has stated that it has only experienced issues with PV panels at the NYPA project site and one other site. (8) Other DLR deployments may not experience the same issues with the PV power supply.

NYPA encountered numerous difficulties with its EPRI Sensors. The EPRI Sensors were initially calibrated incorrectly such that they could not record temperatures below 1 degree Celsius. This issue was problematic because the installation sites in northern New York experienced cold winters. As discussed in Section 2.3, conductor temperature-measuring devices (such as the EPRI Sensors) can only be used to determine effective wind speed when the line is sufficiently loaded. In NYPA's experience, 100 amps or more were typically required for the particular sections studied. Throughout NYPA's project, there were virtually no instances in which the line current and/or temperature were high enough to perform rating calculations with the EPRI Sensors, necessitating reliance on other DLR devices and creating gaps in the data that the EPRI Sensors collected. When the EPRI Sensors could not gather data accurate enough for the DTCR software, dynamic rating calculations were performed using EPRI's DynAmp model. (4)

The Video Sagometers were similarly less accurate at low power levels. The Video Sagometers produced "good" data from which ratings could be accurately calculated only about 10% of the time. (4) NYPA determined that a minimum current of approximately 350 amps was necessary to calculate ratings using the Video Sagometers. The line currents rarely exceeded 350 amps throughout the project and virtually never reached 400 amps. Thus, the Video Sagometers could not be used to calculate ratings most of the time. As with the EPRI Sensors, the DynAmp model was used to calculate dynamic ratings when Video Sagometer data was not accurate enough for the DTCR software. (4)

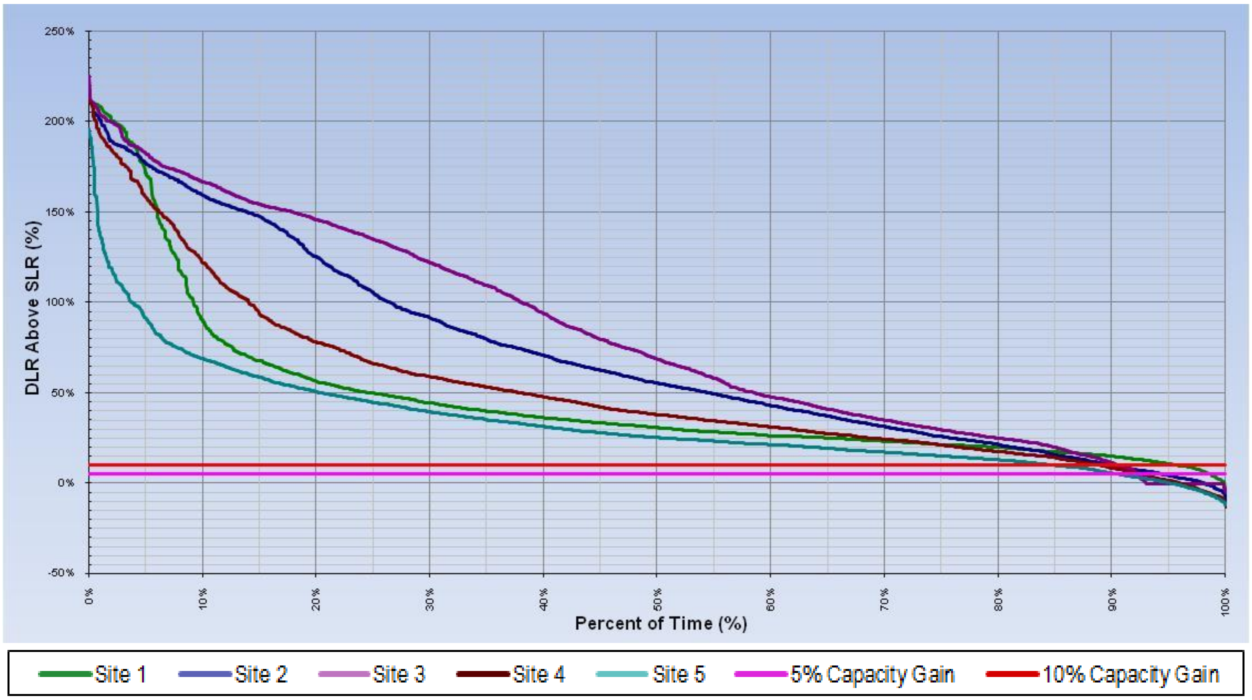
The Video Sagometer is a disadvantageous device for monitoring thermally limited lines because the inherent averaging shields the ability to determine the local conductor "hot sections" in sheltered areas. However, the same device is advantageous on sag-limited lines because it effectively averages the conductor temperature, which determines clearance values. Because many of NYPA's lines are sag-limited, the utility was disappointed that it was unable to properly evaluate the Video Sagometer in this project. (4)

The key lesson learned from NYPA's experiences with bad or missing data is that transmission owners should be aware that conductor temperature-, sag-, or tension-measuring devices cannot accurately monitor lightly loaded lines (i.e., lines carrying loads under 20%-30% of the static rating). A secondary rating method—such as EPRI's DynAmp model or Nexans' NRT-based ratings—should be in place to accommodate periods of light load. (4), (5) Because NYPA's lines were frequently lightly loaded, the devices calculated almost no good ratings for the first year of the project. (4) Consequently, NYPA has revised its selection criteria for potential future DLR deployment sites: whereas NYPA initially selected lines based on their proximity to wind farms (i.e., exposure to high winds), NYPA now believes lines should be selected based on typical load levels, as DLR technologies can be most impactful on heavily utilized lines. (6)

5.2 Lessons Learned from Oncor's DLR Demonstration

Oncor's project revealed many lessons that can be used to immediately address issues with deploying DLR technologies, as well as future extensions of the technology to a broader spectrum of users and applications. First, the project revealed that system characteristics are not static. Oncor learned that congestion is extremely difficult to predict and is driven primarily by market forces, not system outages. (7) Congestion is sometimes chronic, but it is often sporadic and highly volatile. Surprisingly, the lines originally selected for the project, which had been identified for their significant congestion, demonstrated minimal congestion during the project. Fundamental changes to ERCOT's transmission system (i.e., the transition from zonal to nodal pricing) and new generation, retired generation, and new or upgraded transmission lines altered the flow of energy across the grid in the project area. (5) DLR systems can effectively mitigate congestion when applied to appropriate target lines.

Each transmission line is unique, so the outcomes of a DLR system on one line cannot be applied to a different line, no matter how similar the two lines are. This lesson is illustrated in Figure 4; note that, although all 345 kV sites follow a similar general trajectory in terms of released capacity, no two lines have the same characteristics. (5) Oncor has noticed that additional real-time capacity is often available when it is not necessarily needed; however, when operators are scrambling for additional capacity, it is often unavailable. (7) Because system characteristics, especially congestion, are difficult to predict, a DLR system can be a responsive tool to resolve a situation that has a time reference of unknown length but is likely short- rather than long-term (i.e., greater than three to four years). DLR devices are flexible and can be relocated to different lines as congestion trends change. (5)



Source: Used with permission from Oncor (5)

Figure 4. Yearly Cumulative Probability Distribution: Dynamic Rating 20% or Greater than Static Rating, All 345 kV Segments (August 2011–July 2012)

As-built characteristics of the transmission line can be significantly different from the construction plan. Exact structure locations, structure framing, ground-to-line profile, and the exact conductor stringing parameters when the conductor is tensioned and clipped in all impact the true conductor catenary. The most important aspect of this characterization is the direct association of the sag-tension-temperature correlation of the conductor. The state-change relationship is set at stringing and is generally only modeled by software. The assignment of the conductor temperature to a specific sag and tension is critical to all modeling and monitoring of the conductor behavior. (5)

Nexans' CAT-1 System requires an accurate real-time data feed of the line current in each CAT-1 location. (5) Difficulties with the data feed arose on several of the 138 kV lines in Oncor's project, where some of the substation terminals were owned by neighboring utilities and not by Oncor. The communication of the real-time data was not timely enough to satisfy the algorithm's needs, so the algorithm could not accurately determine the line's state. In another case, there were several unmetered taps off of the transmission line that prevented access to the accurate load flow in adjacent line sections. The result was invalid load metering on these 138 kV lines, which generated erroneously low calculated dynamic ratings. The takeaway is that an incorporated line current-sensing device or additional line metering is needed to completely utilize the DLR technologies' capability. (5) Invalid load metering on the 138 kV lines is discussed in Table B-30 in Appendix B.

Oncor did not experience any major communications interruptions. However, Oncor found that radio path analyses needed to be conducted prior to installation to ensure that the CAT-1 devices could communicate on clear radio pathways. Rarely, certain structures or features of the installation sites blocked radio paths, preventing adequate radio communication. These analyses helped determine optimal equipment placement and prevented gaps in data collection. (5)

Oncor discovered that many Automated Meter Systems (AMS) communicated via the same radio frequency that the DLR system used, which occasionally created radio interference and complicated data transfer. Oncor's solution to this communications issue was to alter the antenna layout to improve separation between the DLR system and AMS. However, careful and diligent testing was required to ensure the antenna placement was able to overcome interference in this increasingly utilized radio frequency range. (5) Oncor noted that this issue was not as prevalent on lower-voltage lines, such as 138 kV lines. (7)

Oncor experienced a slight complication with the CAT-1 instrumentation itself. After several months of operation, degradation in the CAT-1 device signal from the load cell to the CAT-1 motherboard was identified on the 345 kV installations due to the "floating dead-end" load cell configuration. Upon examination, Oncor found that spark discharges from individual insulator caps were causing the signal wire sheath to degrade, resulting in moisture ingress and signal attenuation. The CAT-1 devices and their signal wires were replaced, and the insulator assemblies were modified so that each insulator cap and pin was grounded, with the signal wire routed through a piece of PVC conduit to mitigate any electrical discharges between the metal parts of the insulators. This was completed in July 2011. Oncor did not experience any other reliability issues with its DLR devices; the few data interruptions Oncor experienced were most often caused by Oncor's own internal equipment or commercial communication tie-lines, rather than by the DLR devices. (5) Additional minor complications with data collection and measurement are described in Table B-30 in Appendix B.

Another lesson learned from Oncor's project is the difficulty of quantifying the real-time financial benefits of DLR systems, particularly as they relate to congestion mitigation. ERCOT uses its Security Constrained Economic Dispatch tool to identify congestion in real time. The Security Constrained Economic Dispatch tool cannot run simultaneously with and without a dynamic rating in place of the static rating, so although it was clear to ERCOT that real-time capacity increased with dynamic ratings, it was uncertain how the DLR system specifically impacted congestion. Therefore, capacity increases were calculated for Oncor's SGDP project by performing "what-if" scenarios using the day-ahead market analysis tool. In this analysis, Oncor determined that 5% additional capacity could relieve congestion by up to 60% on the target lines with DLR installed, while 10% additional capacity would practically eliminate all congestion on the target lines. (5) Oncor demonstrated that congestion relief is possible with a DLR system, and its range of impact is measureable.

Finally, Oncor developed a "best practices" guide to expedite the future implementation of DLR technologies by other transmission owners throughout the United States. Oncor's "best practices" guide walks transmission owners through the process of planning and carrying out a DLR deployment. In addition to general guidance on installation site selection, cybersecurity considerations, and integration of the DLR system with the operator's control room, Oncor offers guidance on several aspects of a DLR deployment, based on conclusions that the utility drew from its SGDP project experience:

- The need to monitor the entire transmission line rather than a few "critical spans"
- The benefits of a "total-system" approach to DLR integration, which considers the next limiting element on the grid and the role of the DLR system in the greater context of grid operations (i.e., maintains a safe operating range of the relay protection settings on the line)
- The reality that, while a DLR system can increase ratings by as much as twofold on a line, the "usable" range of increased capacity is between an 5% and 30% above the static rating, depending on the probability that the increased capacity is available
- The superiority of utilizing dynamic ratings in real-time operations, which fully captures the technology's benefits in terms of increased Wide-Area Situational Awareness (WASA) and improved grid reliability and flexibility, rather than in planning studies, which focus on the probability that a rating is available a certain percentage of the time

An adaptation of Oncor's "best practices" guide appears in Appendix C of this report. The full "best practices" guide can be found in Section 5 of Oncor's final TPR.

Overall, Oncor documented a high degree of commercial readiness and technological maturity for the DLR technologies it deployed. Oncor demonstrated that these technologies are highly reliable, flexible, and can be fully and automatically integrated with the transmission owner's and system operator's control systems. (7)

5.3 Potential Challenges and Opportunities for DLR Systems

These SGDP projects revealed several potential challenges associated with DLR technologies, as well as some key opportunities. Major challenges and opportunities are discussed in the following two sections.

5.3.1 Challenges

NYPA's and Oncor's DLR projects revealed several potential challenges to the wide-scale implementation of DLR systems, such as ensuring the reliability of DLR data, preemptively addressing cybersecurity concerns, integrating dynamic ratings into system operations, and verifying the financial benefits of DLR systems to system operators and transmission owners. Each of these challenges is discussed below.

5.3.1.1 Reliability of DLR Data

DLR data reliability remains a concern in implementing DLR systems, as demonstrated in NYPA's project. There are two outstanding challenges that must be considered when a DLR system is installed to ensure good data collection and DLR calculation. First, transmission owners must be cognizant of certain DLR devices' limitations on lightly loaded lines. As previously discussed, effective wind speed—and, therefore, the dynamic rating—cannot be accurately determined when lines are lightly loaded. Second, transmission owners should be aware that the "as-built" characteristics of a transmission line are often different from its design. DLR devices that measure sag or tension require a state-change equation in order to calculate conductor temperature, effective wind speed, and dynamic ratings. Since this equation is based on "as-built" characteristics, performing this calculation can be difficult, especially if the line's characteristics differ significantly from its design. Nexans' CAT-1 System simplifies the "as-built" task by automatically establishing an accurate "as-built" relationship between tension and average conductor temperature, requiring no additional effort from the transmission owner. (7) For other technologies, careful measurement and inspection of the line is required to determine the difference between design and field construction.

DLR systems require a stream of input data from sensors in order for dynamic ratings to be continuously available. The DLR software must be up and running on a server and in constant communication with the data sources in order to provide real-time data. NYPA discovered that it is challenging to maintain this hardware and software with no gaps in coverage. Given the present state of DLR technologies, NYPA believes that this challenge makes a "compelling case" for using multiple, redundant DLR devices in order to produce reliable information on dynamic ratings at all times. (4) NYPA found that it often needed to rely on its weather stations for wind measurements when its EPRI Sensors and Video Sagometers were unable to determine effective wind speed (4)

One concern is how to troubleshoot periods of “bad” or missing data. NYPA discovered that it usually needed to send a technician into the field to assess the cause of interrupted data streams, as it was not clear from the control room whether low load levels, DLR instrument malfunction, or communications issues caused “holes” in the data at a given time. NYPA considers remote knowledge of the equipment status an ongoing challenge in implementing a DLR system. (6) As discussed in Sections 5.1 and 5.2, communications interruptions can result in periods of missing data. Many of these issues, such as ensuring that radio frequency paths are clear and server memories do not become overloaded, can be preemptively addressed. Other issues, such as server outages or loss of the PV panels powering DLR devices, must be resolved as they arise.

In contrast to NYPA’s findings, Oncor's project found the DLR data to be highly reliable and accurate. The automated data validation tools built into Oncor’s DLR system made the system self-healing and self-correcting for any gaps or data issues. As a result, Oncor ensured the reliability of the ratings delivered to ERCOT’s Security Constrained Economic Dispatch tool. (5)

Ensuring the reliability of DLR data entering the system operator’s control room and its economic dispatch tool is critical. Data validation measures are an essential component of every DLR system deployed for practical use.

5.3.1.2 Cybersecurity

Cybersecurity is a concern in the integration of DLR technologies into system operations. Both NYPA and Oncor conducted cybersecurity assessments at the outset of their respective SGDP projects. Although Oncor’s cybersecurity assessment did not impact the project schedule, NYPA found that performing such an assessment was time-consuming and expensive. Nevertheless, NYPA agreed that such an assessment was necessary, as the DLR data stream creates a direct communication route into the control room. (7), (6)

With SwRI’s assistance, Oncor assessed the cybersecurity of the integration of the CAT-1 devices and the communications devices that transmitted field data to the IntelliCAT™ server. The cybersecurity assessment was mainly performed as an integral part of Oncor’s development of the demonstration project, not to evaluate the security of the devices applied during the project. The principal objective of the assessment was to validate that the proposed demonstration technology would not create an increased cybersecurity risk for the systems in which it would operate. For security reasons, Oncor did not document the results of penetration testing, including vulnerabilities and alternate configurations, if any, in its final TPR. However, Oncor does identify some of the issues to consider when integrating DLR technologies into a transmission company's existing security protocols. These items encompass the entire lifecycle of the DLR system, from procurement and installation to operation and retirement. (5) Oncor concluded that performing the cybersecurity assessment did not pose significant challenges, although it was nevertheless advisable. (7) Oncor's cybersecurity recommendations are discussed in Appendix C.

5.3.1.3 Integration into System Operations

Control room acceptance of DLR data and the operators' decision to apply the data remain critical issues. Both the NYISO and ERCOT, the system operators impacted by the DLR demonstrations, embraced DLR systems and were willing to take on its associated challenges and risks. (6), (5) Oncor is confident that future DLR systems can be deployed on a broader scale and believes that integrating dynamic ratings into system operations would not be difficult in future DLR deployments, as long as the DLR system interfaces seamlessly with the system operator's Security Constrained Economic Dispatch model. (7) If a DLR system cannot achieve this degree of integration, then retraining system operators to rely on dynamic ratings and creating an appropriate interface through which they can observe and utilize those ratings may remain significant barriers to wide-scale implementation.

As NYPA discovered, the learning curve for navigating DLR systems is steep. (4) Integrating dynamic ratings into the operator's control room is a potentially daunting task, especially since operators need to make contract commitments and allow maintenance outages. (9) Many system operators may not be enthusiastic about embracing the challenges of DLR technologies, especially since reducing system congestion is not as high a priority for them as simply maintaining reliability. Furthermore, transmission lines in certain regions may be lightly loaded so frequently that a system operator may not regard dynamic ratings as useful, except during contingencies. (8) In other cases, as in NYPA's case, the system operator may be willing to take on the challenges of dynamic ratings, but the dynamic ratings themselves may not be accurate enough for real-time integration into system operations. Because of these barriers, it is imperative that DLR data is reliable and accurate when it enters the control room, as confidence erosion is damaging, if not fatal, to DLR deployment success. (5)

Uncertainty remains regarding how a transmission owner can best integrate DLR technologies into system planning, engineering, and operations. One option is that a team of devoted engineers would oversee the DLR software and server, another option is to outsource the software to a third party, and a third approach is to integrate the DLR system directly into system operations.

Since the DLR software itself resides on a remote server, it is possible to house the server in an engineering office, with a responsible engineer or team of engineers at the transmission owner or system operator to oversee the DLR software. NYPA believes that this solution is advantageous because of its simplicity, especially if the owner's transmission lines operate at low power levels. If a transmission owner's engineering team oversaw the DLR system, the operations team would not have to struggle with an unfamiliar system that may be rarely needed. Operations would only need to communicate with engineering when dynamic ratings are needed, and engineering would be able to help operations understand the results. Engineering must be involved in the implementation of a DLR system to ensure that the equipment is maintained and functional and that the performance of the DLR system is reliable. (4)

A similar approach is to leave control of the DLR system in the hands of another team—perhaps the DLR system developer—that would fulfill the engineering needs discussed above. For instance, EPRI is executing a project in which EPRI is performing DLR calculations and then is forwarding them to the transmission owner nearly in real time. An advantage of this solution is that a more specialized team could have more in-depth knowledge of the technology and would not need to learn to use and interpret the DLR system. (4)

A more cohesive approach would be to integrate the DLR system directly into system operations. In this scenario, the server imports real-time data from either inside the SCADA system (such as load from the EMS or other instrument data directly tied to the SCADA system) or from outside the SCADA system (such as the data from the instruments tested during the NYPA project). The server would then export the relevant data back into the SCADA system, where the results could be viewed anywhere that a SCADA interface is made available (such as in the system operators' control room). The server would archive all the data for future analysis (such as for engineering analysis and system planning). (4) This approach is the most integrated, but it may be the most challenging, especially if loads are frequently light. NYPA noted that the NYISO was enthusiastic about this approach, as a direct EMS feed would be more flexible and less complicated than adding another terminal to the system operator's control room. (6) It is significant that this approach was deployed successfully in Oncor's project. Siemens assisted Oncor in integrating the DLR data feed into its EMS and in establishing data validation methods whereby only valid ratings would be transmitted to ERCOT. (5)

Similarly, the DLR system could function as an "alarm system" in the operator's control room. In this case, the line would have an elevated static rating, and the DLR system would track both the dynamic rating and load (either the actual load or the post-contingency load output projected by the system operator's security analysis tool). The trends in dynamic rating and load would be projected, and when the projection indicates that the two trends could converge in 15 minutes, an alarm would be triggered to alert the operator. The operator could then respond as he deems appropriate. Responses might include re-dispatching the system or formulating a remedial action plan that could be utilized should a contingency event actually occur. (5) This approach may be advantageous for lightly-loaded lines that may not require constant monitoring.

Oncor recognized the same issues about how to interface the DLR data with day-to-day operations. To preemptively resolve issues of control room acceptance, Oncor requested that the DLR system be fully integrated into the background operation of ERCOT's EMS, where data validation tools determined the quality and reliability of DLR data in real time. DLR data was posted to the telemetry database for use in both Oncor's and ERCOT's state estimator models. When the data validation tool indicated issues with the availability or reliability of dynamic ratings, alerts were sent to a service desk to be addressed and resolved, rather than burdening system operators or dispatch personnel with resolving such issues.

5.3.1.4 Verifying a DLR System's Financial Benefits

Verifying the financial benefits of DLR systems remains one of the biggest challenges transmission owners that seek to implement DLR technologies will face. This challenge is twofold: quantifying the financial benefits of DLR technologies to the grid is a key challenge, but verifying the financial benefits to transmission owners themselves is also a potential issue. (5)

The biggest challenge is verifying the actual financial benefits of DLR systems to the transmission grid and the system operators. As previously discussed, it may be difficult to persuade system operators that dynamic ratings would be financially beneficial to them. The capacity gained by dynamic ratings can be quantified, and the availability and reliability of the technology and instrumentation can be measured. However, the economic benefit in real time is difficult to assess, especially as it relates to congestion mitigation. This is because system operators are not presently able to perform real-time "what-if" scenarios of economic benefits with and without dynamic ratings; either dynamic or static ratings, not both, may be used in operations at a given time. (5)

Quantifying the value of reliability improvements is similarly difficult, as their financial value is relatively intangible. (5) Nevertheless, the reliability benefits are significant. By facilitating access to increased transmission line capacity, DLR systems provide additional flexibility to the system, allowing the grid to meet both static and transient transfer demands. The more flexible the grid is, the better the system can respond to market- and outage-driven conditions. Increased capacity also maintains an operating margin for meeting grid performance requirements. (7)

Furthermore, the congestion of transmission lines is so volatile and transient that it is difficult to compare current and historical grid operations and congestion costs, whether the analysis spans year to year or day to day. Predicting future grid capabilities is even more challenging. Oncor's project, for example, showed that congestion is very sporadic and volatile and that it is difficult to predict grid behavior for real-time assessment of the benefits of DLR technologies. As previously discussed, Oncor was able to approximate "with DLR" and "without DLR" scenarios by running comparative models in the day-ahead market analysis, with ERCOT's assistance. Based on 2012 congestion levels and costs, Oncor extrapolated that the total congestion impact savings potential resulting from an ERCOT-wide DLR deployment[10] would amount to approximately $20 million, a 3% reduction. (5) However, it is clearly difficult to predict the economic outcomes of DLR systems, particularly as they relate to congestion, because grid capabilities and congestion are so difficult to predict.

A secondary challenge is verifying the financial benefits of DLR technologies to the transmission owner. Educating transmission owners about the benefits of DLR systems is critical to facilitating wide-scale DLR deployment, since many transmission owners may instinctively prefer the comfort of familiar, but more expensive, transmission system upgrades to implementing DLR technologies. (2) It is not challenging to calculate the cost savings that DLR systems unlock as more extensive capital investments are deferred. For instance, Table 13 compares different approaches to increasing ratings through line rebuilds, reconductorings, and DLR installations. Notice that installing DLR systems is often only a fraction of the cost of other solutions (although the increase in capacity is less than with other transmission upgrades).

[10] For the purposes of the study, Oncor assumed that approximately one-twentieth of the lines in ERCOT were instrumented with DLR technologies.

Line Type	Alternative Description	New Rating (% Static)	Cost per Mile
138 kV Lattice, Wood H-Frame	Reconductor Aluminum Conductor Composite Core (ACCC) cable	193%	$321,851
	DLR	110%	$56,200
138 kV Wood H-Frame	Rerate 125 °C Modify structures	130%	$10,561
	Rerate 125 °C Replace structures Rebuild	130% 209%	$6,919 $750,000
	DLR	110%	$29,471
138 kV Wood H-frame	Rebuild	140%	$237,871
	DLR	110%	$16,767
138 kV Wood H-Frame	Reconductor	212%	$750,000
	DLR	110%	$28,323
345 kV Lattice Tower	Raise structure heights	120%	$73,600
	DLR	110%	$26,626

Source: Navigant analysis; data from (5)

Table 13. Alternative Solutions

Verifying the financial returns of DLR projects is complex. The standard return on equity (ROE) for a DLR investment could be minimal, since the transmission company does not directly share the reduction in congestion cost and because the cost of the DLR system can be recouped in a short period of time (typically a few months). If DLR technology is used to solve a capacity problem, when needed, then the benefit may be difficult to quantify, especially if the only avenue for cost recovery is through a rate proceeding. Although federal regulators understand the value of DLR technologies, some state regulators may not have confidence in their potential benefits. If a transmission owner is not collecting the full, allowed ROE for reasons such as regulatory lag or unanticipated derates, DLR systems can provide an avenue to restore the missing ROE. (5)

The Federal Energy Regulatory Commission (FERC) recognizes that DLR technologies can be valuable additions to the grid. FERC is encouraging transmission owners to consider deploying DLR technologies on their transmission systems, both indirectly through FERC Order 1000 and directly through a recent Policy Statement (141 FERC ¶ 61,129). FERC Order 1000 supports DLR deployment by advising transmission owners to pursue “more efficient and cost-effective investment decisions” when upgrading their transmission systems; since DLR technology is significantly less expensive than other transmission system upgrades, FERC Order 1000 indirectly encourages transmission owners to pursue DLR deployment.[11] More recently, FERC explicitly contemplated the use of DLR technologies as a consideration for incentive ROEs.[12]

It is important to realize that a transmission company's ROE is often based on its capital expenditures. In many cases, therefore, a transmission owner may prefer to construct new transmission lines rather than improve the utilization of existing lines, in order to capture a greater return. DLR systems are a useful decision-making tool for capital planning and are particularly beneficial for capital-strapped transmission companies that must choose their capital investments wisely. However, DLR investments' contribution to overall ROE may be minimal or difficult to quantify.

5.3.2 Opportunities

The two DLR demonstrations helped identify several key opportunities for DLR technologies, such as potential applications for following a least-regrets capital investment strategy, calculating ratings for terminal equipment in substations based on real-time ambient temperature data, forecasting day-ahead dynamic ratings, improving transmission line rating methodologies at an operational level, and facilitating the integration of remotely sited wind generation. These five opportunities are discussed below.

5.3.2.1 Enabling a Least-Regrets Capital Investment Strategy

DLR systems deliver flexibility that supports the development of a transmission owner's least-regrets capital deployment strategy. DLR systems and physical upgrades to the grid complement rather than compete with each other. Justification of a capital expenditure for a physical upgrade to the grid typically requires a demand for at least 30% additional capacity. A capital expenditure for DLR systems is justified for smaller capacity needs (less than 30% additional capacity). Together, physical upgrades and DLR systems provide a broad range of solutions for transmission upgrades. When both large and small capacity deficiencies are addressed, the grid is more resilient and reliable, providing flexibility during contingencies (7)

The additional capacity that DLR systems release facilitates the construction of physical upgrades. Additional capacity makes it easier for a transmission owner to obtain outages for

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[11] 136 FERC ¶ 61,051, "Transmission Planning and Cost Allocation by Transmission Owning and Operating Public Utilities," July 21, 2011, at p.2

[12] 141 FERC ¶ 61,129, "Promoting Transmission Investment Through Pricing Reform," November 15, 2012, at p. 21

construction, prevent outages from being cancelled, and extend the construction and maintenance seasons. (7)

Even if synergies with physical upgrades are ignored, DLR systems provide capital spending flexibility in themselves. With rapidly changing generation and load patterns, deployed capital faces increasing uncertainty of earning revenue based on megawatt-hour flows. DLR systems can be easily removed and relocated if the capacity demand fails to materialize, disappears, or is needed only temporarily, thereby precluding stranded assets. DLR systems can be deployed in a matter of months and are installed on existing transmission structures. They can be capitalized like a physical transmission upgrade, and they avoid the delays and costs of siting in environmentally sensitive urban, suburban, or relatively open areas. Because the capacity added through DLR systems is both inexpensive and timely, DLR deployments directly impact grid reliability and the satisfaction of generators, load serving entities, and regulatory agencies. (7)

5.3.2.2 Rating Methodologies for Terminal Equipment in Substations

In most cases, substation terminal equipment—particularly current transformers—are the limiting factors for line ratings. Much like overhead lines, current transformers are known to have significantly higher power capacities than specified by their nameplate ratings. Unlike overhead lines, however, terminal equipment is impacted primarily by ambient temperature, with minimal wind and solar radiation effects. Monitoring substation terminal equipment may be another approach to monitoring transmission system conditions. (4) In fact, monitoring this equipment may be a necessary extension of a DLR deployment. (7) Some transmission owners use ambient-adjusted ratings for substation terminal equipment, while others rely exclusively on static ratings. More recently, some transmission owners are assigning ambient-adjusted ratings for terminal equipment based on real-time ambient temperature data, with fixed assumptions for other variables. (8) Ambient-adjusted ratings for terminal equipment that account for real-time temperature data may become more widespread and easier to implement in the future.

EPRI's DTCR software is capable of calculating ratings based on real-time ambient temperatures for terminal equipment and power transformers. EPRI has begun to develop thermal modeling data for some terminal equipment, such as switches, line traps, and current transformers. In particular, an EPRI project is being organized to model current transformer ratings. EPRI is launching a collaborative project to study current transformer ratings with the goal of defining methodologies to better rate these devices. The project will include laboratory tests of selected samples, including special units fabricated for the project, and forensic analysis. (4)

5.3.2.3 Day-Ahead Rating Forecasts

Dynamic ratings often prompt the question of whether line ratings can be forecasted for different future periods. Short-term (15 minutes to two hours ahead) or near-term (six to eight hours ahead) forecasts are appealing for day-of operations, while day-ahead forecasts could be used to plan markets a day in advance. Many markets already set ambient-adjusted ratings for transmission lines and substation equipment a day in advance, but effective wind speed—which impacts real-time capacity much more significantly than ambient temperature—is not presently incorporated into these ratings.

EPRI and Nexans are exploring rating forecasts in detail. EPRI is in the process of developing a methodology for forecasting effective wind speed, which could be used to forecast day-ahead ratings. (8) Nexans has already developed a capacity forecast engine. Although the capacity forecast engine has not yet been demonstrated in the United States, it was deployed successfully on a pilot project in southeastern France between 2009 and 2010. (17)

In EPRI's experience, forecasted ratings may be more valuable to the system operator than live dynamic ratings, particularly in power systems that do not experience heavy load or significant congestion. While real-time ratings are valuable to the system operator during ongoing contingencies, capacity forecasts could help the system operator avoid contingencies by allowing them to plan dispatch accordingly. (8)

Forecasting ambient temperature and solar radiation is not difficult, but predicting wind speed is a challenge, especially since wind speeds at a specific line location depend heavily on shielding and other factors. EPRI is gathering statistics on wind speed, along with temperature and solar intensity measurements, to forecast wind based on probability and statistical evidence. By extension, forecasted wind conditions would enable EPRI to forecast dynamic ratings. Forecasted ratings would need to be somewhat conservative; for a given forecast capacity probability distribution, the L1, L2, or L5 ratings would be the best candidates for a forecasted rating that system operators could safely utilize. Despite their relative conservatism, these ratings would be more precise than static ratings. (8)

Using forecasted wind conditions to forecast line ratings has two advantages: wind is highly influential on line capacity, and wind-based capacity forecasts are not impacted by line loading. However, forecasted wind conditions and dynamic ratings would be heavily line-dependent, so extensive initial study and data collection—likely involving DLR technologies—would be required. EPRI has expressed confidence in its efforts to forecast wind and calls the prospect of forecasting day-ahead ratings "very promising." (8)

Nexans has developed methodologies to provide accurate, operationally useful predictions of dynamic ratings for day-ahead and day-of markets and operations. Nexans tested multiple forecast algorithms on a 225 kV line in southeastern France. The line was owned by Réseau de Transport d'Électricité (RTE), the transmission system operator in France. Nexans developed forecasts for the day-ahead market and updated these predictions at 15-minute intervals during day-of operations. Nexans' forecasts demonstrated low error (2%-3%) and high usability (97%-98%), with a configurable confidence interval. Besides the benefits of traditional DLR systems, Nexans found that rating forecasts allow for even greater grid flexibility, enabling operators to avoid unnecessary or uneconomical dispatch and reduce locational marginal prices (LMPs) and day-ahead congestion. (17)

5.3.2.4 Improving Static Line Rating Methodologies at an Operational Level

EPRI has hypothesized that dynamic ratings are often more useful to system operators for diurnal or seasonal planning and studies than for streaming dynamic ratings. (8) DLR systems can help define better approaches to setting static ratings, since DLR systems help transmission owners and system operators understand the nuances of how particular lines operate.

As a result of NYPA's SGDP project, other opportunities for improving transmission line ratings at NYPA have been identified. A significant amount of data was collected and archived during the project. This vast collection of data could form the basis of an analytical study to define an improved approach to setting reliable and safe static ratings for transmission lines. (4)

According to CIGRÉ Technical Brochure 299, the line rating conditions in use in the NYISO, which include an effective wind speed of 3 feet per second and a summer air temperature of 35 degrees Celsius, need to be justified by field studies similar to NYPA's SGDP project. The data analyzed in NYPA's project suggest that these conditions are justified in the NYISO transmission system. In future upgrades of the NERC Reliability Standards FAC-008 and FAC-009, it is conceivable that a statistical analysis of line rating weather conditions may be required in addition to the specification of an industry standard heat balance method and reasonable maximum allowable conductor temperatures. NYPA believes that additional, somewhat simplified studies of other, lower-voltage NYPA lines in more sheltered areas would be useful for transmission planning purposes. (4)

Oncor also gained insight into static line rating methodologies through its SGDP project. Oncor suggests that DLR systems can be useful for adjusting static ratings to meet load growth. Most load growth in Oncor's grid is gradual and can be foreseen a year or more in advance, thus creating ideal conditions for capitalizing on DLR technology's rapid (90-day) deployment and low capital utilization. As the need for additional capacity becomes apparent, DLR systems can be deployed on the target lines (usually 9-12 months in advance). That provides sufficient time to gain a clear understanding of exactly where the new higher static rating should be set. Plans for physical upgrades to the lines can then be scheduled in keeping with the transmission company's least-regrets capital spending strategy. (5)

5.3.2.5 Integration of Wind Energy

While NYPA and Oncor sought to relieve system congestion through their SGDP projects, both companies were also interested in examining DLR technologies' impact on wind generation, particularly for resources sited in remote locations. NYPA chose to examine the correlations between wind farm output and dynamic rating and between wind farm output and line loading. (4) Oncor performed analyses to determine the relative increase in wind generation when the study lines' real-time capacities increased. (5)

NYPA's study sites were located near of two wind farms, Ryan Wind Farm and Dudley Wind Farm. Ryan Wind Farm has a greater impact on loads on the two lines rated in this project than Dudley Wind Farm due to the latter farm's smaller size and the relative locations on the system, although the output of both farms impacted power flow and, therefore, line loading. (4)

NYPA found a positive correlation between wind farm output and dynamic ratings, with correlation coefficients in the range of 0.373 to 0.462 for normal conditions across the three study sites. Although these correlations are moderate, the minimum and maximum data retain a consistent slope with the overall trend on a chart of wind farm output and ratings. The correlation between wind farm output and line load was 0.629 at Site 1 and -0.233 at Sites 2 and 3. The weak negative correlation at Sites 2 and 3 indicates that wind farm output may supplant load normally flowing over Sites 2 and 3 in the typical dispatch situations encountered in this study. The conclusion to be drawn from these results is that wind farm output is correlated with dynamic ratings and with load, at least when the lines are geographically close to and experience similar weather conditions to wind farms, as was the case in NYPA's project. (4)

Texas has experienced significant growth in wind generation, so the subject of DLR technology's role in wind integration was of interest to Oncor. In Texas, the majority of wind generation is located in sparsely populated West Texas, and the energy generated must be delivered across half the width of the state on a historically congested transmission system to reach more densely populated areas. Oncor performed analyses to determine the "shift factors" directed toward wind generation when the study lines' capacities increased, using ERCOT's Security Constrained Economic Dispatch tool. For twelve days of data (one data day for each month, encompassing one year of the study), Oncor extracted the shift factors that were directed strictly at wind generation, using the U.S. Environmental Protection Agency's (EPA) eGrid database. To resolve the fact that a large amount of wind generation had been added in Texas since the last update to eGrid in 2007, Oncor's custom mapping file matched new wind generation plants to an existing wind plant in eGrid since the emissions values would remain the same (i.e., zero). (5)

The net result of Oncor's analysis shows that there was an increased shift toward wind generators when dynamic ratings were applied to the studied transmission lines. The net increase in wind was 3% for the year. Only three of the study lines were located in the wind zone, so this potential increase was significant. While this data is not definitive since its sample size is limited, it is significant in the fact that ERCOT's Security Constrained Economic Dispatch tool appears to utilize the increased line capacity to recommend generation shifts to more wind production. A more thorough study, one that analyzes distinct lines involved in wind generation input to the grid and contains more days of data, could be conducted to verify these results. Based on Oncor's observation of a potential increase in wind generation in conjunction with DLR technology, Oncor expects that a reduction in greenhouse gas emissions could be achieved through DLR systems. (5)

While neither project generated definitive data on the role of DLR systems in wind production, both observed positive synergies between DLR systems and wind generation. Installing DLR technology on lines connected to wind farms would allow transmission owners to capitalize on the real-time capacity increase caused by windy operating conditions (to the extent that the next limiting element on the grid allows), in the sense that the dynamic rating confirms increased real-time capacity during periods of increased wind activity, enabling generation owners to increase wind farm output and bolster overall wind production. Thus, DLR systems have the potential to facilitate the integration of wind generation, particularly for wind farms sited in remote locations.

The geographic location of a DLR system and its proximity to wind generation plays a significant role in the potential of the DLR system to integrate wind generation. Northern New York and Texas have considerable wind potential, and Texas has substantial wind generation resources. DLR systems in these transmission systems could have a more significant impact on wind generation being transmitted on the grid than in areas with lower wind potential, where wind generation is necessarily small scale.

5.4 Ongoing Projects

NYPA and Oncor are undertaking two follow-on DLR deployments. Both projects are deploying Nexans' CAT-1 tension-monitoring system. (6), (7)

5.4.1 NYPA's Grant from NYSERDA

NYSERDA awarded NYPA a grant to install Nexans' CAT-1 System on transmission lines in central New York to optimize power flow. NYSERDA is supporting half the funding for the $1 million project, leaving internal NYPA funding responsible for the remainder of the project costs. NYPA selected lines on which it felt a DLR system would have the most significant impact (i.e., lines that are frequently heavily loaded) for CAT-1 installation. The project is meant to provide a baseline assessment to examine potential synergies between DLR data and phasor measurement unit (PMU) data.[13] NYPA estimates that project installation will be complete in mid-2014. (6)

5.4.2 Oncor's West Texas DLR Project

Oncor undertook a second DLR project, the West Texas DLR Project, in early 2013 to relieve congestion around Odessa, Texas. The region around Odessa has experienced 20% load growth over the past three years, driven by increased hydraulic fracturing ("fracking") and conventional oil drilling. Oncor's system planning had proceeded with capital expenditures to add lines and reconductor existing lines to meet new congestion issues and capacity needs. Since the lead times for these projects extended beyond the summer 2013 high-load period, Oncor selected five lines, almost all of which are 138 kV lines, for DLR system installation:

- Odessa–Odessa North (4 DLR units)
- Moss–Amoco Cowden North (3 DLR units)
- Holt–Emma Tap[14] (1 DLR unit)
- Moss–Odessa Southwest–Odessa EHV (3 DLR units)
- Midland East–Winwood (1 DLR unit)

These lines were selected because they are often heavily loaded (approximately 70% of the static rating) and frequently experience congestion, as they are often relied upon to mitigate

[13] As discussed in Section 1.2.1, transmission lines may be limited by voltage or stability constraints, in addition to thermal considerations. Just as DLR technologies monitor thermal constraints, PMUs address voltage and stability constraints. The two technologies may achieve synergies to further optimize dispatch and grid reliability.

[14] Holt–Emma Tap is the only 69 kV transmission line in this project; the other lines are 138 kV lines. (7)

congestion elsewhere on the grid by diverting power from higher-voltage lines. The implementation of this project has been smooth and fast-paced. The West Texas DLR Project was initiated in January 2013 and became operational (including live streaming to ERCOT's control room) in June 2013. For this project, Oncor has continued using the CAT-1 System. Oncor is collecting NERC Compliance Program validation data in conjunction with this project. (7) Additional lines for DLR deployment are under assessment, based on planning needs and congestion exposure during the rest of 2013. (5)

5.5 Conclusion

The transmission system must become more flexible as new renewable and natural gas generation enters the grid. (18) To increase flexibility, many transmission owners follow "least-regrets" planning practices to prevent expensive transmission construction projects from becoming obsolete. (2) DLR technology is inexpensive to install and operationally flexible, making it an attractive alternative to more costly transmission system upgrades.

Most of the time, transmission lines have more available real-time capacity and a greater degree of flexibility than their static ratings imply. DLR systems help a transmission owner observe and take advantage of this capacity. NYPA and Oncor both observed increased real-time capacity on their study lines with DLR systems installed. Oncor observed real-time capacities that, on average, were between 30% and 70% greater than static ratings and between 6% and 14% greater than ambient-adjusted ratings; these results are typical when compared to other DLR demonstration projects. (5) NYPA observed even greater increased real-time capacity of between 30% and 44% above the static rating, largely because the study lines were ideally located in windy, open areas. (4)

However, this increased real-time capacity is not always available. While a particular line may, on average, have 10% or 30% greater real-time capacity than the static rating, it may have less available capacity—or even more—at any given moment. Furthermore, the additional real-time capacity released through DLR technologies may not always be needed. In most cases, real-time capacity increases of 5%-10% above the static rating are sufficient to address most congestion issues. (2) The additional real-time capacity is often greatest when it is not needed. (7) Transmission owners implementing DLR systems must also be mindful of the next limiting element on the grid, which may include switches, circuit breakers, wave traps, and current transformers on substation terminal equipment. (5)

DLR systems offer a wide array of benefits to the transmission owner, customers, and system operators:

- Congestion relief
- Greater transmission system reliability
- Decreased capital costs
- WASA
- Easier integration of renewable energy, particularly wind generation, potentially decreasing greenhouse gas emissions
- Lower power costs for consumers
- Optimized dispatch of existing and new grid assets

Challenges remain in implementing DLR systems. To maximize the benefits of DLR technology and ensure consistently accurate dynamic ratings, transmission owners must recognize the limitations of certain DLR devices on lightly loaded lines, and they must account for differences between the as-built characteristics of the line and its design characteristics. The transmission owner must be willing to confront potential cybersecurity challenges before they arise to ensure that the DLR system is safely and successfully integrated into operations.

Integrating a DLR system into system operations has historically been a challenge. However, Oncor's SGDP project demonstrated that it is possible to successfully integrate live dynamic ratings into a system operator's control room without requiring the operator to manually interpret the data. Oncor is confident that fully integrated DLR systems are commercially viable and can be readily implemented in real-time operations. (7) Oncor considers its project to be highly successful. The project was recognized as one of two finalists in the Smart Grid category for *POWERGRID International*'s Projects of the Year award.[15]

Through NYPA's SGDP project, EPRI learned that forecasts of dynamic ratings may be of greater value to system operators, who could utilize day-ahead ratings to predict and avoid contingencies. (8) Both EPRI and Nexans are pursuing ways to forecast dynamic ratings. (8), (2) Finally, although it can be difficult to quantify the financial returns of DLR projects, the avoided or deferred capital costs are clear and substantial. (5)

DLR systems offer other potential opportunities to improve current transmission system planning practices and pave the way for new developments. DLR systems may help a transmission owner better understand the power system in which it operates, thereby improving static line rating methodologies and planning practices at the operational level. DLR

[15] See POWERGRID International names Projects of the Year finalists

technology can facilitate the integration of new renewable generation to the grid, particularly wind generation.

New technologies and methodologies are in development to provide an even more accurate assessment of grid conditions. These new developments include ratings for terminal equipment in substations, which are often the next limiting element in a transmission system after transmission lines, that are based on real-time ambient temperature data and forecasting dynamic ratings for additional grid flexibility and contingency management. EPRI is developing methodologies for calculating dynamic ratings for terminal equipment in substations and for forecasting dynamic ratings. (8) Nexans has already developed a capacity forecast engine. (2) These new developments, along with ongoing DLR projects, may further enhance transmission owners' efforts to understand the real-time conditions of the transmission systems in which they operate.

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Appendix B. Detailed Project Results

This appendix presents the results of the New York Power Authority's (NYPA's) and Oncor Electric Delivery Company LLC's (Oncor's) Smart Grid Demonstration Program (SGDP) projects in greater detail. The results shown here include tables and probability distributions of dynamic ratings, comparisons of different dynamic line rating (DLR) technologies, Oncor's contingency management analysis, and reasons for the data anomalies that Oncor encountered during its SGDP project.

B.1 Detailed Results of NYPA's DLR Demonstration

The following sections contain data from NYPA's SGDP project documentation. (4)

B.1.1 Static Ratings

The following tables summarize the static ratings for the overall circuit and for the line section with which the DLR devices are associated.

Time Period	Summer (Amps)	Winter (Amps)
Normal (24 hours)	1,089	1,331
Long-term Emergency (4 hours)	1,256	1,460
Short-term Emergency (15 min)	1,410	1,593

Source: Navigant Consulting, Inc. (Navigant) analysis; data from (4)

Table B-14. Summary of Static Ratings for Site 1 (Installation Site)

Time Period	Summer (Amps)	Winter (Amps)
Normal (24 hours)	996	1,200
Long-term Emergency (4 hours)	1,152	1,200
Short-term Emergency (15 min)	1,263	1,428

Source: Navigant analysis; data from (4)

Table B-15. Summary of Static Ratings for Site 1 (Overall Circuit)

Time Period	Summer (Amps)	Winter (Amps)
Normal (24 hours)	1,087	1,331
Long-term Emergency (4 hours)	1,256	1,460
Short-term Emergency (15 min)	1,410	1,593

Source: Navigant analysis; data from (4)

Table B-16. Summary of Static Ratings for Sites 2 and 3 (Installation Site)

Time Period	Summer (Amps)	Winter (Amps)
Normal (24 hours)	876	1,121
Long-term Emergency (4 hours)	968	1,188
Short-term Emergency (15 min)	1,104	1,299

Source: Navigant analysis; data from (4)

Table B-17. Summary of Static Ratings for Sites 2 and 3 (Overall Circuit)

B.1.2 Dynamic Ratings by Site and DLR Device

The following tables summarize the dynamic ratings and load associated with each DLR device at each installation site by season. Ratings are provided for normal, long-term emergency (LTE), and short-term emergency (STE) conditions. The designations "L1," "L2," "L5," "L50," and "L95" refer to the amount of time that each rating was exceeded. For example, the L1 (Level 1%) rating was exceeded 99% of the time; L5 was exceeded 95% of the time, and so on. L50 represents the median magnitude of normal rating. Note that, since the installation sites were on open terrain (no changing elevation, a straight transmission path, minimal shielding, etc.), different equipment types did not generate substantially different ratings. This would probably not be the case on a more complex transmission line. These results suggest that many devices can reliably calculate dynamic ratings, as long as their specific limitations (regarding minimum current density or minimum load) are understood. (4)

Onsite Weather Station						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,138	1,204	1,314	1,826	2,301
LTE	1,460	1,211	1,276	1,380	1,902	2,430
STE	1,593	1,720	1,760	1,826	2,186	2,617
Load		0	0	10	120	250
ThermalRate						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,258	1,315	1,417	1,986	2,568
LTE	1,460	1,327	1,385	1,482	2,087	2,718
STE	1,593	1,786	1,824	1,892	2,313	2,850
Load		0	0	10	120	250
Sagometer						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,140	1,203	1,318	1,895	2,483
LTE	1,460	1,200	1,255	1,381	1,964	2,618
STE	1,593	1,744	1,786	1,850	2,888	2,782
Load		0	0	10	120	250
EPRI Sensors						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,142	1,205	1,322	1,895	2,481
LTE	1,460	1,206	1,266	1,389	1,964	2,616
STE	1,593	1,733	1,765	1,830	2,888	2,772
Load		0	0	10	120	250

Source: Navigant analysis; data from (4)

Table B-18. NYPA Site 1: Winter 2010/2011 (Amps)

Onsite Weather Station						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,089	929	988	1,096	1,533	1,947
LTE	1,256	1,078	1,123	1,220	1,665	2,038
STE	1,410	1,567	1,594	1,651	1,951	2,255
Load		0	5	10	100	250
ThermalRate						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,089	1,235	1,332	1,406	1,855	1,861
LTE	1,256	1,335	1,435	1,541	2,024	1,988
STE	1,410	1,724	1,784	1,842	2,215	2,210
Load		0	5	10	100	250
Sagometer						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,089	988	1,116	1,247	1,708	2,229
LTE	1,256	1,185	1,236	1,341	1,781	2,323
STE	1,410	1,641	1,678	1,740	2,063	2,495
Load		0	5	10	100	250
EPRI Sensors						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,089	916	983	1,100	1,570	2,073
LTE	1,256	1,093	1,135	1,234	1,699	2,172
STE	1,410	1,626	1,659	1,704	1,995	2,361
Load		0	5	10	100	250

Source: Navigant analysis; data from (4)

Table B-19. NYPA Site 1: Summer 2011 (Amps)

Onsite Weather Station						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,101	1,166	1,283	1,783	2,256
LTE	1,460	1,166	1,215	1,336	1,872	2,416
STE	1,593	1,664	1,713	1,779	2,149	2,588
Load		0	5	15	90	345
ThermalRate						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,309	1,384	1,507	1,950	2,601
LTE	1,460	1,385	1,454	1,582	2,049	2,745
STE	1,593	1,789	1,837	1,924	2,272	2,875
Load		0	5	15	90	345
Sagometer						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,105	1,161	1,286	1,908	2,513
LTE	1,460	1,176	1,224	1,350	2,005	2,673
STE	1,593	1,665	1,707	1,782	2,255	2,819
Load		0	5	15	90	345
EPRI Sensors						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,105	1,167	1,290	1,868	2,658
LTE	1,460	1,175	1,229	1,355	1,958	2,663
STE	1,593	1,675	1,725	1,790	2,215	2,818
Load		0	5	15	90	345
Offsite Weather Service						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	926	972	1,027	1,515	2,200
LTE	1,460	1,037	1,069	1,138	1,605	2,321
STE	1,593	1,562	1,592	1,635	1,961	2,517
Load		0	5	15	90	345

Source: Navigant analysis; data from (4)

Table B-20. NYPA Site 1: Winter 2011/2012 (Amps)

Onsite Weather Station						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,089	1,038	1,090	1,191	1,622	2,031
LTE	1,256	1,099	1,141	1,241	1,699	2,115
STE	1,410	1,578	1,607	1,661	1,973	2,319
Load		0	10	20	130	330
ThermalRate						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,089	1,204	1,270	1,368	1,802	2,403
LTE	1,256	1,273	1,339	1,447	1,910	2,556
STE	1,410	1,673	1,720	1,784	2,127	2,691
Load		0	10	20	130	330
Sagometer						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,089	1,048	1,102	1,197	1,656	2,179
LTE	1,256	1,116	1,154	1,247	1,733	2,258
STE	1,410	1,580	1,613	1,669	2,003	2,443
Load		0	10	20	130	330
EPRI Sensors						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,089	1,011	1,082	1,189	1,656	2,166
LTE	1,256	1,085	1,140	1,238	1,732	2,241
STE	1,410	1,611	1,660	1,720	2,028	2,437
Load		0	10	20	130	330
Offsite Weather Service						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,089	886	920	988	1,517	2,067
LTE	1,256	979	1,021	1,080	1,593	2,159
STE	1,410	1,488	1,536	1,590	1,890	2,346
Load		0	10	20	130	330

Source: Navigant analysis; data from (4)

Table B-21. NYPA Site 1: Summer 2012 (Amps)

Onsite Weather Station						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,122	1,192	1,285	1,784	2,296
LTE	1,460	1,228	1,266	1,374	1,860	2,486
STE	1,593	1,760	1,794	1,853	2,173	2,690
Load		0	0	5	40	96
ThermalRate						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,245	1,300	1,421	1,975	2,605
LTE	1,460	1,281	1,384	1,468	2,077	2,762
STE	1,593	1,824	1,863	1,992	2,319	2,894
Load		0	0	5	40	96
Sagometer						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,049	1,122	1,248	1,870	2,545
LTE	1,460	1,222	1,270	1,373	1,950	2,673
STE	1,593	1,731	1,766	1,826	2,231	2,835
Load		0	0	5	40	96
EPRI Sensors						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,049	1,122	1,248	1,868	2,520
LTE	1,460	1,224	1,271	1,376	1,939	2,659
STE	1,593	1,754	1,781	1,840	2,221	2,815
Load		0	0	5	40	96

Source: Navigant analysis; data from (4)

Table B-22. NYPA Site 2: Winter 2010/2011 (Amps)

Onsite Weather Station						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	818	875	967	1,410	1,901
LTE	1,256	1,042	1,072	1,130	1,566	2,022
STE	1,410	1,538	1,561	1,599	1,878	2,238
Load		0	10	25	95	250
ThermalRate						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	1,047	1,079	1,147	1,611	2,388
LTE	1,256	1,147	1,177	1,244	1,747	2,572
STE	1,410	1,608	1,628	1,670	1,999	2,706
Load		0	10	25	95	250
Sagometer						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	898	950	1,031	1,471	2,117
LTE	1,256	1,070	1,101	1,159	1,584	2,225
STE	1,410	1,507	1,545	1,601	1,891	2,400
Load		0	10	25	95	250
EPRI Sensors						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	838	894	981	1,418	2,036
LTE	1,256	1,060	1,087	1,150	1,566	2,158
STE	1,410	1,544	1,570	1,610	1,883	2,349
Load		0	10	25	95	250

Source: Navigant analysis; data from (4)

Table B-23. NYPA Site 2: Summer 2011 (Amps)

Onsite Weather Station						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,138	1,204	1,314	1,826	2,303
LTE	1,460	1,212	1,276	1,380	1,902	2,432
STE	1,593	1,720	1,760	1,826	2,186	2,619
Load		0	0	5	120	250
ThermalRate						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,258	1,315	1,417	1,986	2,569
LTE	1,460	1,328	1,385	1,472	2,087	2,719
STE	1,593	1,786	1,824	1,892	2,313	2,852
Load		0	0	5	120	250
Sagometer						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,140	1,205	1,318	1,895	2,484
LTE	1,460	1,200	1,260	1,382	1,964	2,621
STE	1,593	1,744	1,788	1,849	2,257	2,785
Load		0	0	5	120	250
EPRI Sensors						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,140	1,205	1,322	1,899	2,484
LTE	1,460	1,206	1,266	1,389	1,968	2,615
STE	1,593	1,734	1,765	1,830	2,235	2,774
Load		0	0	5	120	250
Offsite Weather Service						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	937	1,014	1,033	1,560	2,259
LTE	1,460	1,063	1,104	1,140	1,639	2,366
STE	1,593	1,598	1,625	1,646	1,991	2,557
Load		0	0	5	120	250

Source: Navigant analysis; data from (4)

Table B-24. NYPA Site 2: Winter 2011/2012 (Amps)

Onsite Weather Station						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	982	1,055	1,165	1,587	2,016
LTE	1,256	1,071	1,130	1,235	1,677	2,105
STE	1,410	1,552	1,598	1,657	1,962	2,306
Load		0	10	25	150	260
ThermalRate						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	1,117	1,185	1,264	1,665	2,279
LTE	1,256	1,191	1,259	1,346	1,775	2,412
STE	1,410	1,625	1,669	1,721	2,019	2,557
Load		0	10	25	150	260
Sagometer						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	1,033	1,076	1,175	1,600	2,120
LTE	1,256	1,086	1,139	1,246	1,695	2,225
STE	1,410	1,571	1,614	1,674	1,980	2,413
Load		0	10	25	150	260
EPRI Sensors						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	993	1,057	1,165	1,602	2,105
LTE	1,256	1,078	1,137	1,245	1,697	2,209
STE	1,410	1,569	1,614	1,675	1,977	2,395
Load		0	10	25	150	260
Offsite Weather Service						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	866	906	979	1,510	2,081
LTE	1,256	981	1,021	1,078	1,600	2,166
STE	1,410	1,489	1,533	1,595	1,902	2,355
Load		0	10	25	150	260

Source: Navigant analysis; data from (4)

Table B-25. NYPA Site 2: Summer 2012 (Amps)

Onsite Weather Station						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,061	1,116	1,210	1,678	2,222
LTE	1,460	1,174	1,204	1,264	1,729	2,305
STE	1,593	1,715	1,743	1,796	2,072	2,504
Load		0	0	0	40	100
ThermalRate						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,175	1,226	1,331	1,964	2,641
LTE	1,460	1,239	1,282	1,381	2,047	2,782
STE	1,593	1,769	1,798	1,861	2,300	2,912
Load		0	0	0	40	100
Sagometer						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,021	1,071	1,153	1,702	2,335
LTE	1,460	1,127	1,161	1,234	1,776	2,504
STE	1,593	1,610	1,645	1,707	2,802	2,670
Load		0	0	0	40	100
EPRI Sensors						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	869	979	1,095	1,647	2,395
LTE	1,460	1,133	1,167	1,242	1,721	2,487
STE	1,593	1,633	1,666	1,727	2,051	2,665
Load		0	0	0	40	100

Source: Navigant analysis; data from (4)

Table B-26. NYPA Site 3: Winter 2010/2011 (Amps)

Onsite Weather Station						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	817	875	967	1,407	1,900
LTE	1,256	1,042	1,072	1,130	1,563	2,021
STE	1,410	1,536	1,561	1,600	1,875	2,237
Load		0	10	25	95	250
ThermalRate						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	1,042	1,078	1,145	1,611	2,388
LTE	1,256	1,145	1,176	1,243	1,747	2,572
STE	1,410	1,606	1,627	1,669	1,999	2,706
Load		0	10	25	95	250
Sagometer						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	898	949	1,031	1,468	2,117
LTE	1,256	1,070	1,100	1,159	1,584	2,226
STE	1,410	1,506	1,543	1,601	1,892	2,403
Load		0	10	25	95	250
EPRI Sensors						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	835	889	976	1,407	2,023
LTE	1,256	1,057	1,086	1,150	1,559	2,149
STE	1,410	1,542	1,569	1,608	1,878	2,341
Load		0	10	25	95	250

Source: Navigant analysis; data from (4)

Table B-27. NYPA Site 3: Summer 2011 (Amps)

Onsite Weather Station						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,023	1,066	1,147	1,652	2,185
LTE	1,460	1,116	1,152	1,215	1,726	2,321
STE	1,593	1,622	1,657	1,714	2,048	2,999
Load		0	0	5	120	250
ThermalRate						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,170	1,208	1,279	1,916	2,642
LTE	1,460	1,227	1,270	1,344	2,014	2,788
STE	1,593	1,696	1,731	1,796	2,560	2,917
Load		0	0	5	120	250
Sagometer						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,021	1,070	1,153	1,699	2,318
LTE	1,460	1,128	1,161	1,233	1,772	2,478
STE	1,593	1,611	1,645	1,707	2,080	2,648
Load		0	0	5	120	250
EPRI Sensors						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	1,027	1,078	1,163	1,720	2,363
LTE	1,460	1,133	1,167	1,241	1,786	2,503
STE	1,593	1,633	1,666	1,718	2,085	2,669
Load		0	0	5	120	250
Offsite Weather Service						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,331	885	953	1,107	1,758	2,385
LTE	1,460	1,041	1,083	1,178	1,908	2,517
STE	1,593	1,570	1,610	1,698	2,110	2,689
Load		0	0	5	120	250

Source: Navigant analysis; data from (4)

Table B-28. NYPA Site 3: Winter 2011/2012 (Amps)

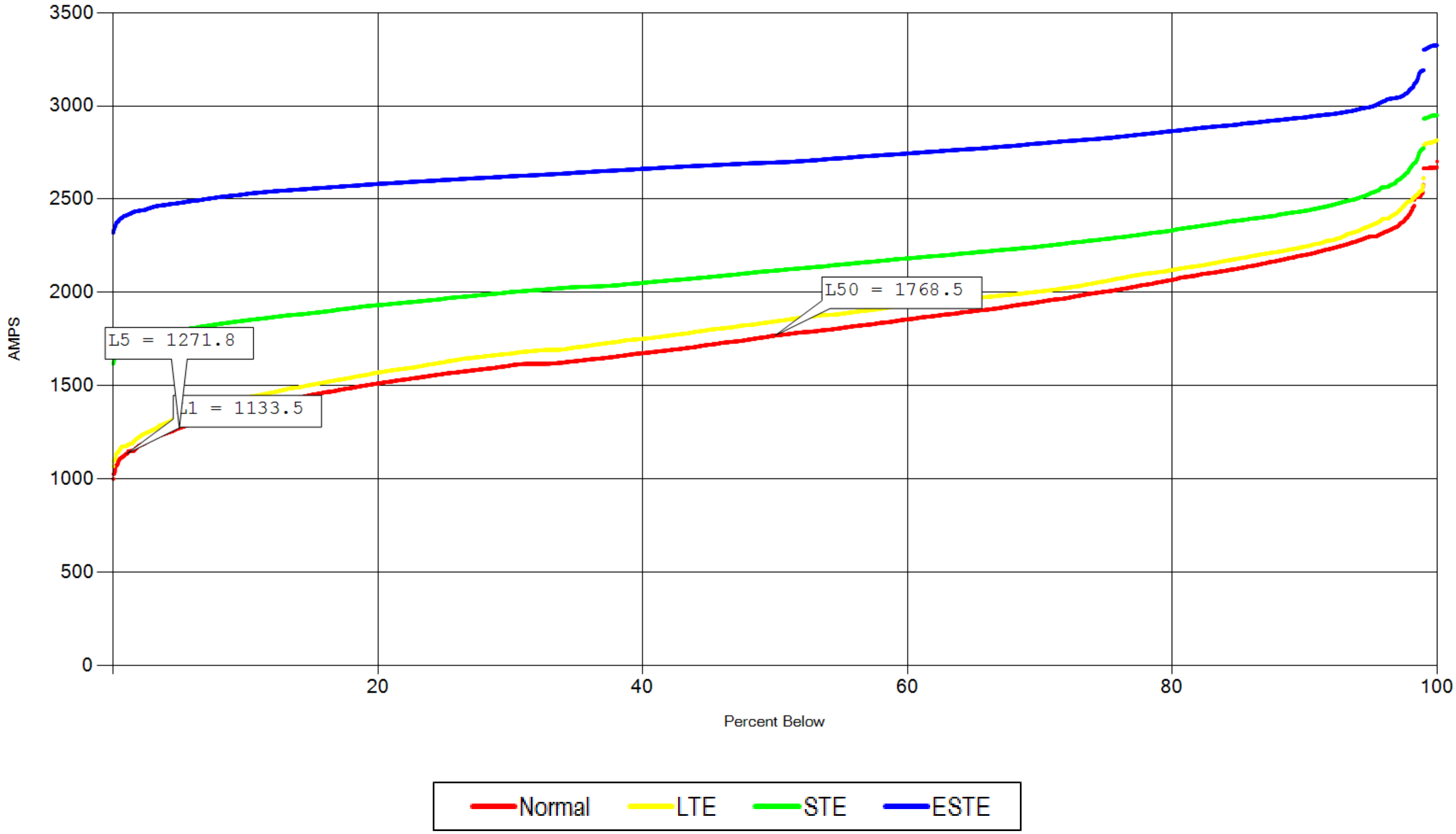
Onsite Weather Station						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	925	971	1,045	1,456	1,917
LTE	1,256	1,048	1,074	1,122	1,534	1,988
STE	1,410	1,534	1,560	1,602	1,858	2,199
Load		0	10	25	150	260
ThermalRate						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	1,080	1,109	1,173	1,610	2,329
LTE	1,256	1,138	1,170	1,231	1,713	2,473
STE	1,410	1,605	1,630	1,671	1,973	2,613
Load		0	10	25	150	260
Sagometer						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	936	983	1,064	1,497	2,058
LTE	1,256	1,050	1,084	1,142	1,585	2,150
STE	1,410	1,534	1,568	1,612	1,599	2,339
Load		0	10	25	150	260
EPRI Sensors						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	929	977	1,048	1,454	2,015
LTE	1,256	1,050	1,081	1,131	1,525	2,102
STE	1,410	1,545	1,572	1,613	1,857	2,300
Load		0	10	25	150	260
Offsite Weather Service						
	Static	**L1**	**L2**	**L5**	**L50**	**L95**
Normal	1,087	880	907	977	1,615	2,167
LTE	1,256	1,013	1,042	1,091	1,731	2,288
STE	1,410	1,522	1,554	1,597	1,990	2,450
Load		0	10	25	150	260

Source: Navigant analysis; data from (4)

Table B-29. NYPA Site 3: Summer 2012 (Amps)

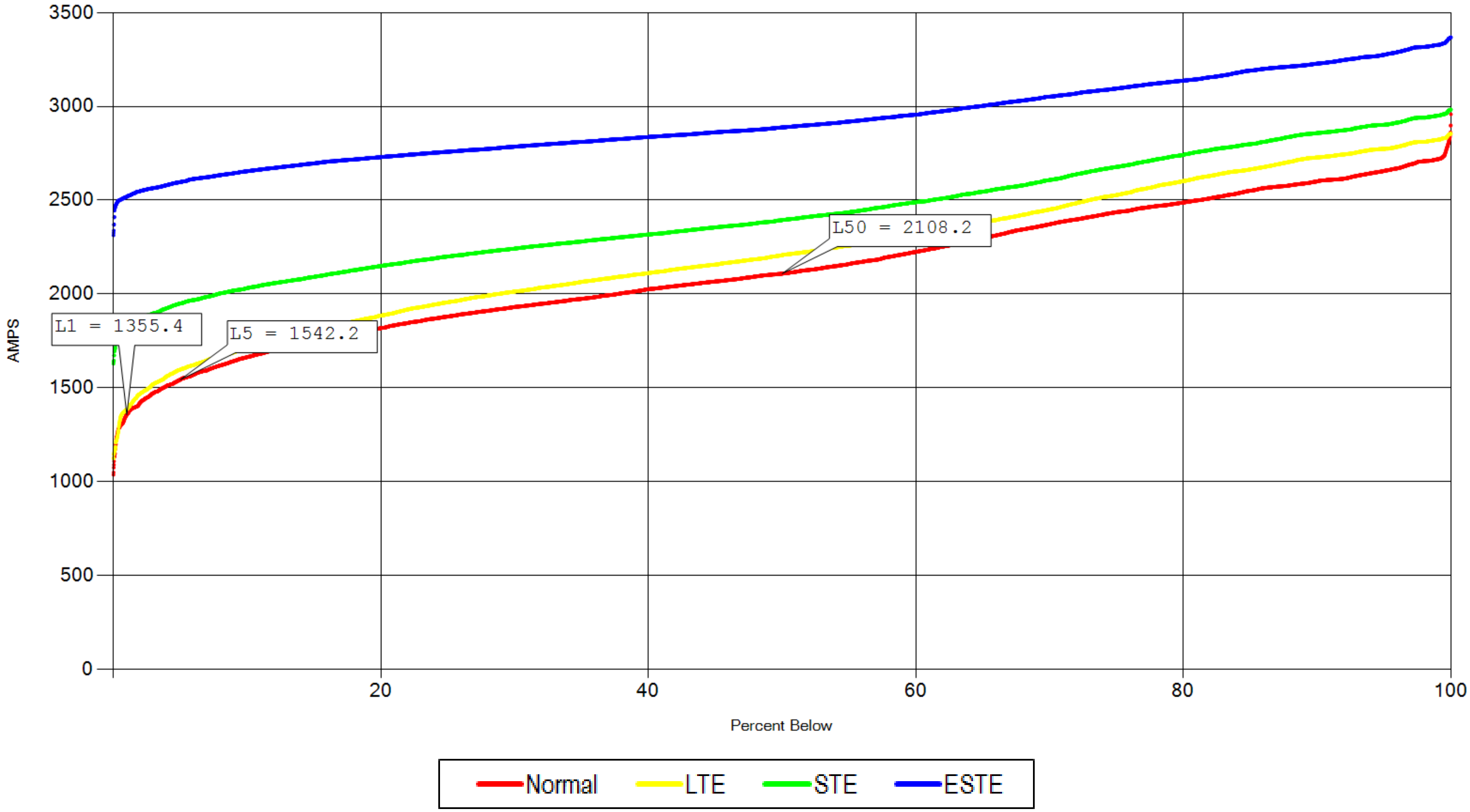
B.1.3 Probability Distributions of Dynamic Ratings

The following figures provide examples of cumulative probability distributions for normal, LTE, STE, and extremely short-term emergency (ESTE) conditions for each DLR device. These figures correspond with ratings calculated during April 2012 at Site 1. For comparison, the winter static ratings for Site 1 are 1,331 amps for normal conditions, 1,460 amps for LTE conditions, and 1,593 amps for STE conditions. (4) Notice that the dynamic rating surpasses these ratings the vast majority of the time but not all of the time.



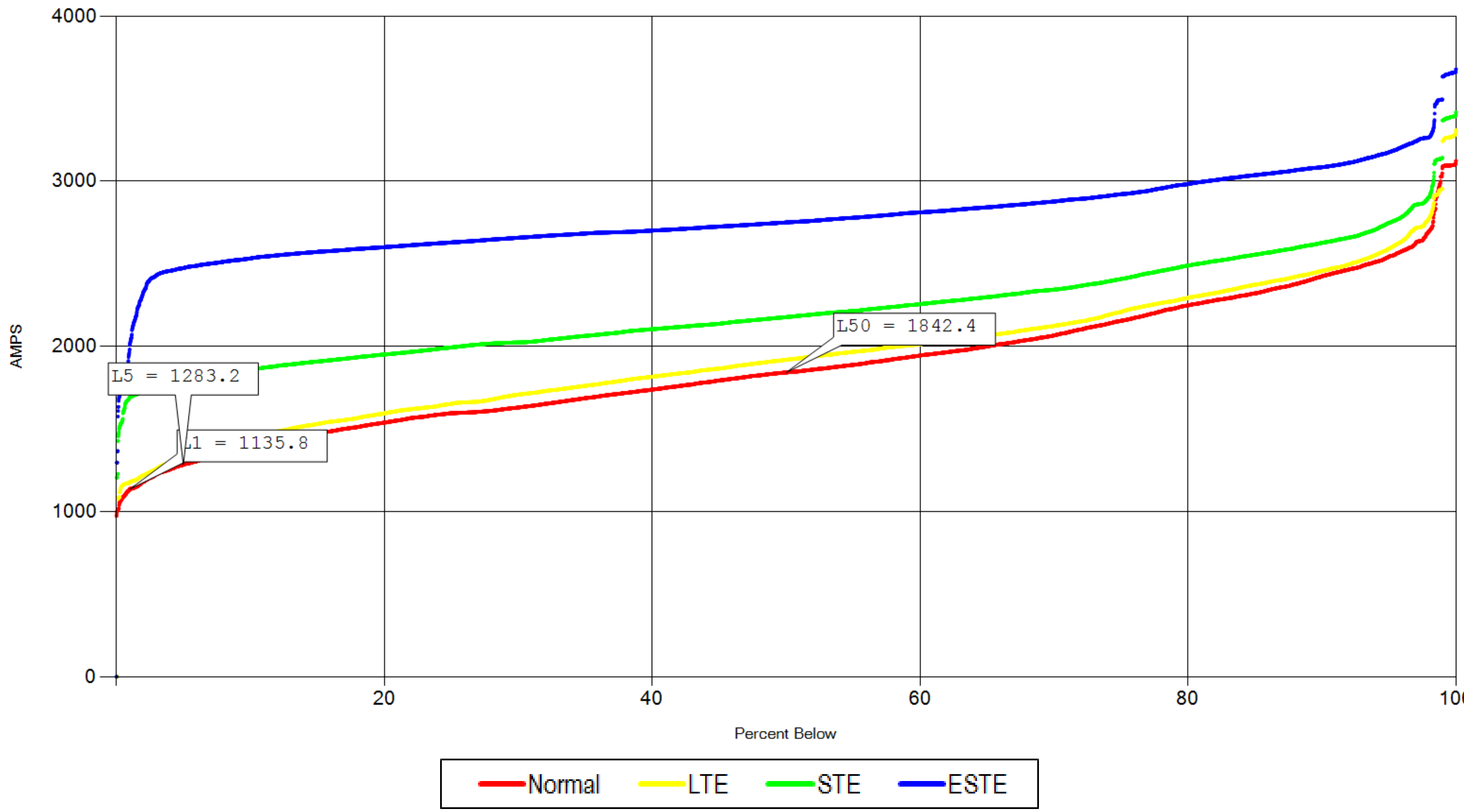
Source: Used with permission from NYPA (4)

Figure B-1. Site 1 Weather Stations (April 2012)



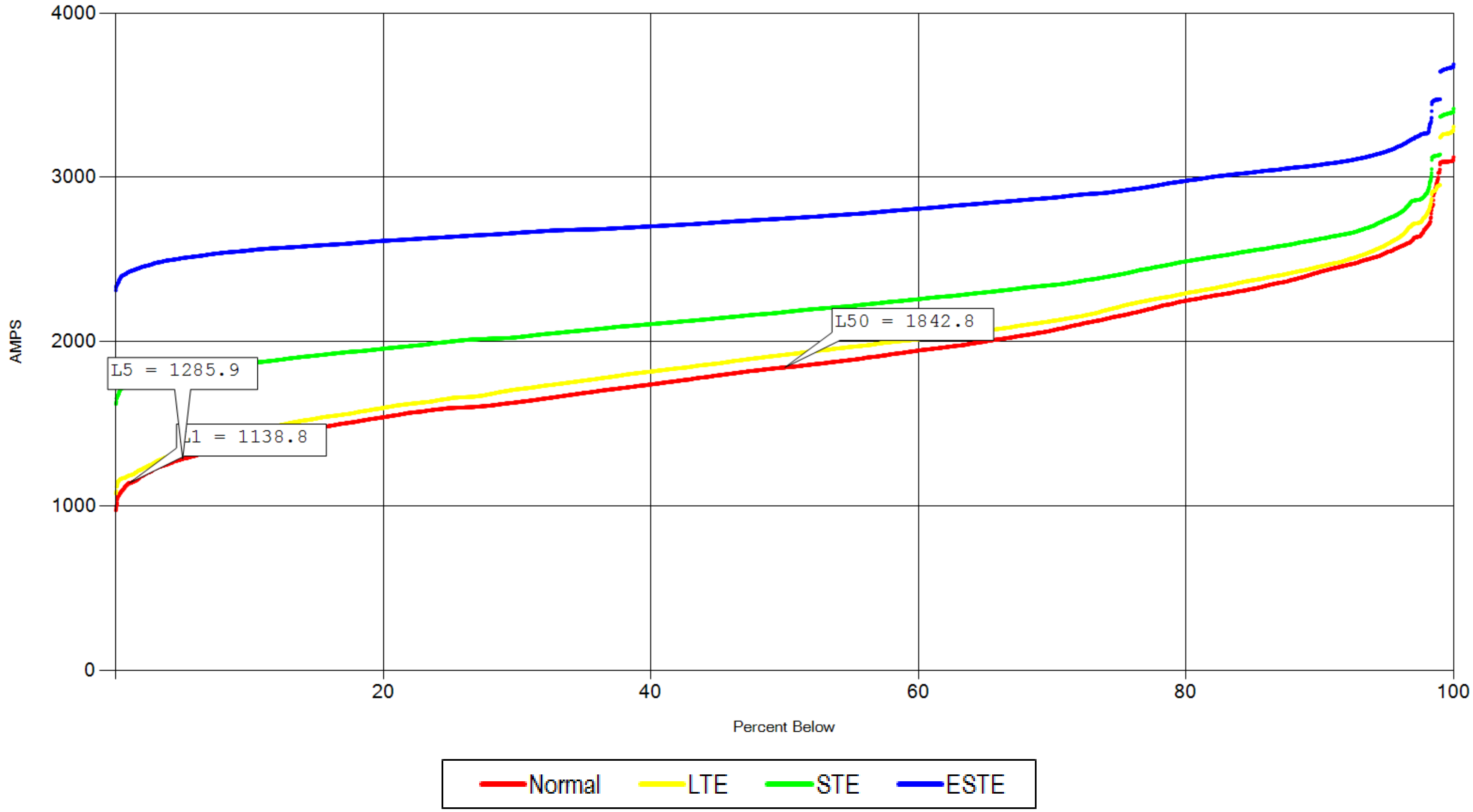
Source: Used with permission from NYPA (4)

Figure B-2. Site 1 ThermalRate (April 2012)



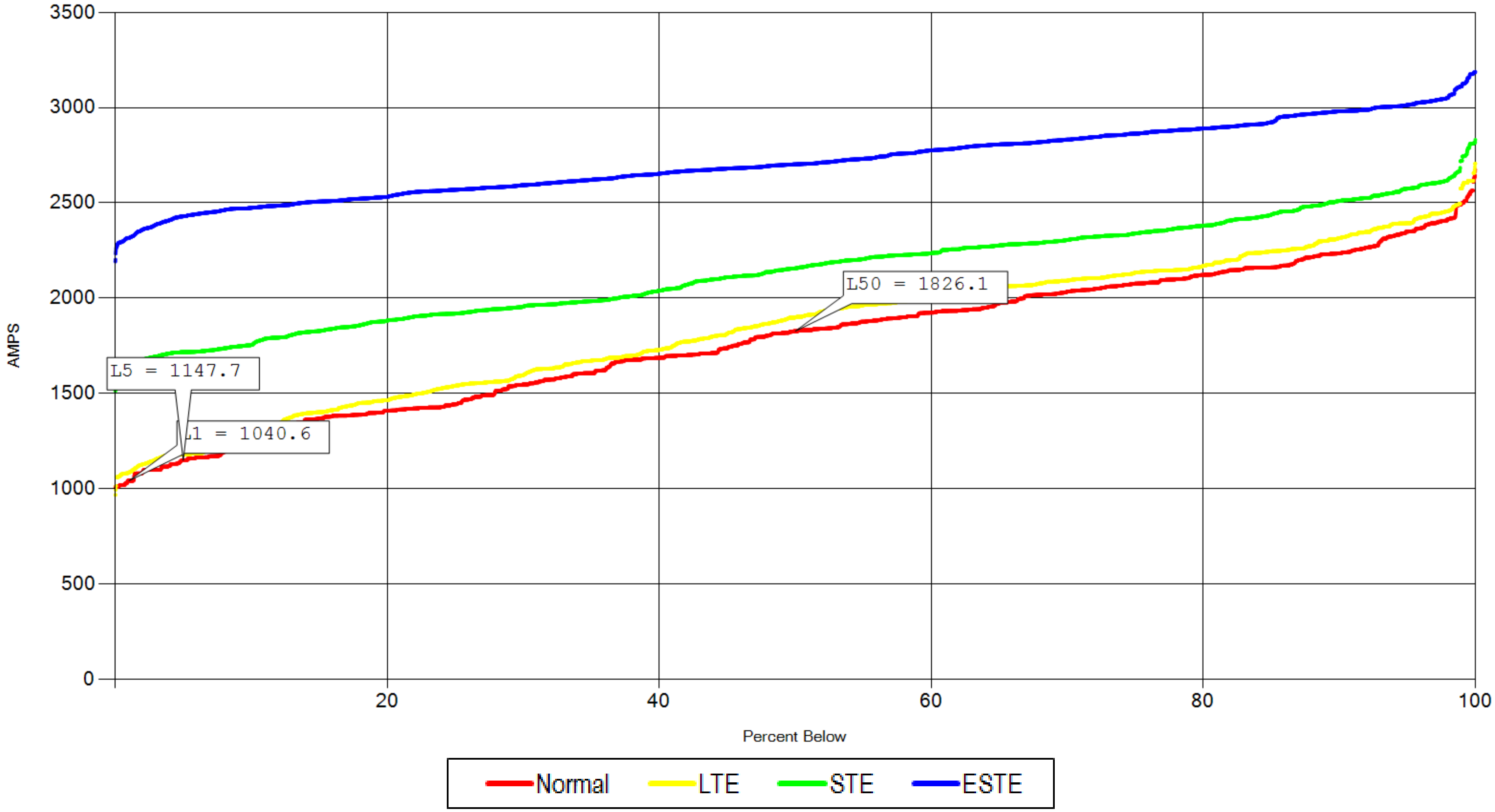
Source: Used with permission from NYPA (4)

Figure B-3. Site 1 Sagometers (April 2012)



Source: Used with permission from NYPA (4)

Figure B-4. Site 1 EPRI Sensors (April 2012)



Source: Used with permission from NYPA (4)

Figure B-5. Site 1 Offsite Weather Service (April 2012)

B.2 Detailed Results of Oncor's DLR Demonstration

The following sections contain data and analysis from Oncor's SGDP project documentation. (5)

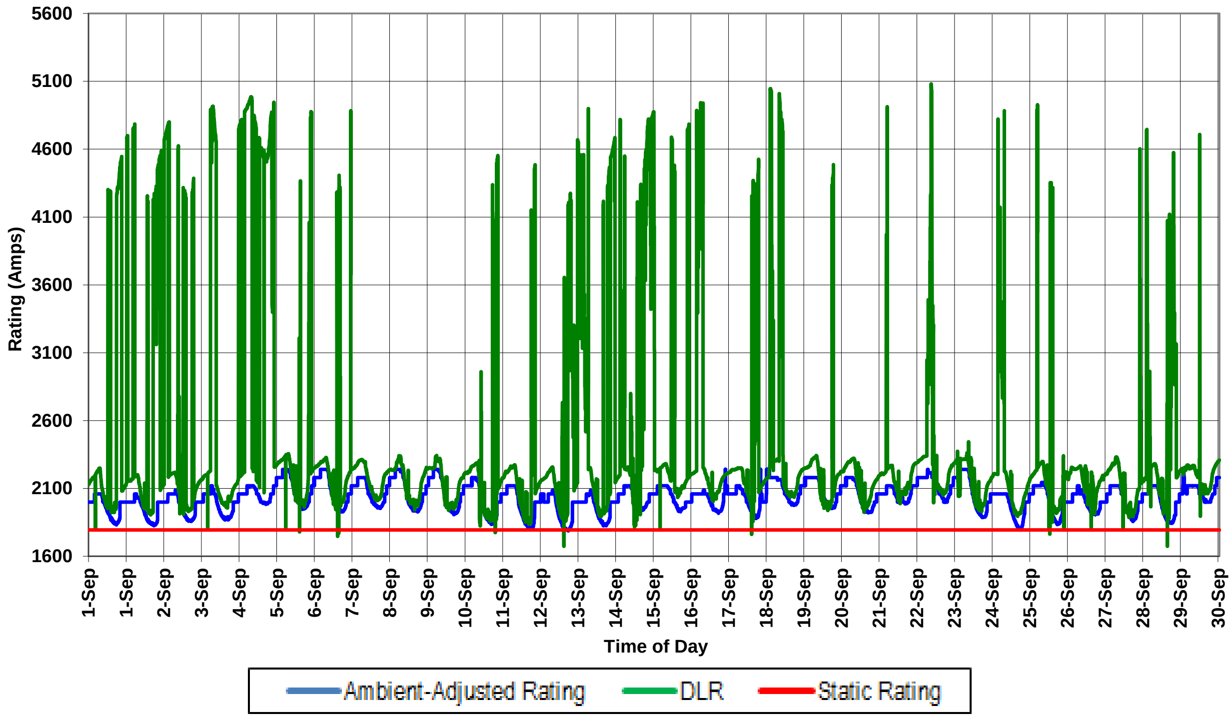
B.2.1 Sample Data Charts

DLR and ambient-adjusted or static ratings were compared in the following ways:

- Charts tracking DLR and ambient-adjusted ratings on a monthly basis as a timeline
- Charts illustrating the difference between DLR and ambient-adjusted or static ratings on a monthly basis as a percent-of-time probability distribution
- Charts illustrating the difference between DLR and ambient-adjusted or static ratings on a monthly basis as a daily distribution

Because September 2011 was relatively warm in the project area and had moderately elevated loads, it was chosen as a month representative of a moderately loaded circuit during summer. The maximum ambient temperature was 104 degrees Fahrenheit (40.1 degrees Celsius), with the average temperature being 83 degrees Fahrenheit (28.4 degrees Celsius). Forty-four percent of the month's ambient temperatures were above 86 degrees Fahrenheit (30 degrees Celsius). (5)

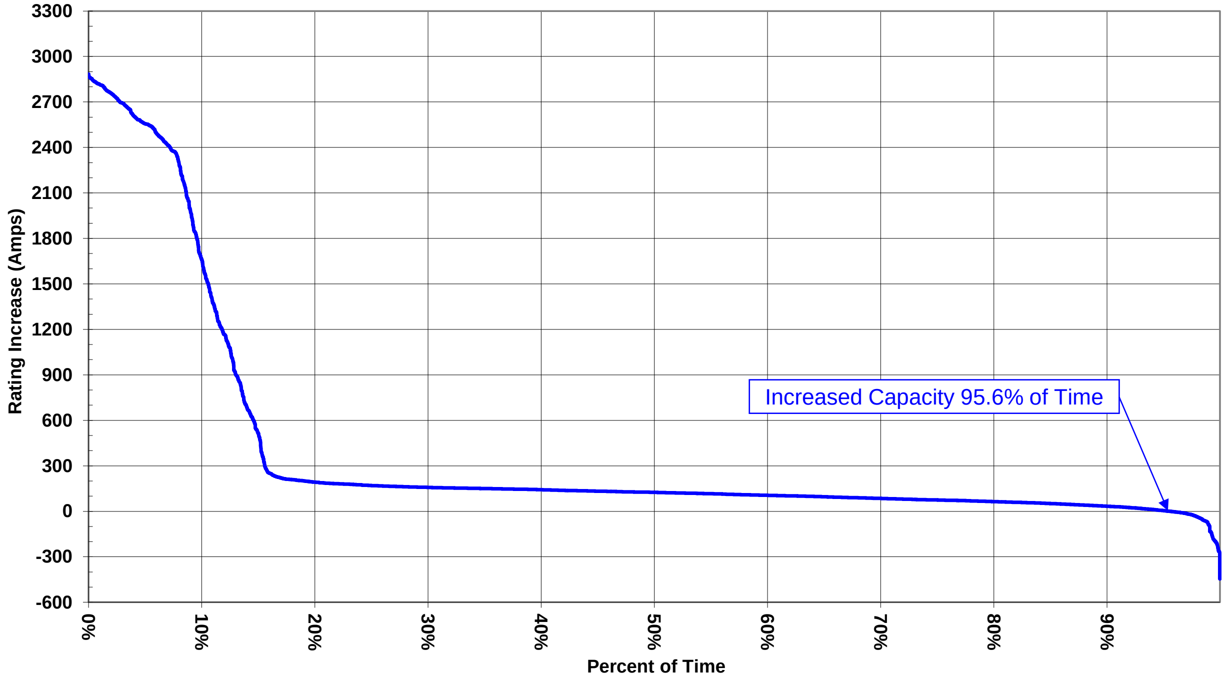
To develop the time series of ratings, data was recorded every two minutes (30 ratings per hour), and the rating for each two-minute interval was plotted. A sample of the resulting chart is shown in Figure B-6. This chart shows ambient-adjusted ratings and dynamic ratings at a 345 kV line, Temple Pecan Creek–Temple Switch, during September 2011. As is typical of many of the study lines, capacity released by DLR technologies is normally above ambient-adjusted rating and exhibits more variation, including periods well above the ambient-adjusted rating and periods at or below the static rating. (5)



Source: Used with permission from Oncor (5)

Figure B-6. DLR and Ambient-Adjusted Rating Time Series (Temple Pecan Creek–Temple Switch, September 2011)

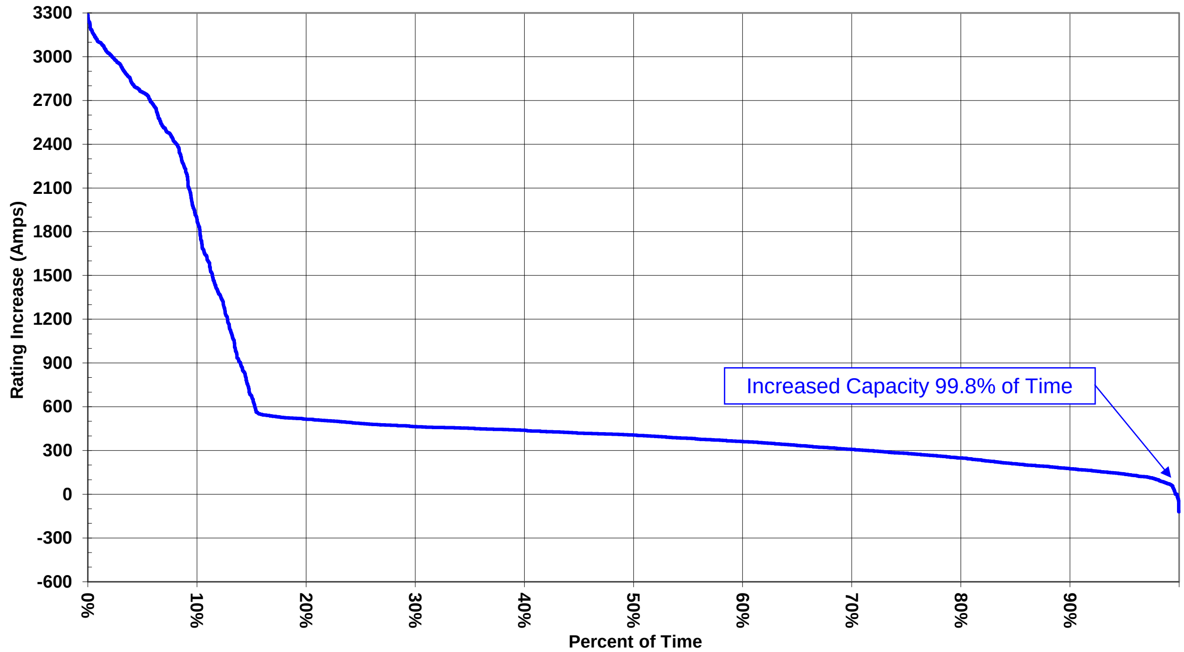
Oncor also developed cumulative probability distributions, showing the increased real-time capacity delivered by DLR technology above the ambient-adjusted rating as a function of percentage of time. The example in Figure B-7 is for Temple Pecan Creek-Temple Switch (345 kV) during September 2011. For 345 kV segments during months with moderate loads, DLR technology typically delivers an increased real-time capacity above the ambient-adjusted rating 80%-95% of the time. This specific example delivered increased real-time capacity 95.6% of the time. Oncor developed cumulative distributions of the difference between dynamic and ambient-adjusted ratings by recording data every two minutes (30 ratings per hour), subtracting ambient-adjusted rating from dynamic rating for each two-minute interval in the month, and plotting the difference as a standard cumulative probability chart. When the rating increase is above zero, the dynamic rating is greater than the ambient-adjusted rating. (5)



Source: Used with permission from Oncor (5)

Figure B-7. DLR Increase above Ambient-Adjusted Rating Cumulative Probability Distribution (Temple Pecan Creek–Temple Switch, September 2011)

Oncor used a similar approach to show the cumulative probability distribution of the increased real-time capacity delivered by DLR technology above the static line rating as a function of percentage of time. The example in Figure B-8 is for Temple Pecan Creek-Temple Switch (345 kV) during September 2011. For most transmission lines, DLR technology typically delivers an increased real-time capacity above the static rating 97%-99% of the time. This specific example had increased capacity 99.8% of the time. Oncor generated cumulative distributions of the difference in DLR and static line rating by recording data every two minutes (30 ratings per hour), subtracting static rating from dynamic rating for each two-minute interval in the month, and plotting the difference as a standard cumulative probability chart. When the rating increase is above zero, the dynamic rating is greater than the static line rating. (5)



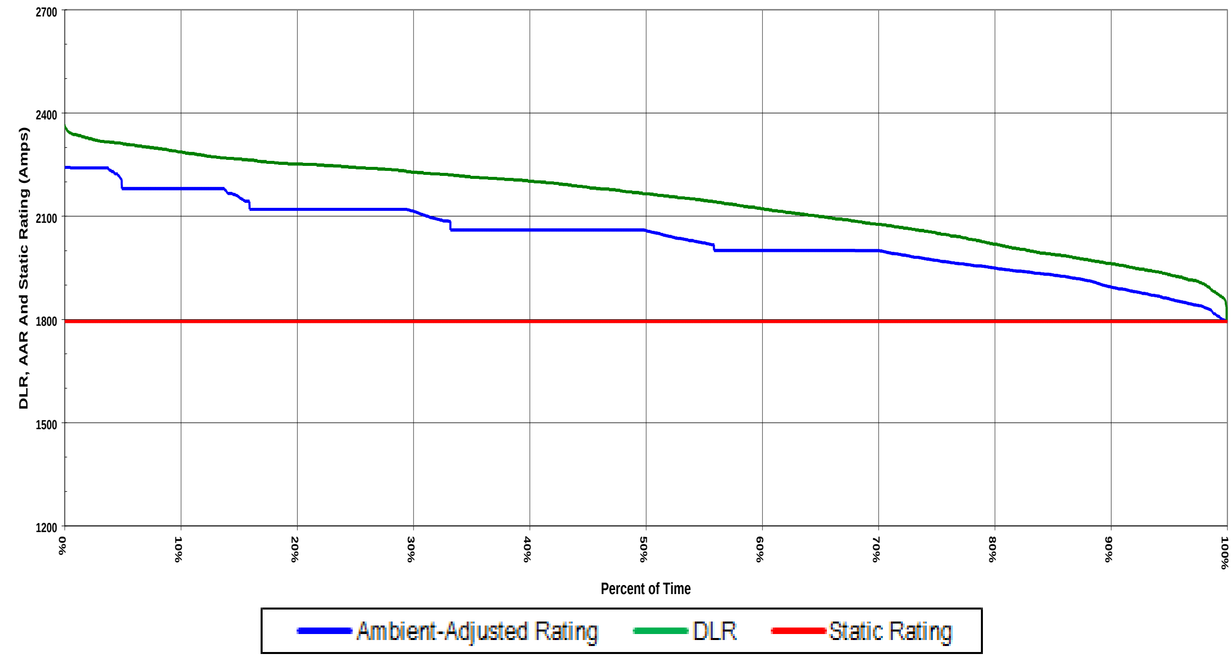
Source: Used with permission from Oncor (5)

Figure B-8. DLR Increase above Static Line Rating Cumulative Probability Distribution (Temple Pecan Creek–Temple Switch, September 2011)

B.2.2 Comparison of Primary and Secondary DLR Technologies

Oncor's DLR system, the CAT-1 System, is a tension-based technology that accounts for the combined, actual effects of wind, solar intensity, and ambient temperature. The CAT-1 System includes a technology that provides net radiation temperature-based (NRT-based) readings. The NRT-based technology accounts for actual ambient temperature and solar radiation but assumes a fixed low wind speed. Unless otherwise noted in this section, all references to Oncor's DLR system utilize results from a combination of tension-based technology and the NRT-based technology. (5)

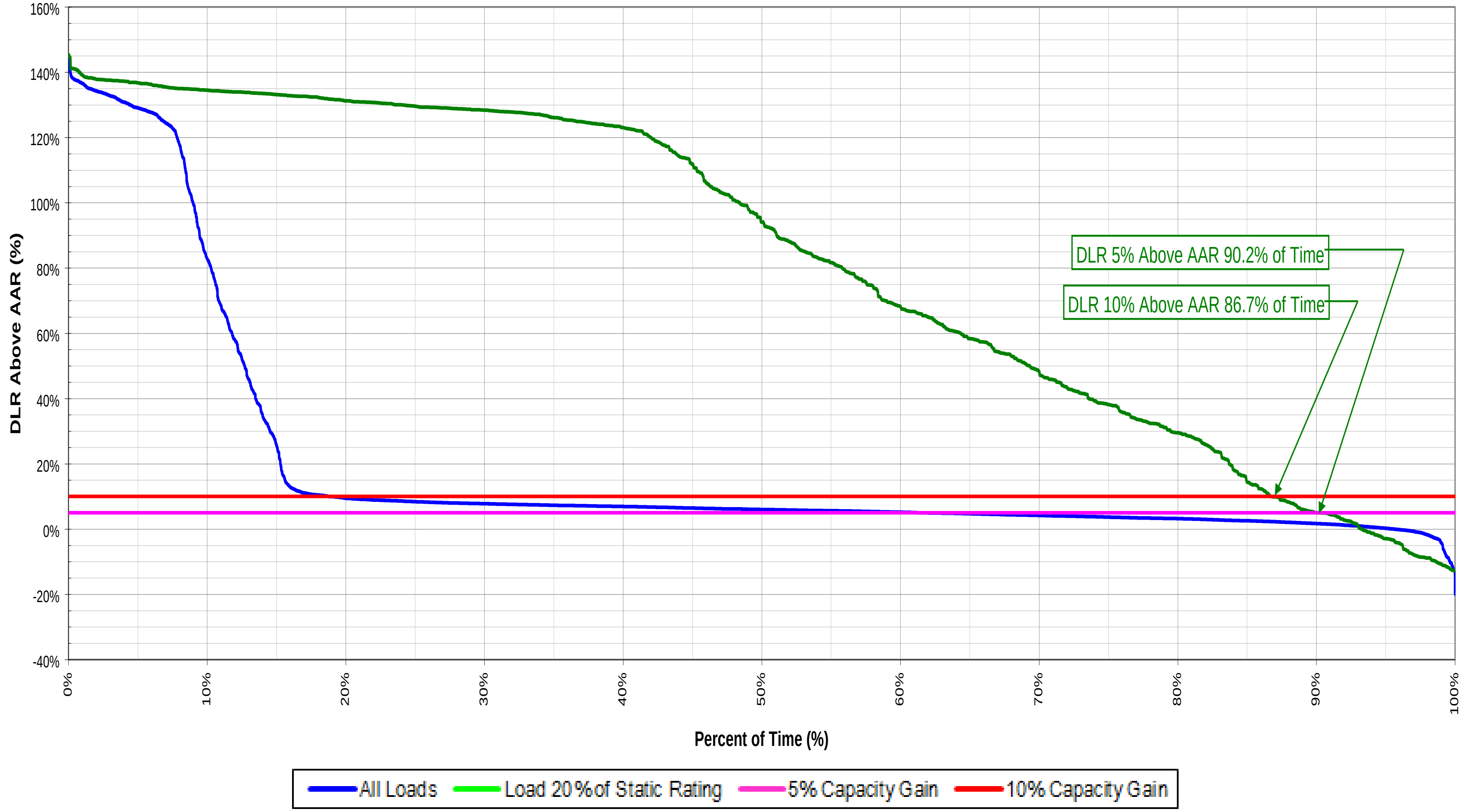
Line loads on a monthly average were less than the threshold required for a tension-based dynamic rating 21%-70% of the time. Under light load conditions (less than 20% of the static rating), conductor temperatures do not rise sufficiently above the ambient levels for the tension-based technology to be effective. Effective wind speed cannot be accurately determined, so a conservative rating is applied assuming a reduced wind speed. In these conditions, NRT-based ratings were calculated. During periods of NRT-based ratings, the ratings provided increased real-time capacity above the ambient-adjusted rating. Figure B-9 is an example of a cumulative probability distribution for Temple Pecan Creek-Temple Switch during September 2011. This example demonstrates the typical capacity gain seen by NRT-adjusted ratings above ambient-adjusted rating. (5)



Source: Used with permission from Oncor (5)

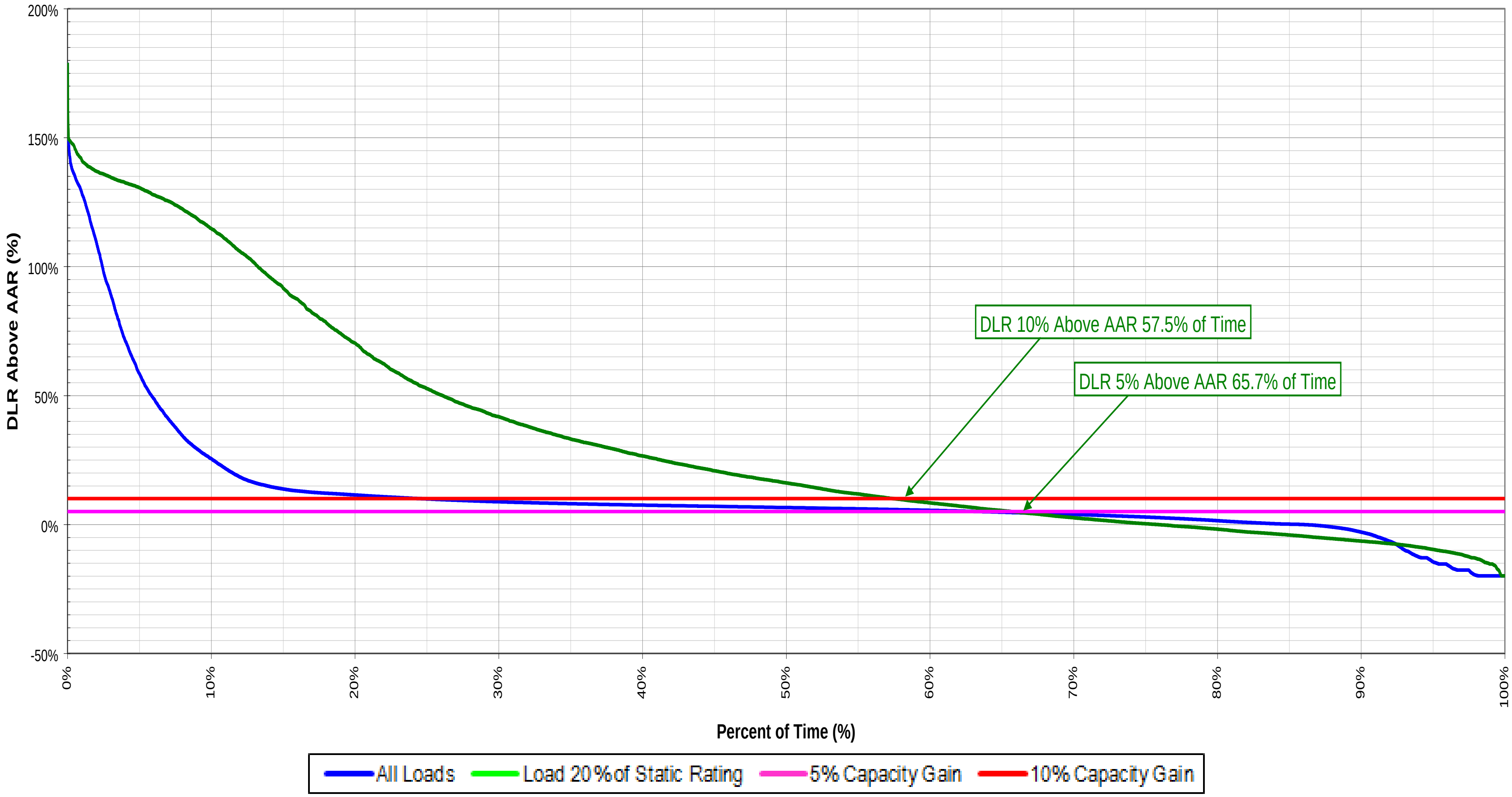
Figure B-9. NRT-Based DLR, Ambient-Adjusted Rating, and Static Rating Probability Distribution (Temple Pecan Creek–Temple Switch, September 2011)

When line loads are above 20% of the static rating, the primary tension technology dominates the dynamic rating by adding the full impact of wind, including its spatial variability, to the rating. Figure B-10 and Figure B-11 show the capacity gained under all load conditions and when loads are greater than 20% of the static line rating. Note that the increased capacity revealed for loads above 20% of static rating is always present. However, the increased capacity simply cannot be accessed without a DLR technology that captures the full spatial impact of wind. (5)



Source: Used with permission from Oncor (5)

Figure B-10. Percent Capacity Gained: DLR above Ambient-Adjusted Rating Probability Distribution (Temple Pecan Creek–Temple Switch, September 2011)

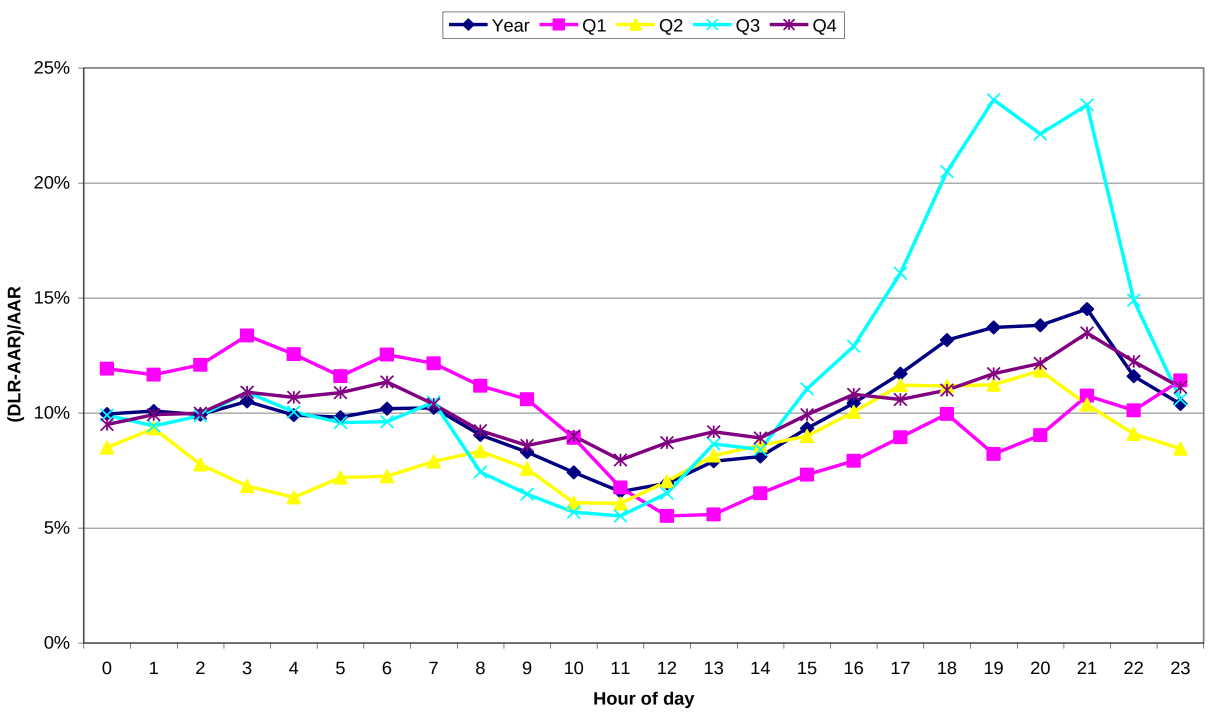


Source: Used with permission from Oncor (5)

Figure B-11. Yearly Cumulative Probability Distribution: DLR above Ambient-Adjusted Rating (All 345 kV Lines, August 2011–July 2012)

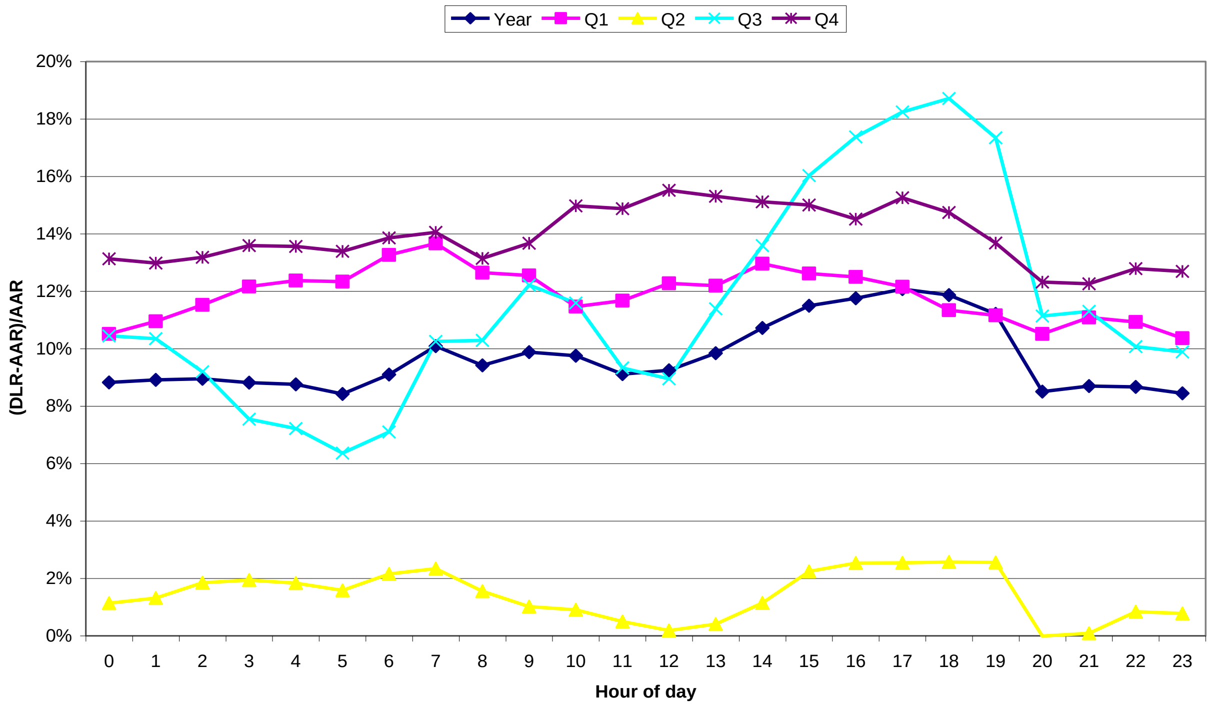
The data was examined for indications of seasonality by dividing the data set into quarters for August 2011 through July 2012. While quarterly results vary, the increased real-time capacity delivered by dynamic ratings above ambient-adjusted ratings was, on average, 6%-14% for 345 kV lines and 8%-12% for 138 kV lines (Figure B-12 and Figure B-13). Between March and June 2012, the lowest loads and the greatest number of load anomalies occurred on the 138 kV segments, forcing the dynamic rating to default to the ambient-adjusted rating (or static rating, in the absence of an ambient-adjusted rating), which accounts for the very low gains during the second quarter of 2012 (Figure B-13). Despite the load issues and reported lower gains, the yearly averages for the 138 kV lines centered around 10% (between 8%-12%). (5)

Discounting the second quarter of 2012's data because of the load anomalies, there is only nominal seasonal variation evident in this particular study.



Source: Used with permission from Oncor (5)

Figure B-12. Daily Distribution (345 kV Lines)



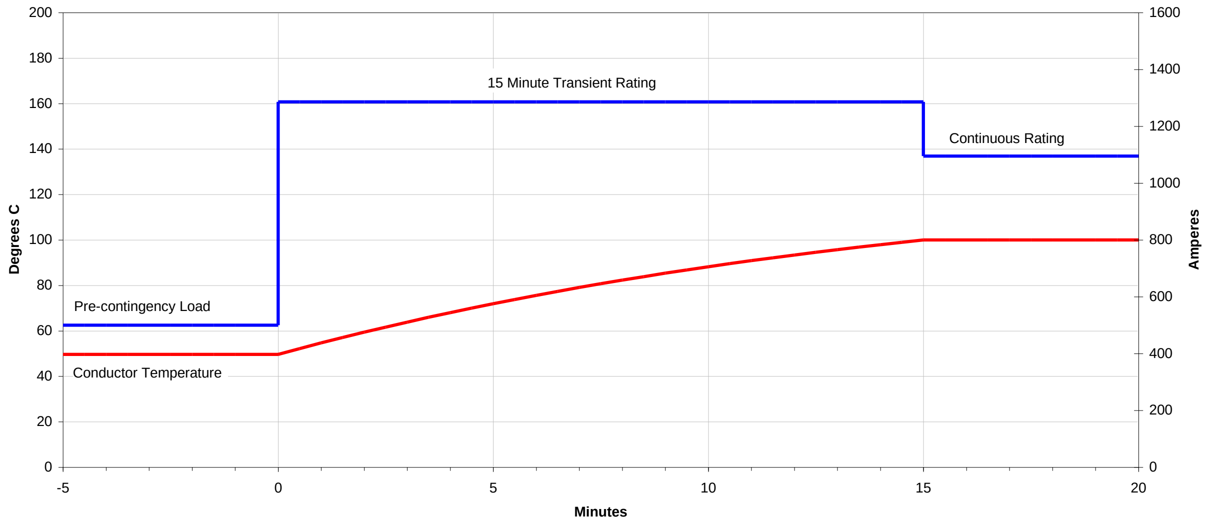
Source: Used with permission from Oncor (5)

Figure B-13. Daily Distribution (138 kV Lines)

B.2.3 Contingency Management Analysis

STE ratings can enable even greater real-time grid capacity gains to be safely tapped for contingency management and for electricity markets that are sufficiently advanced to operate at 15-minute intervals. The average temperature of the conductor is determined in the process of establishing the dynamic rating of a transmission line. That temperature is a prerequisite to determining the real-time transient response of the conductor to a change in load. There are two forms of the transient response that are useful in contingency management: one before the event and one after the event. (5)

Figure B-14 is an example of pre-contingency transient analysis. In this example, the conductor is not permitted to exceed a design temperature of 100 degrees Celsius. Both the load on the line and the conductor's temperature are known at time zero. A DLR system continuously calculates a 15-minute STE rating that identifies how great an increase in load will cause the conductor to reach its 100 degrees Celsius design temperature in 15 minutes, but not before. In practice, an operator can dispatch the system to the STE rating, knowing that, should a contingency event occur, he will have a full 15 minutes to respond. After 15 minutes, the load must be reduced to the real-time continuous rating. (5)

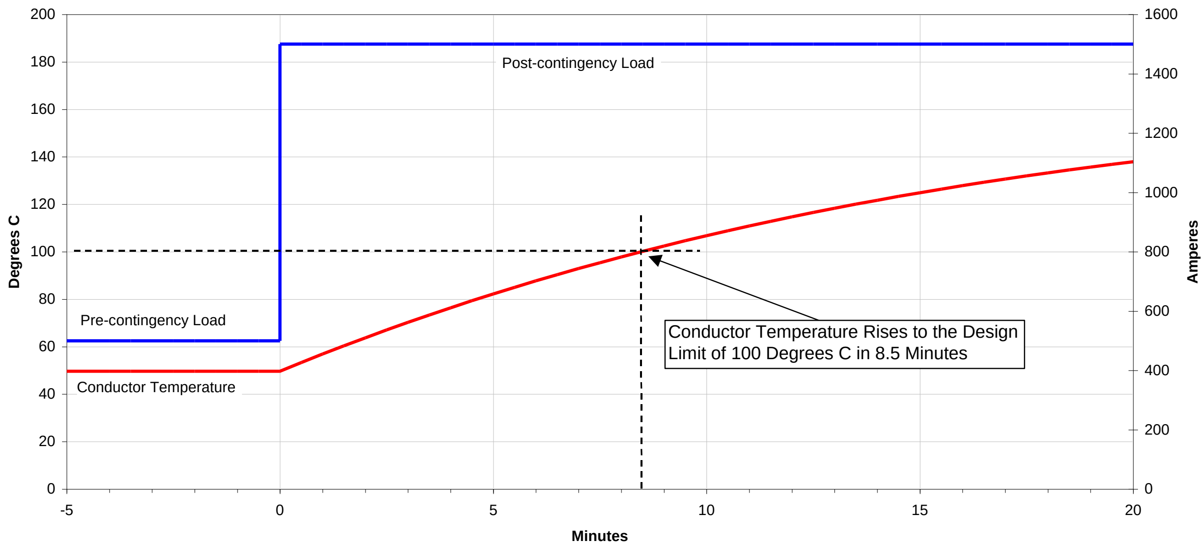


Source: Used with permission from Oncor (5)

Figure B-14. Pre-Contingency Transient Response Analysis (15-Minute Transient Rating)

Figure B-15 is an example of post-contingency transient analysis, where the conductor was previously subjected to a large step current. A DLR system continuously calculates how many minutes will elapse before the conductor reaches its 100 degrees Celsius design temperature for any step in current. In this example, the time is 8.5 minutes. In practice, the operator must reduce load on the line to the real-time continuous rating before 8.5 minutes elapse. (5)

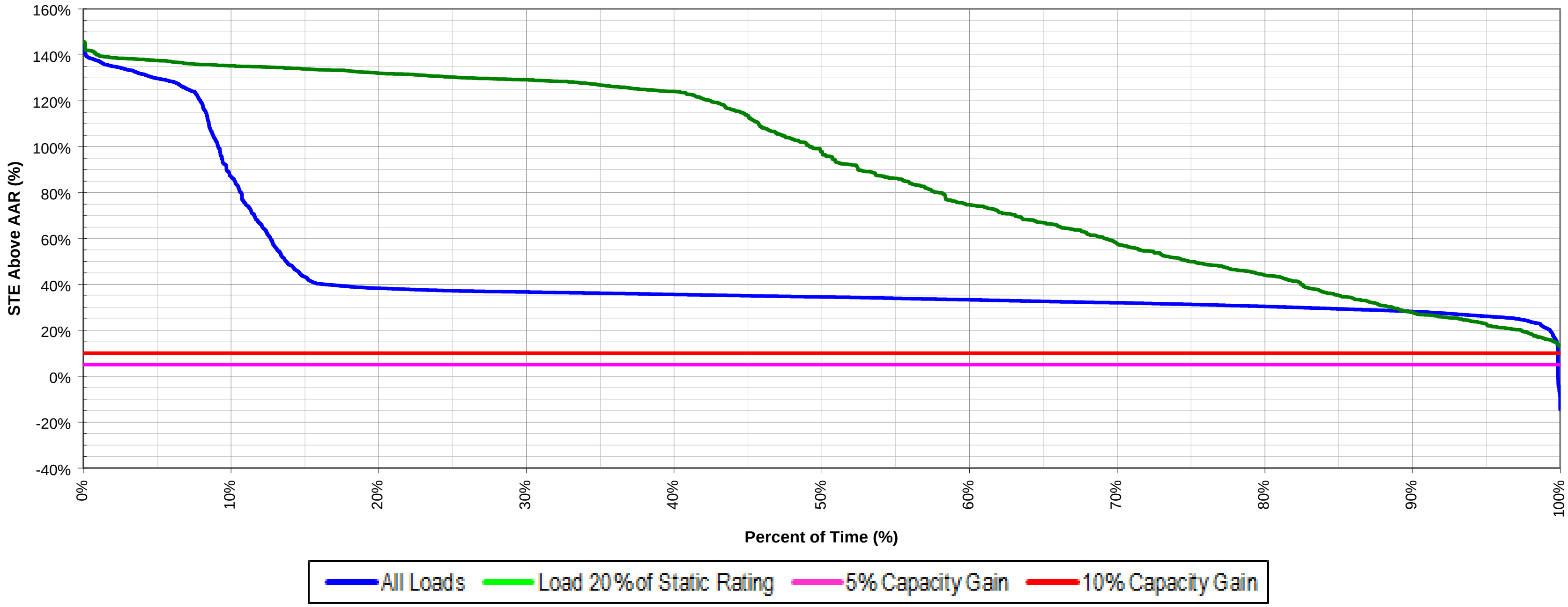
The time available to take corrective actions is valuable information to the operator. If time is short, quick but expensive actions may be required. If a longer time is available, more economical or less-disruptive actions may be taken.



Source: Used with permission from Oncor (5)

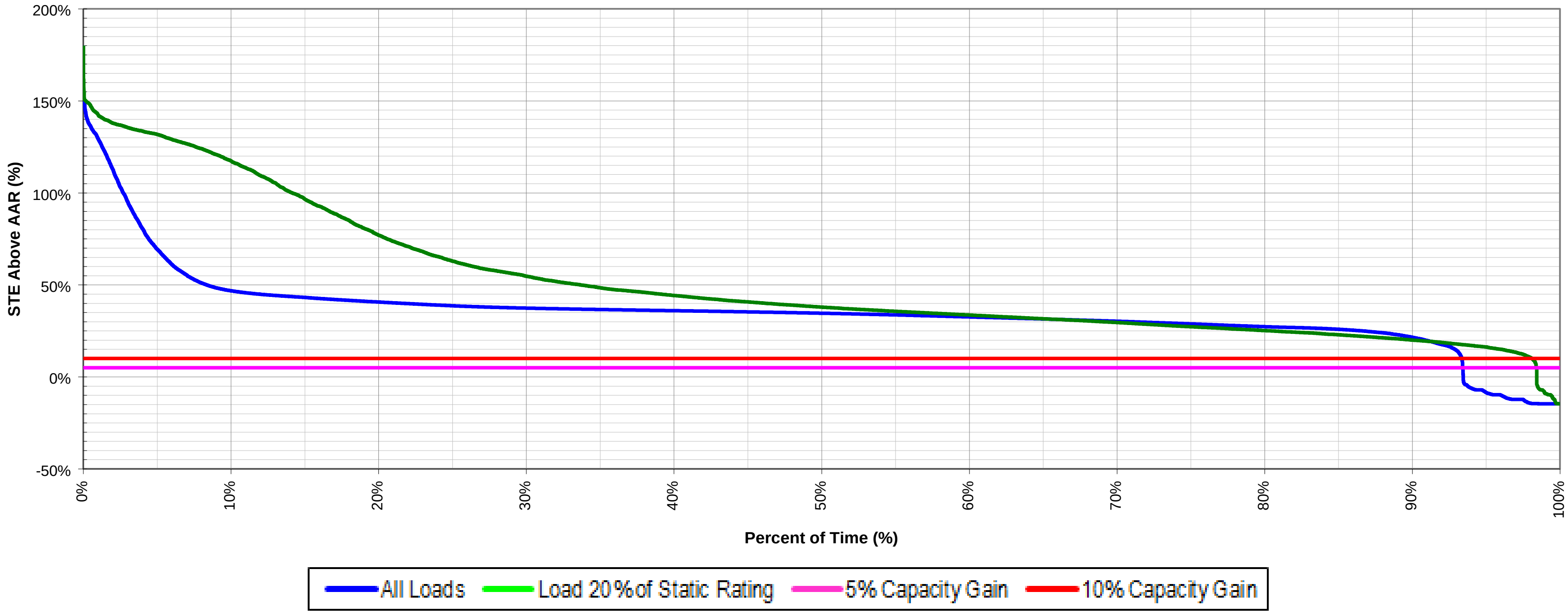
Figure B-15. Post-Contingency Transient Response Time to Design Temperature

Figure B-16 and Figure B-17 show the increased real-time capacity above ambient-adjusted rating that is released by the STE rating. For all 345 kV lines, at least 10% above ambient-adjusted rating is available 93% of the time under all load conditions and 98% of the time under moderate load conditions (when load is greater than 20% of the static rating). Those increased capacities can be safely deployed within a market structure while ensuring lines will always be operated within their limits. (5)



Source: Used with permission from Oncor (5)

Figure B-16. Percent Capacity Gained: STE above Ambient-Adjusted Rating Probability Distribution (Temple Pecan Creek–Temple Switch, September 2011)



Source: Used with permission from Oncor (5)

Figure B-17. Yearly Cumulative Probability Distribution: STE above Ambient-Adjusted Rating (All 345 kV Segments, August 2011–July 2012)

B.2.4 Data Anomalies

Oncor identified several data anomalies, their root causes, and their impacts on the results of the project. (5) These anomalies are summarized in Table B-30.

Anomaly	Description	Impact on Results
Data was corrupted by corona damage at floating dead-end tower sites	The instruments that monitor the transmission conductor are installed at dead-end towers. Since dead-end towers were not located where needed on some transmission lines, floating dead-end towers were constructed. Because the floating dead-end towers constituted a new installation technique for DLR systems, unforeseen corona damage occurred to the instruments' wiring located at the floating dead-end towers. This damage corrupted the data collected prior to August 2011, when the problem was remediated.	All data prior to remedying the signal wiring issue was discarded, resulting in 17 (rather than the anticipated 24) months of collected data.
Low load levels prevented calculation of a true dynamic rating	When lines were lightly loaded (approximately 21%-70% of the time), a variant of dynamic rating, referred to as an NRT-adjusted rating, was calculated; the NRT rating was entered as the dynamic rating in the logs and databases.	NRT-based ratings are generally higher than ambient-adjusted rating but lower than dynamic rating. The widespread application of NRT-adjusted ratings necessitated by widespread low-load conditions significantly depressed the statistics on increased real-time capacity of DLR above ambient-adjusted ratings.
Supervisory Control and Data Acquisition (SCADA) outages prevented data transmission to the Energy Management System (EMS)	SCADA Remote Terminal Unit (RTU) outages occurred, which prevented the transmission line monitors' data from reaching the EMS. During these outages, the dynamic rating associated with the affected monitors defaulted to the static rating, which is consistently lower than ambient-adjusted rating.	SCADA RTU outages depressed the statistics on DLR gain above ambient-adjusted rating.
Invalid load metering on 138 kV lines resulted in erroneously low calculated ratings	Lack of substation metering necessitated calculating load levels on many of the 138 kV segments. The calculated load values were subsequently identified as being erroneously low. Invalid load input to the rating algorithm results in artificially low-calculated effective winds and correspondingly low ratings. Invalid load metering occurred on five of the 138 kV segments.	Line loads reported as erroneously low depressed the statistics on DLR gain above ambient-adjusted ratings.

Anomaly	Description	Impact on Results
Shadowing of net radiation sensors (NRS) interfered with wind speed calculations and led to erroneously low calculated ratings	Shadowing of NRS at some installation sites resulted in calculation of abnormally low effective wind speeds. This also led to artificially low ratings. Field correction of the four worst shadowing sites was completed in April 2012. Refer to Table B-31 for a list of the segments most impacted by shadowing.	Shadowing of NRS depressed the statistics on DLR gain above ambient-adjusted ratings.
Line outages prevented calculation of ratings	Extended line outages on certain segments prevented calculation of ratings. During these outage periods, ratings were defaulted to the static ratings, which are consistently lower than ambient-adjusted ratings.	Extended line outages depressed the statistics on real-time capacity increase above ambient-adjusted ratings.

Source: Navigant analysis; data from (5)

Table B-30. Oncor Project Data Anomalies

Table B-31 shows which line segments were most impacted by shadowing.

Segment	Shadowing Times	Date Corrected
Lake Creek–Temple	9:00 – 12:00	Not corrected (site access issue)
Lake Creek–Temple	10:00 – 12:00	April 19, 2012
Tradinghouse–Temple Pecan Creek	9:00 – 12:00	Not corrected (site access issue)
Trading house–Temple Pecan Creek	10:00 – 12:00	April 19, 2012
Cottonbelt Tap–Spring Valley Tap	8:00 – 11:00	Not corrected (site access issue)
Cottonbelt Tap–Spring Valley Tap	8:00 – 11:00	Not corrected (site access issue)
Bell County–Salado	10:00 – 13:00	April 20, 2012
Jarrell East–Gabriel	16:00 – 18:00	April 18, 2012

Source: Navigant analysis; data from (5)

Table B-31. Lines Most Impacted by Shadowing

Appendix C. Best Practices Guide

The analyses and observations contained in this appendix synthesize two sections of Oncor's final Technology Performance Report (TPR), Section 5: Best Practices Guide and Appendix I: Lessons Learned. (5) This appendix primarily addresses the deployment of Nexans' CAT-1 System, although it is applicable to the implementation of other DLR systems. This guide is meant to provide a roadmap for selecting lines for future DLR systems, developing a deployment plan, and incorporating the DLR results in transmission system operations. The need for dynamic ratings can be assessed through system planning or at the request of the system operator to provide increased real-time capacity on a given line for reliability improvement or congestion relief.

The successful implementation of a DLR system not only includes the calculation of a dynamic rating for the line segment; it also includes the automatic incorporation of this data into the transmission grid telemetry, where reliability assessments associated with N-1 contingencies are performed as part of the system operator's entomic dispatch of generation and reliability management of their grid. The best solution is to install an appropriate number of real-time monitors on a given circuit, analyze the data in real time, forecast the available dynamic rating for the next selected time period (e.g., five minutes to one hour), and post the data for the system operator to apply in their standard procedures.

The system operator can deploy the dynamic rating in one of two formats. In both cases, real-time monitoring is deployed and transmitted to the operations system. In the first option, the dynamic rating is posted to the operating desk monitors, where the operator can access the data, identify the dynamic rating of the line, and decide whether or not to accept that rating and use it for operations. This requires operators to have full confidence in the DLR equipment, such that the operator knows that the displayed ratings accurately portray grid conditions. The second option is to collect the dynamic rating in real time and automatically transmit it into the control system (SCADA or EMS). The system operator then performs periodic iterations of the state-estimator system, which performs operation decisions and dispatch orders. Data validation logic can be built into the EMS to validate the accuracy and authenticity of the dynamic rating before passing it to the system operator. If there are concerns about the dynamic rating for any reason, the dynamic rating reverts to the system-standard rating methodology and sends an alert to a manned desk for assessment and corrective actions.

There is a secondary benefit of real-time streaming of dynamic ratings in the form of increased system awareness. By operating on the data automatically, the system operations environment not only takes advantage of the real-time capacity available but also is immediately aware of it and adjusts to accommodate changes automatically.

DLR systems can also be deployed for planning studies. In this type of deployment, DLR equipment is installed and data is recorded for a certain length of time (ranging from a peak season to a year to several loading cycles or seasons). The data is analyzed to establish an incremental DLR capacity based on the snapshot of historical data. These studies may be coupled with some weather characterization, which may include scaling the rating to a given ambient temperature or to some wind speed from a weather station. Oncor believes that DLR systems are more valuable for real-time operations, as described above, than for planning purposes. Planning studies require more lead time, do not truly utilize DLR technologies' real-time applications, and result in the loss of Wide-Area Situational Awareness (WASA). (5) Other transmission owners, such as NYPA, may regard DLR technologies as potentially useful planning tools. (4)

C.1 Project Planning and Design

This section discusses best practices for planning and designing DLR deployments. The topics discussed here include selection of transmission lines for DLR instrumentation, technology selection, and DLR system design and layout, along with other key planning and design considerations.

C.1.1 Meeting Incremental Load Growth

The need for increased capacity may be discovered during the course of system planning, the regular process of evaluating the impact of load growth and system changes during each annual cycle while identifying projects for consideration and placing them in the development queue for evaluation and ranking for funding authorization. This process may be slow and lengthy. The priority and need may not create enough return on investment (ROI) for the capital authorization of a project, and the project may not proceed to funding and construction. In some cases, these small percentage overloads may be associated with other reliability or operating issues that are less quantifiable in financial terms that would allow the project to proceed to funding and construction.

The need for additional capacity may be the result of some new generation source being placed on the grid, which requires all or some portion of the capacity of an existing transmission path. While the amount of added capacity is typically higher for this type of project, the closer the generation source is coupled to a given circuit, the more likely an existing circuit is a "supporting" line or redundant path for North American Electric Reliability Corporation (NERC) category N-1 contingencies. Under many of these cases, the contingency constraints may be small percentages of increased capacity above the static or ambient-adjusted rating of the line, rather than significant capacity increase requirements.

Congestion constraints can also create a need for increased capacity. In many cases, incremental capacity needs are in the range of a 5%-10% increase. As in the case of the system planning queue, these projects are difficult to push forward to authorization, as their justification on financial terms is not easily quantified or justified for their return on investment.

There are several scenarios for projects that need some incremental capacity improvement but lack the ROI justification to move them forward as capital projects. These projects may be favorable candidates for DLR installation. DLR technologies offer several advantages that can help solve these issues:

- DLR systems can reliably provide incremental capacity improvements with high probability of availability at minimum costs per percent increase in capacity, compared to traditional solutions of upgrades, rebuilds, or additional transmission lines, especially when incremental need is no more than 10%-20% additional capacity.
- DLR systems are flexible. If a system topology change reduces the need for capacity, the DLR equipment can be removed and installed on another line that needs incremental capacity at that time. This minimizes the investment of capital dollars, which may, in the future, have limited need.
- Lead time for DLR deployment from conception to deployment and operating can be short, typically several months, depending on the DLR equipment availability and type of system being deployed. Compare this to lead times for new lines or upgrade projects, which are often significantly longer.
- DLR systems are economical, with high benefit-to-installed-cost ratios.

C.1.2 Solutions for Derated Lines

Another application for DLR technologies may be resolving issues with lines that were derated as a result of addressing NERC reporting requirements. Many transmission owners identified line sections with clearances where the design and construction of a transmission line did not meet clearance requirements or where subsequent changes, such as landslides, construction activities, etc., reduced the design clearances. The resolution to regain full line capacity may be obtained by traditional capital investments, such as increasing structure heights or rebuilding or reconductoring the line. Many resolutions may require substantial investments or extended periods of lead time to secure additional permissions to complete the resolution (e.g., new easements, permits, or outage time to complete the modifications).

Some DLR vendors market their systems as an "alarm system" that notifies the line manager if an operation constraint will be imposed due to a clearance restriction. Such an alarm system requires several steps, including detection, notification, acknowledgement, and corrective action. On the other hand, other DLR systems, such as Oncor's integrated DLR system, act as a monitoring system, mitigating the constraint via an automated, wide-area system awareness that provides the system operator with a quasi-continuous update of the available capacity of the line section. (5) If and when a constraint may develop due to ambient weather conditions or increased loading in the area or on the line, the DLR system maintains system awareness, and the EMS automatically adjusts and optimizes the system on a continuing basis. There is no abrupt change in system characteristics that must be addressed. The static line rating remains at the derated level (i.e., maximum operating temperature based on the available line clearance). By installing DLR technology, the line can be operated at the fully available, real-time capacity of the line based on real-time operating and ambient conditions.

The key aspect in this application is the continuous stream of data to system operations and its ability to work an optimum solution for real-time grid conditions. An "alarm" type system requires a more drastic response. A monitoring system maintains grid reliability automatically and allows the system to adjust to whatever transfer capacity the real-time parameters allow.

C.1.3 Selecting Transmission Lines for Dynamic Line Rating

DLR technology is a tool that can be used on any transmission system to increase the capacity of a given transmission circuit, taking advantage of the cooling effect of wind and ambient temperatures to more fully utilize the capacity of the conductor already installed on the transmission line. The first step in planning for a DLR installation is to determine which lines to monitor. Initial selection involves determining a transfer path where possible and significant commercial constraint is observed. Since the goal of DLR technology is to reduce constraints by allowing the transmission operator to operate the lines at higher than normal current loads, it is recommended that initial installations be placed in transmission paths with high historical constraint problems.

Oncor determined that monitoring of actual line loading and congestion and predicting line loading using a power flow program were the best methods to identify lines as candidates for DLR equipment. This process is the same used for planning upgrades to the transmission system. The process is well-established, validated, and continually modified to address changing transmission conditions. The process has faults, however, in that a number of assumptions about future load growth and generation changes must be made. The basis for these assumptions has considerable uncertainty, particularly where generation assumptions are made.

The variability of actual congestion load events can make it difficult to determine the best lines to monitor. Analysis of congestion versus load growth congestion is sporadic and depends on many variables, such as time of year, generation outages, line outages, or other factors. The impact to downstream lines is difficult to model. Integrating as many variables as practical, as well as careful analysis of planned lines to monitor by experienced transmission operations engineers, can help to ensure a selection of the best lines to monitor for the best economic results from DLR technology.

The transmission owner must take into consideration any planned maintenance outages for the lines identified. Lines that will be out of service for extended periods may not be suitable candidates for near-term data collection using DLR technology. (5)

C.1.4 Technology Selection

Several DLR technologies are currently available in the marketplace. The biggest factor in selecting a technology is the realization that a transmission line is defined by its spatial context with regard to the area it traverses and the ambient environment conditions to which it is exposed. The spatial context and behavior of the conductor, insulator systems, and structures responding to the external influences that affect the dynamic rating performance of the system require a spatially sensitive monitoring system. Point sensors have no spatial context and can only reflect the performance of the wire above a limited length, perhaps one foot in length. Even applying multiple devices along the line gives very limited spatial context of the line's behavior. The placement of point sensors must therefore be carefully considered. Position sensors, however, can determine the spatial context of the line. (5) Refer to Section 2.3 for a discussion of the various types of DLR devices.

C.1.5 DLR System Design and Layout

Once the target lines are identified for DLR installation, the layout of the DLR monitors and selection of technologies can proceed.

The spatial context of a transmission line, as outlined previously, requires the installation of DLR equipment that can monitor the conductor behavior of a stringing section, not a point characterization or a system of multi-point monitoring. The rating of the line is the minimum rating of the monitors installed along the length of the line.

Transmission line alignment is the first order of assessment for locating sensors. The dynamic rating is influenced most by the effective wind speed on the conductor. The closer the incident angle of the wind is to being perpendicular to the conductor, the greater the wind's impact on the line rating. Sheltering from ground cover or terrain can also influence the wind effect on the conductor temperature. Therefore, line orientation is critical to deployment design.

The dead-end structures at the end of line sections with different orientation are primary candidate structures for DLR installations that monitor tension. If the line angle is moderate, the structure may use a side-tension construction. When the orientation changes by 15 degrees or more, Oncor advises that this creates two line sections. (5) If sag or clearance monitoring technology is applied, these locations define the end-points of sections that define separate monitoring requirements.

Additional DLR locations depend on defining the actual ruling span breakdown of the line. Changes in ruling span lengths of various line sections may need independent monitoring from other sections. While the line designer did not install dead-end structures between these ruling span sections, the DLR system depends on the equalization of the conductor horizontal tension over many spans (i.e., insulator swing), which may have varying ruling spans. A DLR system must acknowledge when these ruling spans differ significantly, such that the equalization due to insulator swing in the spans would be different section by section.

Once the stringing sections are identified, the overall lengths of the different sections are reviewed for how long a distance each monitoring site might have to cover. Oncor identified consistent characterization of the stringing section when the distance between DLR monitors were as far as five miles apart and the terrain was no more than rolling hills. The long stringing sections should be evaluated for length and changes in sheltering of the line, such that a sufficient number of monitors are placed to address each of the changes and maintain the “reach” of each monitor at a reasonable length.

If the positional or in-span monitors are being applied, they can be spaced at appropriate locations to monitor each line section. In the case of the tension-monitoring systems, if the length of a stringing section becomes so long that intermediate monitors are needed in a tangent suspension length of line, conversion of one or more structures from tangent to dead-end may be required. Some applications of floating dead-ends have been applied where a dead-end was not available. However, a dead-end structure is preferred.

Running angles up to 15-18 degrees can be typically considered part of a stringing section. Above that angle, the wire tension on the angle makes the insulator swing (and therefore horizontal tension equilibrium) difficult to achieve past that structure. The larger angles will define changes in stringing sections and thus a section break in defining the ratings of the line.

Braced-post and horizontal line posts do not allow as much longitudinal displacement as a suspension insulator string to effectively create horizontal tension equilibrium. Discussions should be held with the respective DLR vendor to discuss their experience with dealing with this type of transmission framing and their system's response. In some cases, enough longitudinal flexibility is provided to create a long stringing section. In other cases, the flexibility will be limited and additional monitoring locations required.

Some DLR vendors suggest analyzing the line for the critical spans (i.e., spans with minimal clearance) and starting the deployment at these locations. However, the critical span is only the critical span for a specific set of operating and environmental parameters. Operating conditions are unpredictable; thus, the critical span may change. A properly deployed DLR system monitors the full length of the transmission line or deploys enough point sensors to accurately assess the average capabilities of the line.

With these considerations, a sufficient number of monitoring sites should be identified. It is a goal to minimize the number of instrument deployments but also necessary to capture each subsection characterization, where a different horizontal equilibrium—and, therefore, effective dynamic ratings—would characterize the line performance.

C.1.6 Determining Placement of DLR Devices

Oncor's DLR vendor, Nexans, prescribes a standard process for placement of the CAT-1 System. CAT-1 remote units, each with two load cells, should be placed along the transmission line in spatial intervals. For example, on a 40-mile transmission line, a CAT-1 unit should be placed at mile 8, 16, 24, and 32. Actual unit placement is determined by identifying any dead-end structures along the line. If dead-end structures are not available in line with the standard spatial arrangement, then structures at the spatial intervals should be converted into floating or standard dead-ends. Oncor advises that using dead-end structures eases installation and reduces cost. (5)

Understanding the sag-tension relationship on the as-built line is critical. In order to receive accurate sag measurements from the DLR system, precise values of span length are needed for each span being monitored. Imprecise measurements can lead to significant sag measurement error. For example, an error of 18 feet in span length equates to a one-foot error in sag for a 138 kV line with an estimated span length of 640 feet under 3,500-pound force tension.

Oncor offers advice on determining the placement of the CATMaster units, which is normally located in a substation, switching station, or microwave station and contains the "receiving" radio and an RTU to facilitate placement of the CAT-1 data onto the SCADA network.

The first step of the process was to determine any and all potential SCADA access sites along the transmission line corridors that were owned by the utility. Any SCADA access sites that have a clear line of sight to a CAT-1 device were found to be potential CATMaster sites.

The next step was to determine the radio coverage that each potential SCADA access site had in the region of the transmission line corridor, which is usually limited to a circumference of about 15-miles. Then, using the software, each CAT-1 radio path was shown in a ground elevation profile plot to determine if there were any obstructions to a potential SCADA access site within 15 miles of the CAT-1 unit. The ideal path from the CAT-1 device to the ideal CATMaster was chosen. The radio paths were tested onsite using a radio test kit. The radio test kit uses equivalent radio types. One radio and antenna was placed near the CAT-1 unit at the correct bearing, and another radio and antenna was placed at the proposed CATMaster site, also at the correct bearing. The radios were then energized, and a radio signal strength test was performed to ensure that the radio path chosen was clear from obstruction. Performing this onsite test ensures that there are no obstructions that may not show up in a topographical software package (e.g., trees, buildings, or other structures).

The importance of performing the onsite radio paths cannot be understated. For example, during the installation of Oncor's SGDP project equipment, the installation of the CAT-1 devices on the Bosque-Elm Mott 138 kV line was performed after the software-based radio path analysis was performed, but before the onsite radio path verification tests could be performed. The software-based analysis indicated that the lines-of-sight were clear, but the Bosque-Elm Mott line was very straight with negligible line angles or changes in structure elevation. This caused the radio paths from two out of the three installed CAT-1 devices to be blocked by the very structures themselves. An additional repeater was executed to alleviate this issue. The onsite radio tests would have caught this issue, and the additional CAT-1 Repeater requirement could have been known prior to installation. Any future DLR installations should not be performed without adequate radio path testing. (5)

While performing the radio path, software analysis does add cost to the project; this cost is small relative to the potential troubleshooting, re-clearancing, crew dispatching, and equipment installation/reinstallation that may be required to ensure a clear communication path. Careful CATMaster placement limits the total number of CATMasters required to receive the CAT-1 data from the transmission line structures and therefore optimizes the cost of materials and installation. In addition, careful planning ensures that the CAT-1 data will be successfully received by the CATMasters. This careful planning eliminates any rework or system problems during the installation phase.

C.1.7 Installation Planning

Proper planning for installation of DLR equipment will make the process smoother and faster. Included in this section are several areas of planning that should be addressed for a successful deployment of a DLR system.

Transmission owners deploying new DLR systems should understand clearance scheduling procedures prior to planning installation. (5) It is usually harder to get required installation clearances on lines that have high historical constraints. Therefore, early planning is required to install DLR technology on high-congestion lines, since clearances may not be grantable on critical lines until the cooler months of the year. For many DLR devices, clearances need to be planned to include an outage period after installation to allow for no-load calibration to occur. In Oncor’s case, clearances were only planned for the length of time required to install the equipment. In several instances, clearances were lifted on the lines before calibration could occur, resulting in additional clearances having to be planned after installation.

Physical location scouting should be conducted. (5) An important aspect of installation planning was the scouting of structures that were identified for installation. This was not always accomplished during the initial project planning stages, and, as a result, some identified structures were discovered to be inaccessible or difficult to reach. This necessitated some last-minute changes to installation planning that could have been avoided if field scouting had been conducted prior to final selection of the installation structures.

Physical scouting of the structures selected for placement should look at sunlight patterns to determine where shading of the NRS might occur during sunlight hours. Notes should be taken and provided to the installation planning group so that a proper location to mount the sensor can be identified in the drawing for that structure to ensure that the sensor is not shaded by the structure during the day.

The vendor should also review the installation plan. With the vendor being the expert on their DLR technology and the transmission owner being the expert on their transmission lines, it is important for the two to identify and coordinate early and often during the installation planning process. The vendor should provide the owner with the installation parameters required for their system. The owner should then develop engineering drawings that show the structure modifications necessary for installation and the bill of materials required to complete the installation during a single scheduled clearance.

C.2 Equipment Installation

Equipment installation includes considerations for scheduling installation and crew training, installing the equipment according to the vendor's specifications, and calibrating and integrating equipment into the EMS.

C.2.1 Installation Scheduling

At Oncor, installation scheduling went according to typical plans for scheduling line maintenance where an outage is required, with a few exceptions unique to the DLR installation. For DLR installation, it was necessary to include the vendor in the installation schedule, allowing vendor personnel to perform as onsite engineering resources throughout the duration of the installations to support the installation crews. Vendor personnel were able to provide additional installation training and guidance on the finer details of the installations, specifically where problems or questions arose.

There were a few cases where the installation foreman found that some structures were inaccessible or hard to reach. This caused a few last-minute structure changes. In future DLR installation projects, it is recommended that this scouting be performed during the planning phase and not during installation, as it caused a few last-minute updates to occur in documentation and configuration, all of which could have been avoided if the structure access had been confirmed prior to installation. Additionally, the landowner of one structure would not allow the installation crew to be on his property, forcing the installation crew to make a last-minute structure change. A method to avoid this issue must be established. The takeaway from Oncor's experience is to not take landowner access permissions for granted.

C.2.2 Crew Scheduling and Training

While dependent on the size of the installation being conducted, it is recommended that a minimum number of crews be utilized to conduct the entire installation. This allows for more efficient training to be conducted and for the crew to become more experienced and more efficient for each subsequent installation. Because only one team was utilized during Oncor's SGDP project, the team became more efficient over time and was able to complete some installations ahead of schedule, allowing line clearances to be released sooner and lines to be re-energized earlier. (5)

Engineering drawings based on installation details and specifics provided by the vendor were of great assistance to the installation crews. These drawings included a bill of materials required for each installation structure.

It is recommended that engineering drawings developed by the transmission owner be provided to the vendor for review in order to ensure that the installation details for the DLR technology are correct. A joint review session of installation drawings would allow them to be validated for accuracy and completeness prior to their delivery to the installation crews. (5)

C.2.3 Equipment Calibration and Integration into the EMS

Once the equipment is installed, individual technologies have their own specific calibration needs. The calibration process is required to associate the measured quantity with the equivalent conductor temperature of the monitored line section. Line ratings depend on an accurate correlation of the measured quantity to the equivalent conductor temperature and the variables that drive the thermal performance of the conductor (i.e., the current flowing in the line, the ambient temperature, the solar absorption of the conductor, and the effective wind speed). Knowing these parameters allows the calculation of the maximum operating temperature associated with the clearance constraint of the line design.

The calibration process defines the “as-built” sag-tension-temperature characteristics of the ruling span section and thus its thermal behavior. Each technology and vendor has a unique calibration process, which needs to be followed to set the forecasting product of the DLR system. Many require a line outage of several hours longer than the conductor size’s time constant.

DLR systems have to be integrated into the transmission owner’s EMS in order to make the dynamic ratings effective in enabling real-time capacity release.

Nexans has specific hardware requirements for the DLR server, which Oncor met as part of its SGDP project. Alarm codes, as defined by the vendor, were implemented within the EMS using a different naming convention. This created confusion when Oncor discussed alarm events with the vendor. When implementing alarm codes within the EMS, it is recommended that the transmission owner work with the vendor to define a DLR EMS alarm code map to allow for quicker discussion and resolution of alarm codes. (5)

C.3 Implementation with the System Operator

This section discusses strategies for facilitating system operator acceptance of the DLR system, meeting interoperability and cybersecurity concerns, and including considerations for the next limiting element on the grid.

C.3.1 System Operator Acceptance

System operators must have confidence in the DLR system to provide accurate ratings with high reliability and availability (minimal interruption of the dynamic rating). Dynamic ratings must be inherently simple to apply and intrinsic to system operations. These criteria are met in the following ways.

Accuracy. The dynamic rating model and algorithms must accurately assess the ambient conditions along a transmission line and their impact on the line's capability. The predicted full capacity of the line must also be accurate so that the dynamic rating is a reliable and accurate assessment of the line's capability. The effective ambient temperature and wind speed on the many spans of the transmission section are incorporated into the characterization of the current status of the line. Ambient temperature and wind speed also help characterize how increased power transfer will affect the conductor sag and respective clearances.

Reliability. Beyond the accuracy of the calculated rating, the reliability of the system in terms of confidence in the calculated value is critical to the system operator's acceptance. A series of sanity checks for DLR systems address these criteria:

- Rating within acceptable range
- Sufficient number of monitors available for predicting the line section's performance
- Cybersecurity concerns addressed from an intrusion and/or "spoofing" aspect

Availability. The DLR system must have a high level of availability and reliability of performance. If there are frequent interruptions to the monitoring system and ratings calculations, the system operator will not be able to depend on having a consistent forecast of the true dynamic rating.

Minimal impact on current operations protocol. The introduction of the new DLR system and its real-time operations must not impose additional burden on the system operator's staff and protocol. Real-time streaming of the dynamic rating within the communication and control system (SCADA or EMS) best achieves this criterion. The system operator's staff does not have to take additional steps to assess the availability or status of the dynamic rating, as the system incorporates the dynamic rating into the real-time system status after performing an appropriate level of quality checks. The system automatically reverts to the traditional rating methodology (i.e., a static or ambient-adjusted rating) if any sanity checks performed within the DLR system determine that the rating's accuracy or availability is questionable. No operator intervention is required.

By using the DLR technology and protocol as applied in Oncor's SGDP project, this model does not require additional training of the operation's staff. The protocol is built into the control system such that the introduction of the real-time dynamic rating is fully transparent to the system operator's staff. The validity and accuracy logic checks built into the control system provide alerts to a specific transmission owner engineer, who is informed if there is an issue with any component of the DLR system, from communications to accuracy and cybersecurity issues. A protocol directs the engineer in how to address the alarm and resolve any issues.

In the event of invalid or inaccurate dynamic ratings, the control system reverts the rating to the traditional rating methodology. The system operator's protocol continues to operate and uses that rating for the next economic dispatch and reliability nodal assessment; the system operator is not required to intervene or make decisions. When the issue with the DLR system is resolved, the dynamic rating is reintroduced to the operations telemetry.

C.3.2 Interoperability and Cybersecurity

The accumulation and security of the real-time data depends on the technology used for DLR systems and the transmission operations and IT environment. Certain DLR technologies use communication technology to send the dynamic rating to local accumulators at a nearby substation, where it is inserted into the SCADA system through an RTU. Once in the SCADA system, the data is transmitted to system operations for processing, quality and integrity checks, and introduction to real-time operations. Other DLR technologies are based on cellular communication. This may require a dedicated server at the transmission owner's office where the DLR processing and quality checks are performed before the data is introduced to the operating environment. Some transmission owners' IT and cybersecurity requirements may require that the server reside outside of the firewall first and then introduce the data to system operations. Other transmission owners may allow the raw data to come across the firewall.

The transmission owner must coordinate with the DLR technology vendor for the specific protocol required to bring the data into the system operator's purview. One vendor or more may be involved in the remote monitoring systems on the transmission line and then parallel paths transcend to the juncture with the EMS, which coordinates the introduction of the ratings into the system telemetry.

Interoperability of the DLR systems defines their ability to perform certain functions independent of the transmission owner's IT environment yet to conveniently and transparently interface with the owner's EMS environment. The various vendors of DLR equipment communicate across this interface in a number of ways, and it is important that the transmission owner and vendor have an open commitment to work collectively to bridge the gap. It is in the vendors' interests to be accommodating of the transmission owner's network and protocols; similarly, the transmission owner must be willing to work with the vendor to make the communication as efficient and reliable as possible.

This interoperability is important in the DLR industry, as each DLR technology available is essentially unique. DLR technology is not a commodity market where multiple vendors make interchangeable components that can interface seamlessly into the application. DLR technologies are not interchangeable from a hardware perspective; however, from a communications and interoperability standpoint, they should ideally interface seamlessly to the transmission owner's EMS environment.

Cybersecurity is a lifecycle commitment for DLR technology that must begin with vendor approval and be carried through deployment. Procurement of DLR equipment must require the vendors to address cybersecurity at their equipment level, as well for all subsystems they may purchase and incorporate into their system. Cybersecurity addresses the protection of DLR technology and data on multiple levels: in onsite hardware, in the communications paths and links, and in the DLR data itself.

Cybersecurity should address the protection of the equipment in the field such that any attempts to break into the equipment and associated equipment facilities are identified, logged, and communicated to an appropriate system awareness location. It should be designed to identify if there is any intrusion in the data communications path between remote data acquisition site and the eventual data delivery point at the utility. Surveillance and alarms should be applied for intrusions in the data path where market participants or others attempt to alter, append, replace, or interfere with the DLR data collection, transmission, and processing.

Cybersecurity is a concern from equipment conception through development, installation, operations, and maintenance for the lifecycle of the instrumentation. System modifications and updates should be made to ensure the DLR system is current with the technology environment.

The list below highlights some of the items to consider when installing the DLR system into an existing secure utility. Although many of the recommendations made here are valid for a system that extends beyond the DLR system, the outline provided below focuses on the DLR system and its interface with the transmission owner:

- Procurement
  - Perform risk assessment
    - Identify potential threats to the system and assign likelihoods and impacts

        - Determine controls necessary to mitigate those threats
    - Include security requirements in the request for proposal (RFP)
        - Require data confidentiality, communications integrity, and user authentication
        - Require physical security of components in the system
        - Establish a secure way to change keys and, possibly, encryption algorithms
        - Mandate that security requirements “flow down” to suppliers of suppliers
        - Mandate that all third-party communication links are secure
        - Establish a standard for the components that references external standards, compliance requirements, and terms
    - Perform validation of the vendor’s security mechanisms (typically performed by an independent third party), which in itself may require a separate procurement standard and protocol
        - Ensure that all security requirements are being met
        - Verify that the proposed system does not contain vulnerabilities
        - Provide documentation of assets and utilized encryption algorithms and technologies
    - Maintain evidence of security practices and risk management through proper documentation
- Installation
    - Establish a secure method for installation of device-specific security keys
    - Establish an approach for verifying that the system is configured and deployed securely
    - Establish an alerts-and-alarms response plan to ensure secure operation
    - Train users and operators on new system and security processes
    - Maintain evidence of security practices and risk management through proper documentation
- Operations
    - Establish a routine security review of the deployed system, security processes, users, and operators (this may be part of annual NERC Compliance)
    - Rotate keys (in a secure fashion) periodically to prevent possible cryptographic attacks
    - Update systems with patches that fix potential security flaws, as released by vendor

- Maintain a test system to verify patches and the security of the system before implementation in the production system
- Perform regression testing on new software and firmware
- Investigate all suspected security events as per established response plan
- Perform configuration management and maintain accurate and up-to-date system documentation
- Ensure that utilized security technology is not past recommended end-of-life
- Identify vendors for replacement components and/or obtain spares for critical system devices
- Provide a way to train users and operators on the system and security (this may be covered in annual NERC Critical Infrastructure Protection [CIP] compliance training)
- Log and audit information relevant to security
- Proactively assess system requirements and actively pursue and manage mitigation activities
- Maintain evidence of security practices and risk management through proper documentation

♦ Retirement

- Establish a procedure for disposing of devices in a secure fashion (clearing memory of passwords, keys, other sensitive information)
- Change passwords and keys as necessary for personnel once access is no longer required
- Ensure that out-of-date documentation is disposed of properly
- Monitor device failures for possible trends in failure modes
- Maintain evidence of security practices and risk management through proper documentation

C.3.3 Next Limiting Element

The transmission line is not the only element that can constrain the capacity of a line. Switches, circuit breakers, wave traps, and current transformers on equipment all have ratings that cannot be exceeded during operations in terms of real loading and for N-1 contingency. As discussed in Section 5.3.2, these ratings may be static or ambient-adjusted; ambient-adjusted ratings based on real-time ambient temperature data are also possible.

When designing a DLR system, the associated equipment ratings must also be considered. Once a line has been selected for DLR implementation, all of the elements on the path or monitoring the load flow on the path must be checked to ensure that their rating exceeds the anticipated increase in capacity being gained via the DLR equipment. Another area that requires review is the relay settings. If the allowable ratings change is over a range broader than the relay settings are governing, the associated equipment ratings must be addressed to accommodate whatever range is allowed with the dynamic rating. One way to manage this is to cap the maximum ratings increase allowed with a DLR system at 125% (or another value) of the static rating. This contains the ratings swing and makes the task of setting equipment ratings easier.

C.4 Example Project

As a template, the following description of the deployment of tension-monitoring DLR installation will provide an example of how the system was designed and deployed.

Through its system planning practices, the transmission owner selects five lines for dynamic ratings. For each line, the plan and profile or section maps are reviewed to analyze a breakdown of the line topography searching for tangent sections that run in the same direction. Each section is compared to the others for length, compass bearing, topography, and terrain. In addition, any wire size changes, different stringing sections, and configurations are identified. Many lines have identical characteristics except compass bearing of several line sections. For those sections with the same bearing, the need to monitor each depends on the distance between them and any terrain changes between them.

The primary consideration for laying out the monitor locations is how different the effective wind can be on each section of conductor. If the sections' orientation, distance from each other, or sheltering differs, they need monitoring. The focus is on determining the line's minimum "maximum dynamic rating." If one section could be different from another, the DLR system must be designed and laid out to capture that difference.

Through Oncor's SGDP project, it has been shown that monitoring devices on a stringing section have a reach of several miles and that their accuracy in predicting the conductor temperature can be 1 to 2 degrees Celsius. If these patterns translate to other DLR deployments, there is no need for additional redundant monitors. The prescribed monitors will provide sufficient redundancy within themselves to accurately characterize the line's dynamic rating.

Once the preferred set of monitor locations is identified, the means of communicating the information back to the transmission owner's EMS facilities must be identified. Then, the protocol to assess the validity of the data and the assignment of each line's dynamic rating are executed. As an example, if the remote systems required a line-of-sight radio system to bring the data to the EMS, an evaluation of practical RTU sites must be considered. This involves several factors, including determining if the RTU capabilities match the interoperability requirements of the DLR equipment and determining whether the line-of-sight radio paths require repeater stations. If a cellular retrieval system is used, then the proper equipment and software at the firewall to the EMS must be established to meet the transmission owner's IT and cybersecurity requirements. In either case, the remote data is brought inside the transmission owner's IT firewall at some point, where the data is evaluated for compliance with acceptable ranges and validity before dynamic ratings are calculated. The prescribed dynamic rating is then posted to the system's real-time status telemetry and applied in all operations tasks.