International Renewable Energy Agency

DYNAMIC LINE RATING

INNOVATION LANDSCAPE BRIEF

International Renewable Energy Agency

ISBN 978-92-9260-182-9

Citation: IRENA (2020), *Innovation landscape brief: Dynamic line rating*, International Renewable Energy Agency, Abu Dhabi.

ABOUT IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

ACKNOWLEDGEMENTS

This report was prepared by the Innovation team at IRENA's Innovation and Technology Centre (IITC) and was authored by Arina Anisie and Francisco Boshell, with additional contributions and support from Shikhin Mehrotra (KPMG India).

Valuable review was provided by Jean-Luis Repetto and Rena Kuwahata (Ampacimon), Andrea Michiorri (Mines ParisTech University), along with Harold Anuta, Gayathri Nair, Laura Casado, Elena Ocenic, Nina Litman-Roventa, Martina Lyons and Paul Komor (IRENA).

DISCLAIMER

1 BENEFITS

Dynamic line rating (DLR) reduces congestion on power lines, optimises asset utlisation, improves efficiency and reduces costs. This permits increased solar and wind integration, reduces curtailment for these variable renewable energy (VRE) sources and makes power generation dispatch more cost-effective.

DYNAMIC LINE RATING

- **Less grid congestion and reduced curtailment**
- **Cost-effective generation dispatch**

2 KEY ENABLING FACTORS

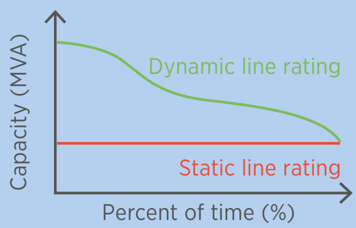
- Algorithms to calculate ampacity
- Digitalisation for real-time monitoring, communication and control
- Regulatory incentives for cost-efficient grid operation

3 SNAPSHOT

- → Oncor Electric Delivery, a US utility, implemented DLR and observed ampacity increases of 6–14% for 84–91% of the time.
- → Several transmission system operators in Europe, including Amprion (Germany), Terna (Italy), RTE (France) and Elia (Belgium), are implementing DLR.

WHAT IS DYNAMIC LINE RATING?

DLR refers to the active varying of presumed thermal capacity for overhead power lines in response to environmental and weather conditions. This is done continually in real time, based on changes in ambient temperature, solar irradiation, wind speed and wind direction, with the aim of minimising grid congestion.



DYNAMIC LINE RATING

Dynamic line rating (DLR) enables the better use of the existing grid, allowing maximised VRE integration by taking advantage of shifting weather conditions and their effects on a power line's thermal capacity.

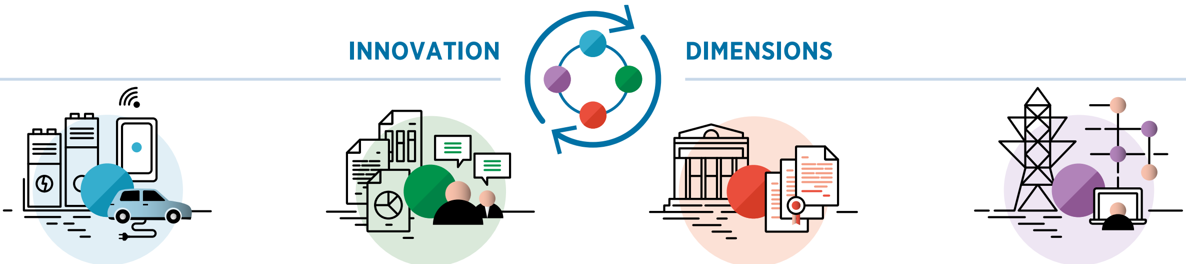
ABOUT THIS BRIEF

This brief forms part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, "*Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables*" (IRENA, 2019a), illustrates the need for synergies between different innovations to create actual solutions. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.

INNOVATION DIMENSIONS



ENABLING TECHNOLOGIES

1 Utility scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

This brief examines a crucial system operation innovation known as dynamic line rating (DLR), which has become increasingly relevant with higher shares of VRE sources in the power system. DLR seeks to increase the ampacity (i.e. the rating) of transmission lines, thus mitigating grid congestion and facilitating the integration of VRE (i.e. wind and solar energy). The concept of DLR is presented and illustrated using different case studies, demonstrating the economic and technical benefits it provides to numerous stakeholders, including utilities, power system operators and VRE plant owners.

The brief is structured as follows:

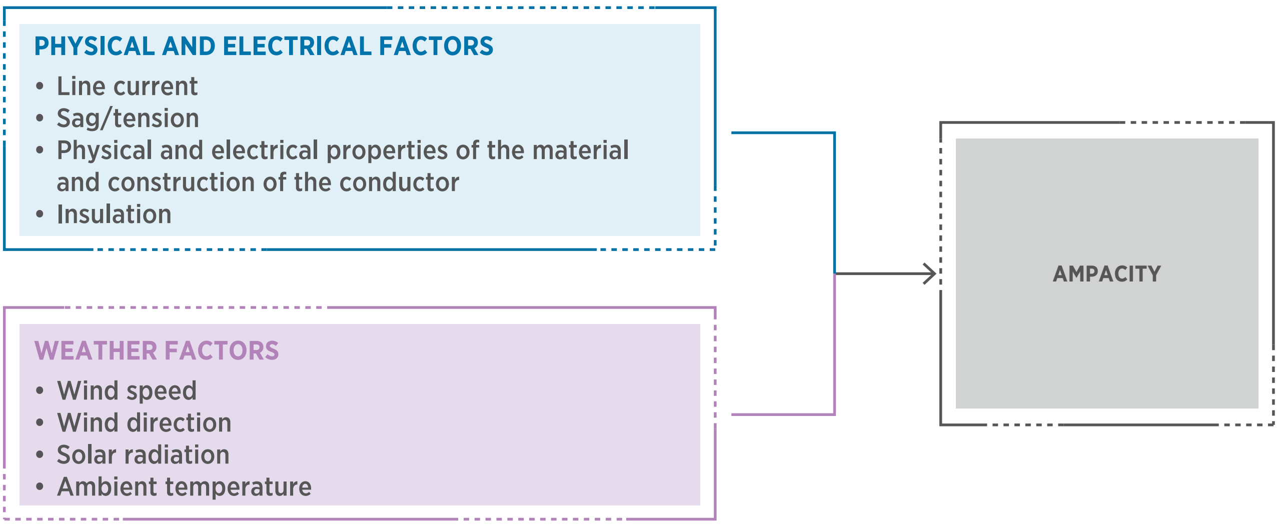
I. DESCRIPTION

Grid congestion occurs when network components reach their thermal limits due to large electricity flows. DLR is the ability to vary the thermal capacity of an overhead transmission or distribution power line (cable) dynamically in real time, depending on the varying environmental conditions (ambient temperature, solar radiation, and wind speed and direction). The aim is to maximise loading at every point in time. Both heating and cooling of the overhead line can affect its thermal capacity with a downward and upward variation in capacity, respectively. A line's thermal capacity will be higher, for example, when it is cooled by wind or when the temperature drops, allowing more electricity to flow through the line.

Power conductors, such as overhead lines, can carry only a specific amount of current (i.e. the maximum current rating or ampacity) at a given temperature. Passing more current through the conductor leads to overheating of the cables, which results in high levels of power loss. Other factors that influence the ampacity are the sag[1] and tension of the line, the insulation and the physical and electrical properties of the conductor.

Traditionally, system operators have used "static thermal ratings" for transmission and distribution conductors based on expected local extreme meteorological conditions to calculate their theoretical, rather than actual, ampacity. However, the ampacity of a conductor is constantly changing and depends on various factors. Figure 1 lists several factors that affect the ampacity of a transmission cable.

Figure 1 Factors affecting the ampacity of a conductor



1 *Sag is the difference in level between the points of support and the lowest point of a conductor. Lower sag means a tight conductor and higher tension, whilst higher sag means a loose conductor and lower tension.*

Static thermal ratings fail to take into account the variation in the ampacity of a transmission or distribution line due to changes in ambient weather conditions (such as wind speed, wind direction, solar radiation or ambient temperature). DLR systems have the capacity to use sensor-based monitoring and offer the possibility to estimate the ampacity of a transmission line on a real-time basis by observing the ambient weather conditions.

Although DLR systems have been available since the 1990s (mainly explored in France and Belgium), their use has not been widespread due to low levels of correlation between times of high electricity demand and generation (i.e. an increase in power flow through cables or lines) and the availability of higher grid capacity (i.e. instances with high ampacity). Moreover, transmission capacity is generally oversized as the design of transmission lines has been predominantly based on the highest expected power flow.

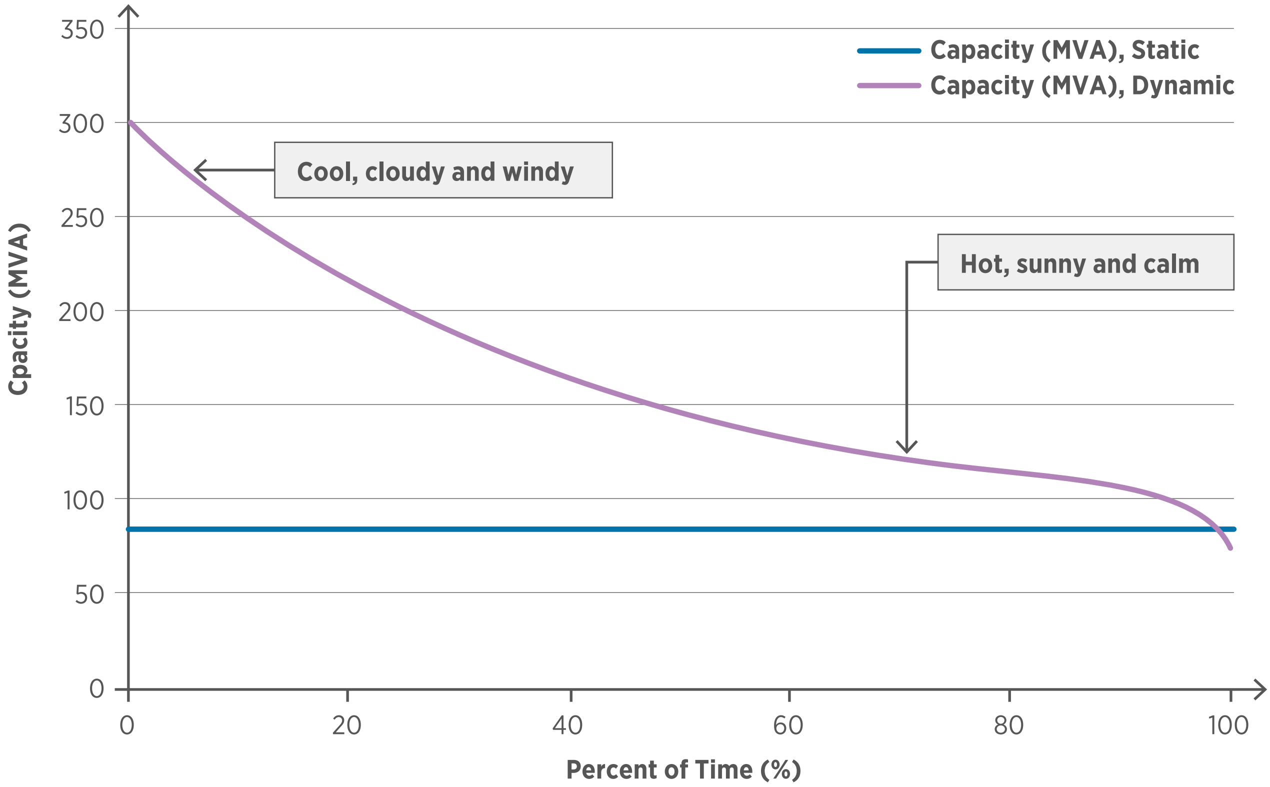
Due to the rapid deployment of VRE causing increased renewables infeed and decreasing infeed from conventional power plants, power flows in the existing grid infrastructure are changing. Changes in infeed and offtake characteristics cause new peak power flows that have not been recorded before on transmission routes.

To adapt to these shifting conditions caused by the decarbonisation of power generation fleets, DLR can promote better use of existing grid infrastructure whilst integrating larger shares of VRE.

There is, for instance, a strong business case for DLR on lines transporting wind energy thanks to the high correlation of wind power infeed with DLR benefits, with increased ampacity due to the cooling effects of wind. When locations with high wind resources are far from the demand centres, line loading increases to the point where traditional grid operation procedures need to be changed to ensure grid security. However, the presence of winds can reduce the temperature of cables through convective effects (also called concurrent cooling). Such conditions have been estimated to increase the ampacity of close transmission cables by between approximately 100% and 200% (Goodwin *et al.*, 2014; Zeiselmair and Samweber, 2016).

Figure 2 illustrates how the capacity of a transmission line can vary depending on weather conditions. The static ratings generally assume the worst-case weather conditions, using lower limits of capacity in order to maintain adequate security conditions in any situation.

Figure 2 Schematic comparison of static and dynamic current limit



Note: MVA = megavolt ampere.
Source: Based on ENTSO-E (2015).

Many grid operators are now considering using DLR systems as a practical means of increasing their transmission capacity. Belgium's transmission system operator (TSO), Elia, has been working since 2008 to test and develop DLR systems that can provide forecast estimates of the ampacity over different time horizons (from a five-minute basis to the following two days) (Elia, 2020).

In most cases, relatively modest levels of rating increase (5% to 20%) over static ratings are sufficient to resolve system operational challenges. Therefore, DLR offers system operators a rapidly deployable, low-cost method of increasing line ratings, which can be implemented without the need to build new physical infrastructure or put key lines out of service.

II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

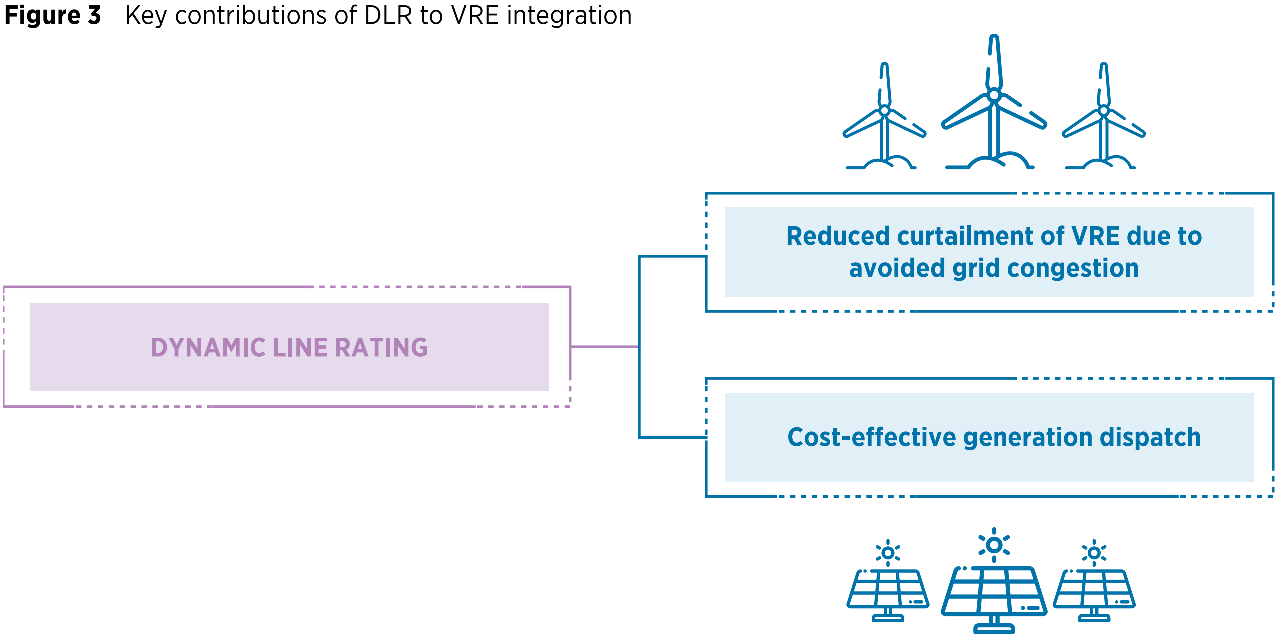
DLR offers many applications and benefits to the power system. It reduces congestion in the power system, optimises asset utilisation in a safe manner, results in additional income from existing power generation assets, improves cost efficiency of the lines and avoids investment in new lines. All these can ultimately result in lower prices for consumers, faster integration of distributed energy resources and greater power system integration of VRE.

DLR can contribute to overall system planning, because it can forecast the power-carrying capacity. Using DLR can also enhance grid resilience, key to maintaining security of supply.

In the case of substations or power lines being lost to natural or man-made calamities, a resilient grid provides alternative transmission paths around the damaged portion of the grid. With reliable hour(s)-ahead to day(s)-ahead forecasting, DLR can provide "emergency" rating for all remaining in-service lines (McCall and Servatios, 2016).

Whilst DLR has numerous important benefits to the power sector, the following section focuses on those benefits with a direct impact on VRE integration (Figure 3).

Figure 3 Key contributions of DLR to VRE integration



Reduced curtailment of VRE due to avoided grid congestion

DLR facilitates integration of a higher share of renewable generation by increasing the effective transmission or distribution network capacity. This in turn reduces the need for investment in transmission network reinforcements, at least in the short to medium term.

There are particularly great synergies between DLR and wind energy. In wind resource-rich areas, the wind enables turbines to produce power while it cools nearby transmission lines. Therefore, the transmission capacity of the lines increases with wind speed, because of the increased cooling. So, a correlation between wind power generation and the transmission capacity of close lines exists (dynamic limit). Thus, when planning wind power integration, considering the dynamic line limit rather than the static limit increases estimated capacity (Fernandez *et al.*, 2016). This favourable correlation has been made use of in several pilot projects. One example is Belgium, where DLR is implemented on the lines that connect the offshore wind farms in the North Sea to the mainland (Ampacimon, 2019).

Cost-effective generation dispatch

DLR deployment can increase transmission and distribution capacity, which in turn can increase the amount of power available for dispatch. This increased power supply can then contribute to reducing generation dispatch costs. Furthermore, the implementation of DLR can also enhance intraday operations, as short-term decisions are also based on real-time thermal rating information.

It also enables the reduction of congestion costs, due to more accurate forecasts by traders and generator commitments in day-ahead markets, as well as a more efficient real-time market with a better estimation of expected transmission capacity. In addition, the transmission capacity gain can be used for power trades on the market, especially in the case of interconnected market areas. This results in additional income from existing generation assets.

Potential impact on power sector transformation

- DLR implemented by Elia, the TSO in Belgium, resulted in a **30% increase in a line's current** (Elia, 2019). The same result was achieved by RTE, the French TSO, when implementing DLR (RTE, 2017).

- The TWENTIES project, under the EU FP7 research and technology programme, involved various stakeholders, including European TSOs, generators, and power technology and wind equipment manufacturers. It concluded that DLR forecasts lead to an average **increase in transmission capacity of 10–15%** (Pavlinić and Komen, 2017).

- Grid congestion costs reached EUR 1 billion in 2017 and 2018 in Germany. The cost of congestion is about EUR 4 million (USD 4.8 million) per day, while the average dispatch cost is EUR 23 000 per gigawatt hour (GWh). For example, Line Ville Ost, which links Rommerskirchen and Sechtem, had 393 hours of redispatch, resulting in a 273 GWh reduction at one end and a 271 GWh increase at the other, totalling 431 GWh redispatched. Applying DLR on this line would result in a **25% capacity increase on the line 50% of the time**, and a **15% gain 90% of the time.** On a typical day, this would save 6 hours' redispatch of 200 MW, meaning 1 200 MWh avoided redispatch. This would **save EUR 27 000 per day** (Ampacimon, 2019).

- AltaLink conducted an analysis for a wind plant installation in Canada and found concurrent cooling avoided the need for system upgrades. The analysis showed an **average 22% capacity increase** over static ratings 76% of the time (Bhattari *et al.*, 2018).

- According to simulation studies carried out by Estanqueiro *et al.* (2018), DLR deployment **can reduce curtailment** due to ampacity issues and **increase mean ampacity by 20–40%**. In windy conditions, the ampacity was seen to increase by as much as ~150% of the nominal ampacity.

- Small changes in weather conditions can have a considerable impact on the ampacity of a transmission line. Assuming a 20-mile long aluminium conductor steel reinforced transmission line with a static line rating of 787 amperes at 40 °C, zero wind and a midday in summer, changes in the ampacity can be seen under various weather conditions (Table 1) (Aivaliotis, 2014).

Table 1 Key facts about the emerging role of distribution system operators

	Change in ampacity	New ampacity
Ambient temperature		
2 °C fluctuation	+/- 2% capacity	
10 °C drop in ambient	+11% capacity	874 amperes
Solar radiation		
Clouds shadowing	+/- a few percent	
Middle of night	+18% capacity	929 amperes
Wind increase of 1 m/s		
45° angle	+35% capacity	1 060 amperes
95° angle	+44% capacity	1 130 amperes

Note: m/s = metre per second.
Source: Aivaliotis (2014).

III. KEY FACTORS TO ENABLE DEPLOYMENT

Defining algorithms for ampacity calculations

Different algorithms exist for the calculation of the ampacity of the particular span or tensioning section. Most existing algorithms, however, introduce uncertainties. These may be substantial, especially when the loading of the line is approaching the maximum conductor temperature, for example 80 °C. Moreover, algorithms should be tailored to the specific conditions and implementation philosophy of grid operators. Improvements in ampacity calculation algorithms are critical for the large-scale adoption of DLR (ENTSO-E, 2015).

Figure 4 shows the complexity in assessing the DLR. Besides formulating a good algorithm for ampacity calculation, a large amount of data is needed as input, such as:

- Physical properties of the conductor.
- Geographical information for all spans.
- Atmospheric conditions for all spans.

This is so the operator can be aware of hotspots like spans with low clearance or reduced conductor cross-section.

Digitalisation for real-time monitoring and communication systems

Given the large number of factors that can influence the ampacity of a line and the need for real-time data, digitalisation has an important role in enabling the use of DLR and enhancing its benefits. Line monitoring equipment must be in place and connected to systems that can communicate in real time with system operators, to support them in decision making. This means that the backbone monitoring and communications infrastructure has to be robust and up-to-date. Smart devices connected to the internet, like sensors along the transmission and distribution lines, coupled with digital technologies like artificial intelligence and big data, enable the use of DLR (for more information see the *Innovation landscape briefs: Internet of things* [IRENA, 2019b] and *Artificial Intelligence and Big Data* [IRENA, 2019c]).

A project by Oncor Electric Delivery Company employed a fully automated DLR system capable of collecting various transmission line parameters at remote locations on the transmission line. The DLR system then passed the data to the system operator and Oncor for transmission capacity allocation and decision making. However, the system's data communication proved not fast enough to satisfy the decision-making algorithm's needs (US DOE, 2014), which highlights the importance of monitoring, communication and control systems.

To harness the benefits of DLR, transmission and distribution line monitoring systems and equipment need to be well integrated into the networks. Line monitoring systems can be deployed on the lines, or in proximity to the lines, to capture real-time weather conditions (Ntuli, *et al.*, 2016). This equipment must capture data such as actual line conditions, critical weather parameters, circuit loads and transmission line temperature. Outputs can then be used when making operational decisions for thermal load management on the lines. Field data, applied to industry standards such as IEEE 738 and Cigre TB498, provide "real-time" ampacity ratings. These ratings can be enhanced into forecasts with algorithms, including mathematical methods combining statistics, modelling and weather forecasts, to support the operation of the grid.

Regulations to encourage optimised operational solutions

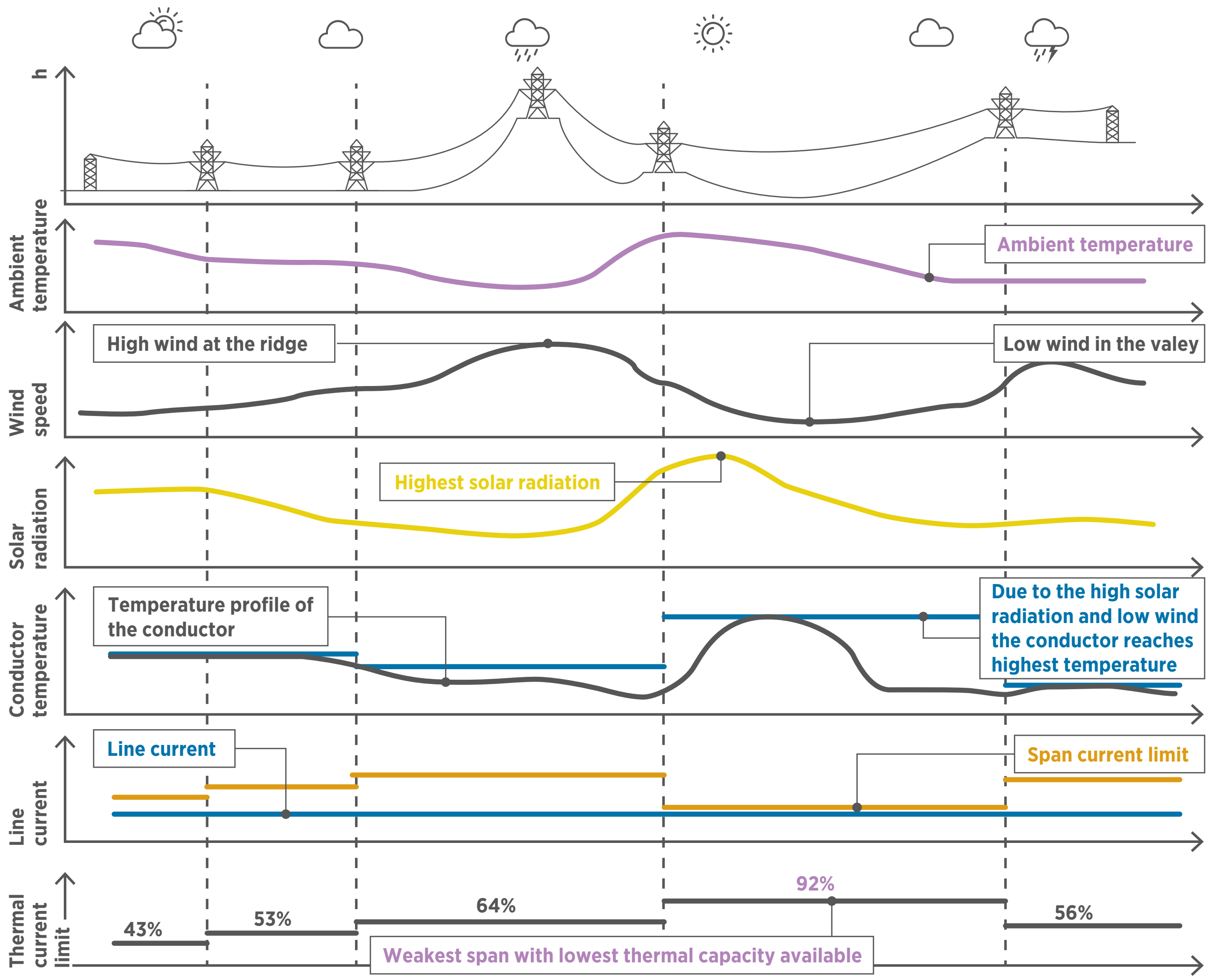
Traditionally, investment cost-based regulation approaches ("rate of return regulation" or "cost-plus regulation") were widely used in liberalised power sectors for grid operation and investment decisions. The rate of return model provides a regulated transmission company with a certain pre-defined "rate of return" on its regulatory asset base.

Cost-plus regulation is another approach, in which a predefined profit margin is added to the investment costs of the grid operator. These regulations based on capital expenditure (CAPEX) provide limited incentive for TSOs to minimise their investment in new physical infrastructure and create a favourable environment for CAPEX over operational expenditure (OPEX) solutions.

This CAPEX incentive has been increasingly investigated by regulators, and in response they have developed OPEX-based regulations to give grid operators the incentive to improve operational practices by increasing the efficient use of existing infrastructure. Rewards and penalties incentivise system operators to achieve the goals by allowing them to share the "extra profit" if they exceed the transmission capacity targets set by the regulator. Incentives for OPEX-related solutions can lead to innovative ways of operating the power system, such as DLR, which can help reduce or avoid CAPEX investment in new physical infrastructure, whenever possible.

In vertically integrated power systems, the incentive of the power system operator to make use of DLR is driven by the fact that it can dispatch the power generated by its own VRE assets more cost-effectively, thereby reducing the need for CAPEX for new lines and increasing the rate of return on their power generating portfolio.

Figure 4 The variability of influencing factors on DLR



Note: Thermal current limit is the maximum current permitted to ensure no conductor material is damage and no maximum line sag is exceeded.

Source: ENTSO-E (2015).

IV. CURRENT CONTEXT AND ONGOING INITIATIVES

Since the implementation of flow-based market coupling in 2015 in the former capacity calculation region of Central-West Europe, some TSOs include DLR in the calculation of cross-border transmission capacity. This can increase the tradable volume of electricity among countries in the European market. For example, in 2017–2018 the thermal limits were increased by 20% in cold weather conditions when electricity demand was high. In 2018 Amprion installed 28 new weather stations in addition to the 14 existing ones. These are located along the most heavily loaded lines at meteorologically exposed locations (i.e. pylons and substations), and it estimates that capacity values can be increased by up to 37% under appropriate weather conditions (Amprion, 2019).

Moreover, within the flow-based market coupling methodology, following its Decision No. 02/2019, the Agency for the Cooperation of Energy Regulators (ACER) reinforced the obligation in the so-called "Core" capacity calculation region (concerning TSOs from 13 countries) to gradually replace seasonal limits with a dynamic limit for each hour of transmission capacity made available for trading on the pan-European intraday market.

Table 2 lists a range of DLR initiatives and projects implemented in various countries.

Table 2 Example of countries implementing DLR

Country	Case study
Belgium	Belgium's TSO, Elia, uses DLR on several overhead lines to increase its import capacity. Belgium has faced interconnection issues due to increased need for imports following the shutdown of nuclear plants with a capacity of 3 000 MW in 2014. Belgium imports electricity from neighbouring countries through interconnectors, but the maximum import capacity – based on traditional seasonal rating of the transmission lines crossing the Belgian border – would be insufficient to supply winter peak demand. Elia implemented DLR, resulting in thermal ratings (due to wind cooling) of more than 200% of the seasonal rating on power lines. However, other transmission system assets (for example, transformers and circuit breakers) have lower ratings. The rule applied for Belgian lines limits the gain generated by the dynamic rating to 130% of the seasonal rating (Bourgeois, 2017).
Bulgaria and Slovenia	The Flexitranstore project, under EU Horizon 2020, is conducting a demonstration project on two sites, one in the electricity grid of Electro Ljubljana, Slovenia, and the second in northeastern Bulgaria on the 220 kilowatt power line Karnobat-Varna. The project aims to demonstrate sensor technology that allows power system operators to effectively handle and prevent sudden and often fatal failures, especially during icy weather conditions, increasing system security and reliability by reducing icing phenomena and facilitating cross-border power exchanges (Flexitranstore, 2017).
France	French TSO, RTE, started experimenting with DLR technologies in 2009 and conducted pilot projects including "Ampacité" and "Ampacité 2" between 2012 and 2018. The main rationale for RTE is to optimise the integration of wind farms, most of which are connected to the sub-transmission grid under 63 kilovolts (kV) and 90 kV (RTE, 2017).
Italy	Italian TSO, Terna, is conducting pilot applications of DLR systems on four of its transmission lines, namely Spezia-Vignole (380 kV), Bargi-Calenzano (380 kV), Misterbianco-Melilli (220 kV) and Benevento-Foiano (150 kV). The project involves the deployment of DLR equipment on the transmission line itself and at two end-point substations. It also utilises the weather forecast data taken from the Epson Meteo Center to estimate the DLR value. This has allowed greater capacity on transmission lines during favourable weather conditions, enabling the increased integration of wind energy generation from nearby wind farms (Carlini, Massaro and Quaciari, 2013).
Texas (U.S.)	Oncor Electric Delivery Company, a transmission and distribution system operator in Texas, implemented a DLR system in a project funded under the US Department of Energy's Smart Grid Demonstration Program. On average, line congestion costs the Oncor transmission system in Texas about USD 250 000 per line per day (Clean Energy Grid, 2014). The DLR system monitored the real-time capacity of eight transmission lines that were being used for daily operations and wholesale market transactions. The project covered five 345 kV and three 138 kV transmission lines; it had an installed cost of USD 4.833 million. The real-time capacity of the 138 kV lines increased by 8–12% on average, while the 345 kV line experienced 6–14% increase in real-time capacity on average. As a second project, Oncor deployed DLR on five lines in West Texas for congestion relief (US DOE, 2014; Engerati, 2014).
Uruguay	In 2018 renewable energy sources accounted for 97% of the power generated in Uruguay, with wind power accounting for 22% in the same year. Uruguay's utility could increase its share of wind power in the total generation mix thanks to a combination of innovations, including the application of DLR on its transmission lines. Given that the renewable power generating assets are distributed throughout the country, but the capital, Montevideo, which is the key demand centre, lies at the south of the country, transporting power through the country was a key challenge. Increasing the transmission line rating dynamically at sub-hour level, in addition to hourly forecasts, helped reduce the curtailment of wind power.[2]
Viet Nam	In the smart grid roadmap for Vietnam, DLR was identified as a tool to improve operational efficiency and to alleviate concerns on lines that are experiencing rapid load growth (World Bank, 2016)

2 *Information presented by UTE, Uruguay's government-owned power company, during the IRENA "Workshop on innovative solutions for achieving 100% renewable power systems by mid-century" in Montevideo, Uruguay, in July 2019 (www.irena.org/events/2019/Jul/Workshop-on-Innovative-solutions-for-achieving-100pc-renewable-power-systems-by-mid-century).*

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS

Implementation of the following steps:

- line identification;
- sensor installation;
- data communication;
- data analytics;
- computing and temperature forecasting;
- validation (for improved visualisation).

Hardware:

- DLR equipment such as line monitors that are self-contained (encompassing auxiliary power, communications and all measurement sensors), sag detectors, weather stations, data loggers and communication devices.

Software:

- Tailored algorithm for transmission capacity calculation for each line.
- Data logging software to record and analyse data from DLR equipment.
- Data analysis software deployed by system operators to analyse data generated by DLR systems. These software must be interoperable with existing software used by system operators.
- Forecasting algorithms, complemented by artificial intelligence tools, to improve DLR performance, minimising weather forecast and operational errors.

Communication protocols:

- 4G/5G-enabled DLR equipment that can be used for real-time relay of data to system operators.

REGULATORY REQUIREMENTS

- In liberalised electricity markets, regulation incentivising OPEX-based solutions and enabling innovations in grid operations, including digital technologies.
- Mandated or incentivised measurement of transmission capacity limits on the power system based on real-time thermal ratings of transmission and distribution lines.

STAKEHOLDER ROLES AND RESPONSIBILITIES

Increased collaboration between various data providers:

- Improved communication channels for collaboration between meteorology data providers, VRE asset owners, power supply utilities or generators, and the transmission and distribution system operators to improve understanding of power supply and demand flows, which help tailor the actions required to limit and reduce congestion.

Transmission and distribution system operators:

- Studying the most congested lines on the system and assessing the cost-effectiveness of implementing DLR, *e.g.* by comparing the cost-benefit analyses of DRL with investment in new transmission lines. Transmission lines that are not congested, or do not limit market activity (where applicable), may not benefit fully from DLR. Similarly, power systems that are constrained by voltage, stability or substation limitations may not benefit from DLR. However, DLR may increase significantly welfare benefits by increasing the volume of traded electricity across borders, where investment in new transmission lines would be very costly.
- Integrating DLR in system operation tools and procedures: DLR data streams need to be integrated into the processes that underlie the markets, such as the calculation of tradable transmission capacity for intraday and day-ahead markets, where such arrangements are in place.
- Providing technical training for staff for deployment of DLR technologies.
- Conducting pilot projects aimed at increasing the understanding of the costs and benefits of this technology.

ABBREVIATIONS

ACER Agency for the Cooperation of Energy Regulators

CAPEX Capital expenditure

DLR Dynamic line rating

GWh Gigawatt hour

IRENA International Renewable Energy Agency

kV Kilovolt

MVA Megavolt ampere

MW Megawatt

MWh Megawatt hour

m/s Metre per second

OPEX Operational expenditure

TSO Transmission system operator

VRE Variable renewable energy

4G Fourth generation

5G Fifth generation

BIBLIOGRAPHY

ACER Decision No 02/2019.

Ampacimon (2019), "Smart grid world of innovations: Dynamic line rating webinar", ENTSO-E, www.youtube.com/watch?v=C6LP363zSmo.

Amprion (2019), "Amprion Market Report 2019", www.amprion.net/Dokumente/Dialog/Downloads/Stellungnahmen/Amprion-Market-Report-2019.pdf.

Aivaliotis, S. K. (2014), "Dynamic line ratings for optimal and reliable power flow", www.ferc.gov/CalendarFiles/20100623162026-Aivaliotis,%20The%20Valley%20Group%206-24-10.pdf.

Bhattari, B. *et al* (2018), "Improvement of transmission line ampacity utilization by weather-based dynamic line rating", IEEE Transactions on Power Delivery, Vol. 33, No. 4, pp. 1 853–1 863.

Bourgeois, R. and Lambin, J. (2017), "Dynamic Ratings Increase Efficiency," March 8, 2017, https://watttransmission.files.wordpress.com/2018/01/ampacimon-dynamic-ratings-increaseefficiency_belgium-transmission-grid.pdf.

Carlini, E. M., F. Massaro and C. Quaciari (2013), "Methodologies to uprate an overhead line: Italian TSO case study", Journal of Electrical Systems, Vol. 9–4, pp. 422–439.

Clean Energy Grid (2014), "Dynamic line ratings", https://cleanenergygrid.org/wp-content/uploads/2014/08/Dynamic-Line-Ratings.pdf.

Elia (2019), "Smart grid world of innovations: dynamic line rating", ENTSO-E, www.youtube.com/watch?v=C6LP363zSmo.

Elia (2020), "Dynamic line rating", www.elia.be/en/infrastructure-and-projects/our-infrastructure/dynamic-line-rating.

Engerati (2014), "Oncor demonstrates dynamic line rating", www.engerati.com/transmission-distribution/oncor-demonstrates-dynamic-line-rating-system/.

ENTSO-E (2019), "Smart grid world of innovations: Dynamic line rating", European Network of Transmission System Operators for Electricity, www.youtube.com/watch?v=C6LP363zSmo.

ENTSO-E (2015), "Dynamic line rating for overhead lines", European Network of Transmission System Operators for Electricity, https://docstore.entsoe.eu/Documents/SOC%20documents/Regional_Groups_Continental_Europe/Dynamic_Line_Rating_V6.pdf.

Estanqueiro, A. I. *et al.* (2018), "DLR use for optimization of network design with very large wind (and VRE) penetration", Stockholm, 17th Wind Integration Workshop.

Fernandez, E. *et al.* (2016), "Review of dynamic line rating systems for wind power integration", Renewable and Sustainable Energy Reviews, Vol. 53, pp. 80–92.

Flexitranstore (2019), "Demonstration 3: Dynamic line rating technology", www.flexitranstore.eu/Demo-3.

Goodwin, T., Aivaliotis, S., Mohr, R., Stelmak, R. (2014), "Integrating enhanced dynamic line rating into the real-time state estimator", https://cigreindia.org/CIGRE%20Lib/CIGRE-Paris-Session-2014-papers-Report/B2/B2_208_2014.pdf.

IRENA (2019a), "Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables", International Renewable Energy Agency, Abu Dhabi.

IRENA (2019b), "Innovation landscape briefs: Internet of things", International Renewable Energy Agency, Abu Dhabi.

IRENA (2019c), "Artificial intelligence and big data", International Renewable Energy Agency, Abu Dhabi.

McCall, J. C. and B. Servatios, (2016), "Enhanced economic and operational advantages of next generation dynamic line rating systems", CIGRE.

Ntuli, M. *et al.* (2016), "Increasing the capacity of transmission lines via current uprating: An updated review of benefits, considerations and developments", 2016 Australasian Universities Power Engineering Conference (AUPEC), Brisbane.

Pavlinić, A. and V. Komen (2017), "Direct monitoring methods of overhead line conductor temperature", Engineering Review, Vol. 37, Issue 2, pp. 134–146.

RTE (2017), "Sensors on power lines to measure the wind and integrate more renewable energy in Haute-Marne" (press release), www.rte-france.com/sites/default/files/20170627_cp_rte_capteurs.pdf.

US DOE (2014), "Oncor's pioneering transmission dynamic line rating (DLR) demonstration lays foundation for follow-on deployments", US Department of Energy, www.smartgrid.gov/files/Oncor_DLR_Case_Study_05-20-14_FINAL.pdf.

World Bank (2016), "Smart grid to enhance power transmission in Vietnam (English)", World Bank Group. , Washington, DC.

Zeiselmair, A. and F. Samweber (2016), "Overhead line monitoring", www.ffe.de/publikationen/veroeffentlichungen/639-freileitungsmonitoring.

DYNAMIC LINE RATING
INNOVATION LANDSCAPE BRIEF

IRENA HEADQUARTERS

P.O. Box 236, Abu Dhabi
United Arab Emirates

www.irena.org