COMBINING HIGH RESOLUTION FORECASTS WITH DYNAMIC LINE RATING

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Kurzfassung: We present a Pilot Service using Destination Earth digital twin data demonstrating how high-resolution weather forecasts can benefit operations of high-voltage transmission lines and grid planning. The service implements compound meteorological event detection algorithms combined with CIGRE and IEEE 738 thermal models to compute Dynamic Line Rating (DLR) along user-defined overhead line routes. Results from Austrian (APG, Energienetze Steiermark) and Belgian (Elia) transmission system operators demonstrate spatial heterogeneity in ampacity along transmission corridors, enabling identification of critical bottleneck segments that limit corridor capacity.

Keywords: Dynamic Line Rating, Weather Forecasting, Transmission Grid, DestinE, Compound Event Detection, CIGRE Thermal Model

1 Introduction

Dynamic Line Rating (DLR) represents an advanced approach to managing the thermal capacity of high-voltage transmission lines. In contrast to static rating methodologies, which rely on conservative assumptions about ambient conditions (typically assuming low wind speeds of 0.6 m/s and high ambient temperatures), DLR dynamically adjusts transmission limits based on real-time weather and operational information [1]. This enables more accurate and often higher ampacity estimates, supporting optimized grid operation and improved integration of variable renewable energy sources [2].

The thermal behavior of overhead conductors is governed by the heat balance between joule heating, solar absorption, convective cooling, and radiative heat exchange with the environment [3,4]. Wind speed has been identified as the dominant factor affecting conductor cooling, with convective heat transfer increasing approximately with the square root of Reynolds number [5]. However, the combined effect of multiple meteorological parameters—temperature, wind, radiation, and precipitation—creates compound events that are particularly relevant for DLR operations.

The HiReNext pilot service, developed within the Destination Earth (DestinE) initiative [6], exploits high-resolution numerical weather prediction (NWP) forecasts for DLR calculations along user-defined overhead line routes. The service addresses key operational challenges: temporal forecasting of favorable and unfavorable conditions, spatial identification of capacity bottlenecks, and quantitative ampacity estimation for decision support aligned with day-ahead market timelines.

2 Compound Event Detection Algorithm

The detection algorithm identifies meteorological conditions that create favorable or unfavorable DLR situations through compound event analysis. Following the approach of Michiorri et al. [2] and building upon CIGRE recommendations [3,4], the system evaluates the simultaneous occurrence of multiple meteorological factors rather than single-parameter thresholds. This compound approach is motivated by the fact that that conductor temperature results from the combined contribution of multiple heat transfer mechanisms, where individual parameter deviations may be compensated by others. This detection is used to find regions with unfavourable conditions and enable a triggering of hectometric forecasts for those regions which are converted to ampacity along the power line segments (see Section 6).

2.1 Meteorological Thresholds

The threshold values are derived from CIGRE Technical Brochures 207 and 601 [3,4], which establish standardized weather parameters for overhead conductor ratings. Table 1 summarizes the meteorological thresholds implemented in the detection algorithm, evaluated at conductor height (typically 40-80 m AGL depending on tower configuration).

Table 1: CIGRE-based meteorological thresholds for DLR condition detection

Parameter	**Critical (Unfavorable)**	**Favorable**	**Physical Basis**
Wind speed	< 2 m/s	> 5 m/s	Convective cooling dominates heat dissipation; scales with $Re^{0.5}$
Ambient temperature	> 30°C	< 20°C	Temperature gradient (T_c - T_a) drives convective/radiative transfer
Solar radiation	> 600 W/m^2	< 400 W/m^2	Direct heating of conductor surface; absorbed via α_s coefficient
Precipitation	—	> 0.1 mm/h	Evaporative cooling enhancement: 20-50% increased heat transfer

The wind speed threshold of 2 m/s represents the transition between natural and forced convection regimes [4]. Below this threshold, convective cooling becomes highly dependent on local turbulence and buoyancy effects, increasing uncertainty in thermal predictions. The temperature thresholds reflect typical European summer conditions where 30°C represents heat wave conditions with elevated grid loads, while 20°C provides comfortable thermal margin for capacity increases.

2.2 DLR Condition Score and Methodology

The detection system computes a composite DLR score following a categorical approach inspired by IPCC likelihood scales, ranging from -3 (very unfavorable) to +3 (very favorable). Table 2 presents the scoring methodology and condition categories used for operational alerting.

Table 2: DLR condition score categories and operational implications

Score	**Category**	**Definition**	**Operational Action**
≤ -2	Very Unfavorable	Multiple critical thresholds exceeded simultaneously	Capacity reduction required; monitor closely
-1	Unfavorable	Single critical threshold exceeded	Exercise caution; verify with measurements
0	Neutral	All parameters within normal range	Static rating applies
+1	Favorable	Single favorable threshold met	Consider moderate capacity increase
≥ +2	Very Favorable	Multiple favorable conditions simultaneously	Significant capacity increase possible

2.3 Data Processing: Deterministic and Probabilistic Approaches

The detection algorithm supports both deterministic and probabilistic processing modes. For deterministic forecasts (e.g., AROME, ALARO high-resolution models [5]), spatial uncertainty is addressed through lateral sampling of ±1 grid points perpendicular to the line corridor, effectively creating a 3-point ensemble for each line segment. This approach reduces sensitivity to single grid-point values and captures sub-grid spatial variability.

For ensemble forecasts (e.g., ECMWF ENS with 51 members), the system applies k-means clustering to reduce ensemble dimensionality while preserving forecast uncertainty. The clustering operates on the 4D weather cube (time × latitude × longitude × height), identifying K representative scenarios (typically K=5-7) that span the ensemble spread. Each cluster centroid represents a plausible weather evolution with an associated probability weight derived from cluster population. This approach transforms the ensemble from 51 individual trajectories into actionable probability statements:

$$P(ampacity > baseline) = \Sigma_i\, w_i \times I(Imax,i > I_0)$$

where w_i is the cluster weight and I(·) is the indicator function.

3 Numerical Weather Prediction Integration

The pilot service integrates multiple NWP data sources at different spatial resolutions, enabling both continental-scale early warning and local high-resolution analysis.

3.1 Multi-Scale Approach

- **Continental scale:** ECMWF IFS ensemble forecasts (~9 km resolution) provide 48-hour DLR condition detection across Europe, enabling identification of regions requiring detailed analysis.
- **Global Digital Twin (4.4 km):** The ECMWF IFS-based Global Digital Twin provides the foundation for continental-scale DLR assessment at ~4.4 km horizontal resolution. This includes both deterministic runs and ensemble forecasts (51 members), enabling probabilistic early warning of unfavorable DLR conditions 2-5 days ahead across the European domain.
- **Regional scale:** AROME/ALARO forecasts (~2.5 km resolution) provide high-resolution analysis for Austrian (GeoSphere Austria) and Belgian (RMI) domains, capturing mesoscale meteorological features relevant to transmission corridors. Migration towards the C-LAEF Alpe Adria ensemble model (16 ensemble members, 1 km resolution) ongoing. These convection-permitting models capture mesoscale phenomena—valley winds, sea breezes, frontal passages—that significantly impact local DLR conditions.
- **Hectometric scale:** DestinE Extremes Digital Twin data (~500 m resolution) enables sub-kilometer analysis for critical line segments, essential for capturing microclimate variations in complex terrain. This resolution captures terrain-induced flow modifications in Alpine valleys and complex coastal zones that are unresolved at coarser scales.

3.2 Data Access via Polytope

Access to DestinE data products is implemented through the Polytope API, ECMWF's feature-based data retrieval service [8]. Polytope enables efficient extraction of meteorological fields along user-defined line geometries without requiring download of full model domains. The service supports:

- Spatial subsetting: Extraction of bounding boxes or point-based transects along transmission corridors
- Vertical profiles: Multi-level extraction at 2m, 10m, 50m, 60m, 80m, and 100m AGL for boundary layer representation
- Temporal windowing: Selective retrieval of forecast lead times relevant for TSO operations (0-48h for day-ahead planning)

- Parameter filtering: Retrieval of DLR-relevant variables only (T, u, v, SSRD, precipitation) to minimize data transfer

3.3 4D Weather Cube Extraction

Meteorological conditions are extracted along transmission line geometry using a 4D weather cube with dimensions (time, along_line, across_line, height). The implementation uses xarray for lazy-loaded data handling and spatial extraction via bilinear interpolation to model grid points. Vertical extrapolation employs the power law for wind speed:

$$U(z) = U(z_{ref}) \times (z/z_{ref})^{\alpha}$$

where α ranges from 0.15 (flat terrain) to 0.25 (complex Alpine terrain) following Petersen et al. [9]. Temperature interpolation uses linear profiles between available model levels, validated against radiosonde observations in the Austrian Alps.

4 Thermal Model Implementation

The service implements two industry-standard thermal models for ampacity calculation: CIGRE (TB 207/601) and IEEE 738-2012 [6]. Parallel implementation enables cross-validation and provides uncertainty bounds on capacity estimates arising from methodological differences.

4.1 Conductor Type Assumptions

Table 3 presents the conductor parameters used for Austrian and Belgian transmission lines. Parameters are based on manufacturer specifications for ACSR (Aluminum Conductor Steel Reinforced) types commonly deployed in European grids.

Table 3: Conductor parameters for thermal model calculations

Parameter	ACSR Drake (220kV)	ACSR 240/40 (110kV)	Generic Alpine
Diameter [mm]	28.1	21.8	25.0
Cross-section [mm²]	403	243	300
R_{20} [Ω/km]	0.072	0.119	0.095
α_R [1/°C]	0.00403	0.00403	0.00403
Emissivity ε	0.5	0.5	0.5
Absorptivity α_s	0.5	0.5	0.5
T_{max} [°C]	80	80	80

4.2 CIGRE Heat Balance Implementation

The CIGRE model solves the steady-state heat balance equation: $q_{joule} + q_{solar} = q_{conv} + q_{rad}$. The implementation follows TB 601 formulations with iterative solution for conductor temperature. Key components include:

Joule heating: $q_j = I^2 \times R(T_c) = I^2 \times R_{20} \times [1 + \alpha_R(T_c - 20)]$ accounting for temperature-dependent resistance.

Convective cooling: Calculated using CIGRE forced convection correlations with Nusselt number functions of Reynolds number, incorporating wind angle correction (worst-case 90° perpendicular assumed) and air property corrections for elevation (density reduction ~10% per 1000m).

Radiative cooling: $qr = \pi \times D \times \varepsilon \times \sigma \times (Tc^4 - Ta^4)$ using Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8}$ W/(m^{2}K^4).

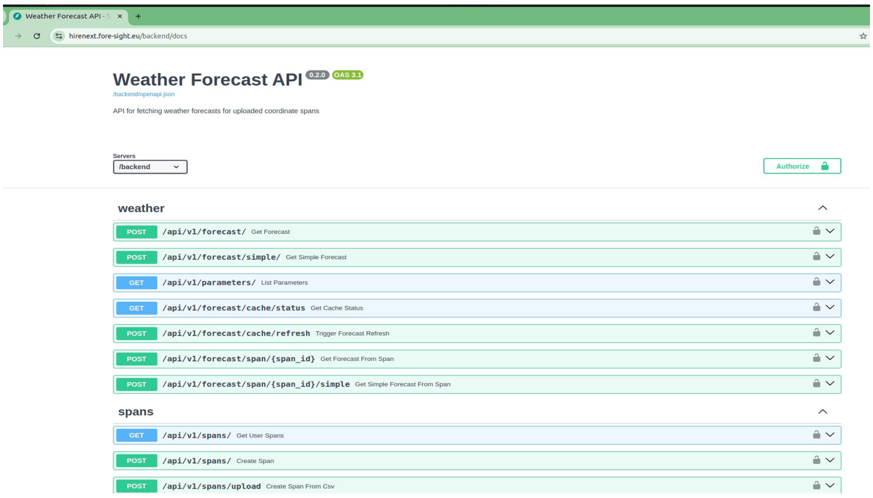
4.3 Technical Implementation

The thermal model is implemented in Python using object-oriented design for extensibility. The core calculation uses an iterative approach with convergence tolerance of 0.1°C:

The IEEE 738 implementation uses the NREL/Statnett linerate library for validation. Comparison for the Belgian Quaregnon-Trivieres 150kV line shows CIGRE yields mean ampacity of 2159 A (+169.8% vs. 800 A static rating) while IEEE 738 yields 1349 A (+68.6%), reflecting methodological differences in convective cooling parameterizations under moderate wind conditions.

5 Web API and interface

The service has been developed within the framework of the Destination Earth (DestinE) initiative [7]. Results from the service are accessible through both a web application and an Automatic Programming Interface (API, as depicted below), ensuring flexible access for a wide range of users.



Weather Forecast API

/backend/openapi.json

API for fetching weather forecasts for uploaded coordinate spans

Servers: /backend

weather

POST `/api/v1/forecast/` Get Forecast
POST `/api/v1/forecast/simple/` Get Simple Forecast
GET `/api/v1/parameters/` List Parameters
GET `/api/v1/forecast/cache/status` Get Cache Status
POST `/api/v1/forecast/cache/refresh` Trigger Forecast Refresh
POST `/api/v1/forecast/span/{span_id}` Get Forecast From Span
POST `/api/v1/forecast/span/{span_id}/simple` Get Simple Forecast From Span

spans

GET `/api/v1/spans/` Get User Spans
POST `/api/v1/spans/` Create Span
POST `/api/v1/spans/upload` Create Span From Csv

Figure 1: Web API interface for DLR within Destination Earth framework.

The interface allows registered users to:

1. Define their spans of interest by uploading coordinates, enabling focused analysis over specific geographic areas.
2. Evaluate temporal variations of meteorological conditions along the selected coordinates, facilitating the study of trends and dynamics relevant to their applications.

The application will be publicly available through the DestinE Platform, making it broadly accessible to researchers, decision-makers, and other stakeholders interested in high-resolution environmental data.

6 Results

6.1 Continental-Scale Detection

Figure 2 shows the BASE (Wind+Temperature) and EXTENDED (Radiation+Precipitation) DLR condition indices computed from ECMWF IFS forecasts across Europe for selected timesteps within the 48-hour forecast horizon. The BASE index combines the two most influential parameters for conductor cooling—wind speed and ambient temperature—while the EXTENDED index additionally incorporates solar radiation heating and precipitation-induced evaporative cooling. The detection algorithm identifies significant spatial and temporal variability, with favorable conditions (green shading) predominating in coastal regions (North Sea, Atlantic coast) and elevated terrain where persistent wind exposure enhances convective cooling. Unfavorable conditions (red shading) concentrate in continental lowlands during anticyclonic weather patterns characterized by light winds and elevated temperatures. The 6-hourly timesteps (+00h, +12h, +36h) reveal clear diurnal patterns: nighttime hours show improved DLR conditions due to reduced solar radiation and lower ambient temperatures, while midday hours under clear skies present the most challenging thermal conditions. This continental-scale detection serves as the trigger mechanism for on-demand hectometric forecasts: regions showing unfavorable conditions (score ≤ -1) are flagged for high-resolution DestinE Extremes analysis to resolve local variations that may differ from the coarse-resolution assessment.

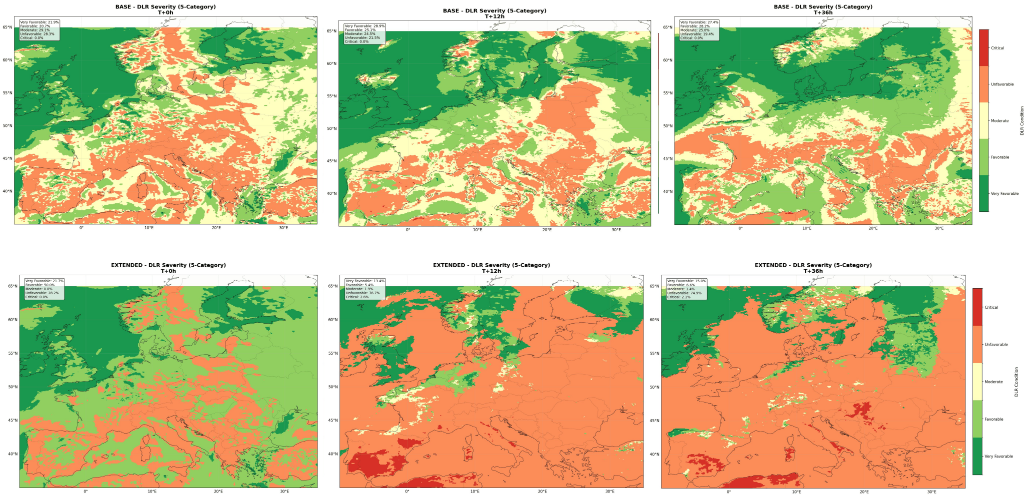


Figure 2: Continental-scale DLR condition detection using ECMWF IFS forecasts. Top row: BASE index (Wind + Temperature); Bottom row: EXTENDED index (including Radiation + Precipitation). Columns show +00h (initialization), +12h, and +36h forecast lead times. Color scale ranges from very unfavorable (red, score ≤ -2) to very favorable (green, score ≥ +2).

6.2 Transmission Line Analysis

6.2.1 Belgian analysis

Detailed analysis was performed for Elia's Quaregnon-Trivieres 150kV transmission line in Belgium using DestinE Extremes hectometric data (~500 m resolution). Figure 3 shows the location of the transmission line and the individual pylons.

Figure 3: location of the Quaregnon-Trivieres 150kV transmission line in Belgium.

Figure 4 shows the temporal evolution of meteorological conditions and computed ampacity over the 48-hour forecast period. Temperature at conductor height (40 m AGL) ranges from 10–22°C, well below the critical threshold of 30°C. Wind speeds of 4–6 m/s persist throughout most of the forecast period, providing sustained favorable convective cooling. The analysis reveals predominantly favorable DLR conditions with scores of +2 to +3 for most timesteps. A brief unfavorable period occurs around 12 February 16:00 UTC when wind speeds temporarily drop to ~0.5 m/s, creating a short-duration capacity reduction event despite moderate temperatures. The CIGRE thermal model computes ampacity ranging from 589 A (minimum during the low-wind event) to 2314 A (maximum), with mean capacity of 2159 A representing +170% increase versus the 800 A static rating. The IEEE 738 model yields more conservative estimates with mean ampacity of 1349 A (+69%), reflecting methodological differences in forced convection parameterization at moderate wind speeds. This model spread (CIGRE vs. IEEE) provides implicit uncertainty bounds for operational decision-making.

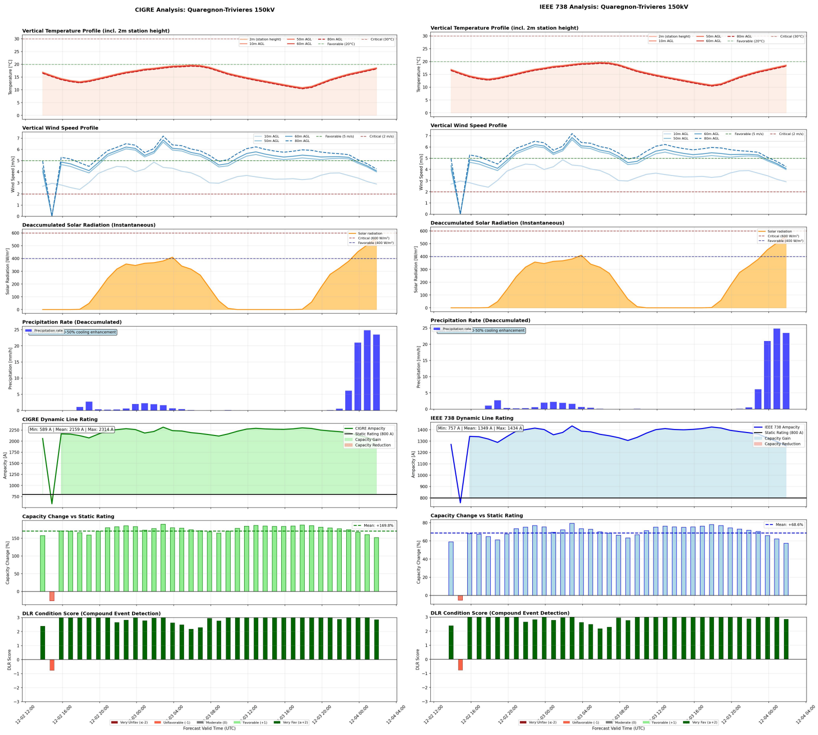


Figure 5: Temporal DLR analysis for the Belgian segment 380 kV corridor. Panels show meteorological parameters at conductor height (60 m AGL) and CIGRE ampacity versus 1200 A static rating.

6.2.1 Austrian analysis

Analysis was performed for Austrian Power Grid's (APG) Westtirol–Zell am Ziller 220 kV transmission corridor in the Tyrolean Alps using AROME forecasts at 2.5 km resolution. This line traverses challenging Alpine terrain at elevations of 600–1200 m ASL, where valley wind systems create pronounced diurnal variability in DLR conditions. Figure 5 presents the temporal evolution of meteorological parameters and computed CIGRE ampacity over a 48-hour forecast period. The analysis reveals a characteristic Alpine pattern: favorable DLR conditions (score +2 to +3) develop during afternoon hours when thermally-driven up-valley winds exceed 5 m/s and provide enhanced convective cooling. Conversely, early morning hours (04:00–08:00 UTC) show neutral to unfavorable conditions due to nocturnal cold-air drainage producing calm winds (<2 m/s) in valley locations. The CIGRE model computes ampacity ranging from 890 A during calm nocturnal conditions to 2450 A during peak afternoon ventilation, with mean capacity of 1680 A representing +40% over the 1200 A static rating. Notably, brief unfavorable periods with ampacity below baseline occur during transition periods when wind direction shifts between day and night regimes. These events, while short-lived (2–4 hours), represent the operationally limiting conditions that define conservative day-ahead planning margins. Complementary analysis for Energienetze Steiermark's 110 kV lines (Bruck–Mürzzuschlag, Arnstein–Modriach) shows similar diurnal patterns but with reduced amplitude due to lower terrain complexity. Mean ampacity increases of +25–35% versus the 600 A static rating were computed for favorable periods.

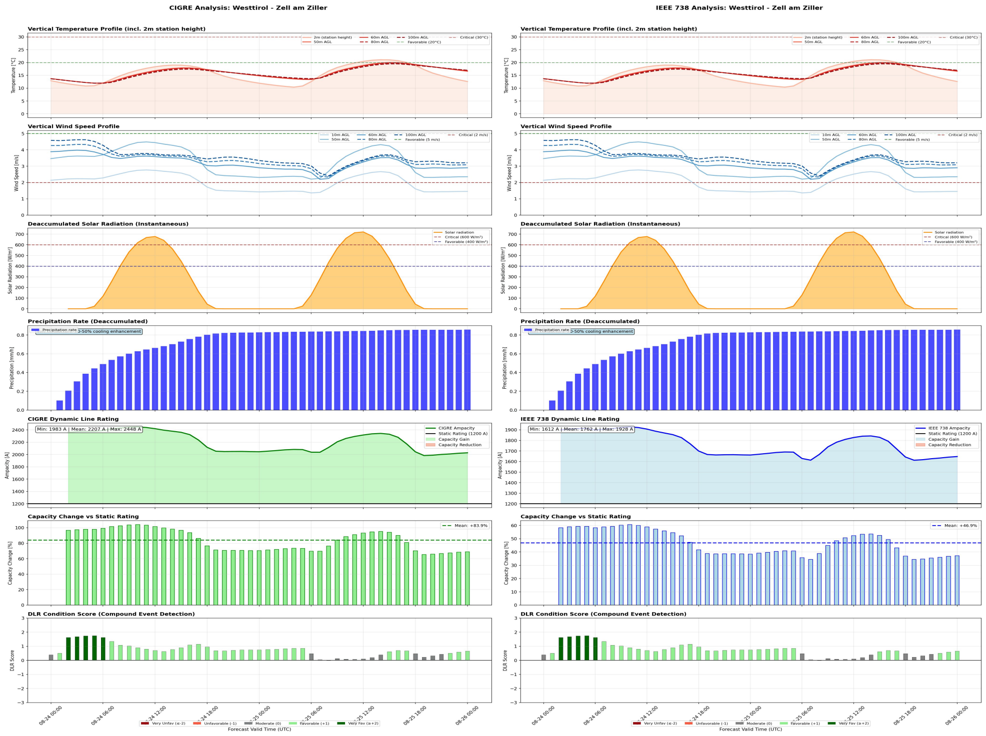


Figure 5: Temporal DLR analysis for APG Westtirol–Zell am Ziller 220 kV corridor. Panels show meteorological parameters at conductor height (60 m AGL) and CIGRE ampacity versus 1200 A static rating. Diurnal valley wind patterns create pronounced day/night variability in capacity estimates.

6.3 Spatial Bottleneck Identification

Figure 6 demonstrates the spatial analysis capability along the Quaregnon-Trivieres 150 kV corridor, decomposed into 79 pylon-to-pylon spans. The hectometric DestinE resolution (~500 m) resolves meteorological gradients along the 25 km line extent that would be homogenized at conventional NWP resolution. At the analyzed timestep, wind vectors indicate predominantly easterly flow at 4–6 m/s at conductor height (40 m AGL), with temperature ranging from 10°C at the northern terminus to 22°C at the southern end. This 12°C gradient along a single transmission corridor illustrates the importance of spatially-resolved analysis. The compound DLR score shows 70 spans with favorable conditions (score ≥ +1, green markers) and 9 spans with neutral conditions (score = 0, yellow markers), with no unfavorable segments at this timestep. The bottleneck identification functionality marks segment 0 (northernmost span) with computed ampacity of 2144 A as the corridor-limiting element. Despite favorable conditions elsewhere reaching 2300+ A, the entire corridor capacity is constrained by this single segment—demonstrating the operational principle that a transmission line's effective rating equals its weakest link. This spatial granularity enables TSOs to identify specific infrastructure where targeted measurements or localized weather stations would provide the greatest operational benefit.

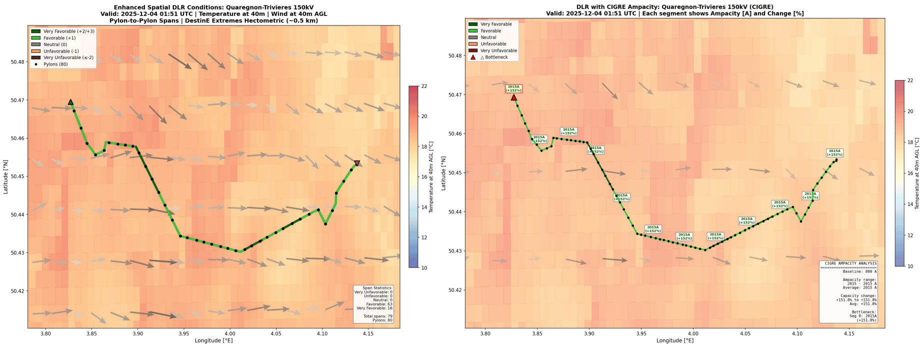


Figure 6: Spatial DLR conditions along the Quaregnon-Trivieres corridor at [timestep]. Left: Temperature field with line geometry overlay. Center: Wind vectors at conductor height. Right: Per-segment DLR classification with bottleneck identification (red triangle marks limiting segment).

6.4 Grid-Point Trigger Assessment

Figure 7 presents the domain-wide DLR condition detection used for triggering on-demand hectometric forecasts. The grid-point analysis evaluates 1489 × 1489 points (~2.2 million grid cells) across Belgium and surrounding regions, classifying each point according to the compound DLR score categories. At the analyzed timestep, the domain statistics show: 40% of grid points with favorable conditions (score ≥ +1), 34% neutral (score = 0), 26% unfavorable (score = -1), and 0% critical (score ≤ -2). The spatial pattern reveals favorable conditions concentrated over the North Sea coast and Ardennes highlands where terrain exposure enhances wind speeds, while the central Belgian lowlands show predominantly neutral to unfavorable conditions. Comparing domain-averaged statistics with the line-specific analysis reveals important operational insights: the Quaregnon-Trivieres corridor (79 spans favorable, 0 unfavorable) experiences significantly better conditions than the domain average, with 89% of spans in favorable categories versus 40% domain-wide. This discrepancy demonstrates the value of transmission line-specific analysis over domain-averaged assessments, and validates the multi-scale approach where coarse-resolution screening identifies regions of concern while hectometric analysis resolves the actual conditions along critical infrastructure.

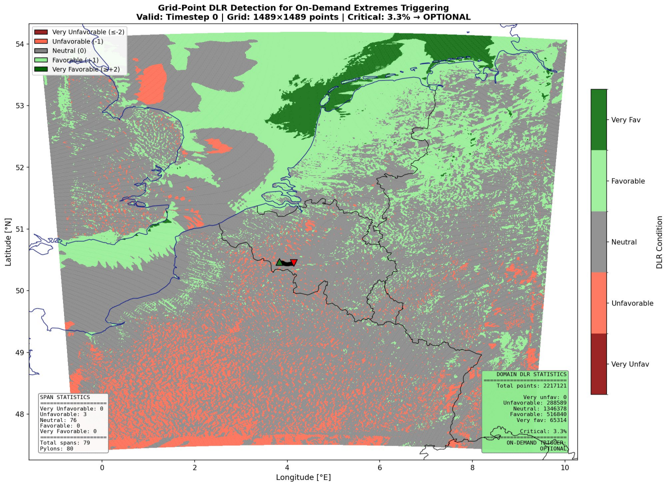


Figure 7: Domain-wide DLR detection for hectometric forecast triggering. Grid-point classification (1489×1489 points) with category statistics. The Quaregnon-Trivieres transmission line overlay demonstrates that line-specific conditions (89% favorable) exceed domain-average conditions (40% favorable).

7 Conclusions

The HiReNext pilot service demonstrates successful integration of DestinE high-resolution forecasts with thermal line rating calculations. The compound event detection algorithm provides operationally relevant identification of favorable and unfavorable DLR conditions at both continental and local scales. Combining the CIGRE/IEEE 738 thermal models with spatially-resolved meteorological analysis enables TSOs to identify specific bottleneck segments that limit corridor capacity, rather than relying on line-averaged conditions. Results from Austrian (APG, Energienetze Steiermark) and Belgian (Elia) transmission lines demonstrate capacity increases of +68% to +170% versus static ratings during favorable conditions, while the spatial analysis identifies critical segments where local microclimate conditions limit the entire corridor. The 48-hour forecast horizon supports day-ahead grid planning and enables optimized utilization of transmission capacity while ensuring grid security. Future development includes probabilistic forecasting using ensemble models and statistical postprocessing techniques [10] to capture uncertainty bounds (important for safety margins), machine learning enhancement of detection algorithms, and extension to additional European TSO partners within the DestinE framework.

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