

STRUCTURAL VULNERABILITY AND CASCADE RISK ANALYSIS IN TRANSNATIONAL POWER GRIDS

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Ensuring the resilience of electricity transmission systems has become a strategic priority for every country. Rising demand, rapid growth of variable renewable generation, and tighter interconnection between national grids have significantly increased the complexity and vulnerability of power systems. Large-scale blackouts, though rare, demonstrate how local disturbances can propagate through highly interconnected networks, producing severe socio-economic consequences. On 28 April 2025, the Iberian Peninsula experienced one of the most severe blackouts in recent European history, with a rapid cascade of generation losses in southern Spain and subsequent disconnection from the continental European grid. While the proximate causes involved low-frequency oscillations and protective relay actions, the event underscores the structural fragility of transnational electricity networks. Traditional approaches to blackout analysis rely on dynamic simulations of power flows, frequency stability, and protection system responses. While indispensable, such methods can be computationally intensive and heavily dependent on system-specific operational data. In contrast, network analysis methods provide a complementary perspective: by abstracting power grids as graphs of nodes (buses) and edges (transmission lines), they enable the detection of structural vulnerabilities that may predispose systems to cascading failures.

This study introduces a network-analytic approach for identifying structural precursors of blackouts and for stress-testing the resilience of transnational grids. By applying graph-theoretic metrics, community detection, and a heuristic cascade simulator to open-source PyPSA-Eur data, mapped onto geographic coordinates from OpenStreetMap, the framework demonstrates how topology alone can yield insights into grid fragility and cross-border dependencies. The results indicate that topological stress testing can reproduce several qualitative features observed in the April 2025 blackout: high-centrality nodes in Portugal coincide with critical interconnectors; simulated cascades disproportionately sever Spain–France and Spain–Portugal links; and fragmentation metrics reveal a rapid transition from connected to isolated national grids. While not a substitute for dynamic stability models, this approach provides a complementary layer of analysis being computationally lightweight, data-transparent, and scalable to continental systems.