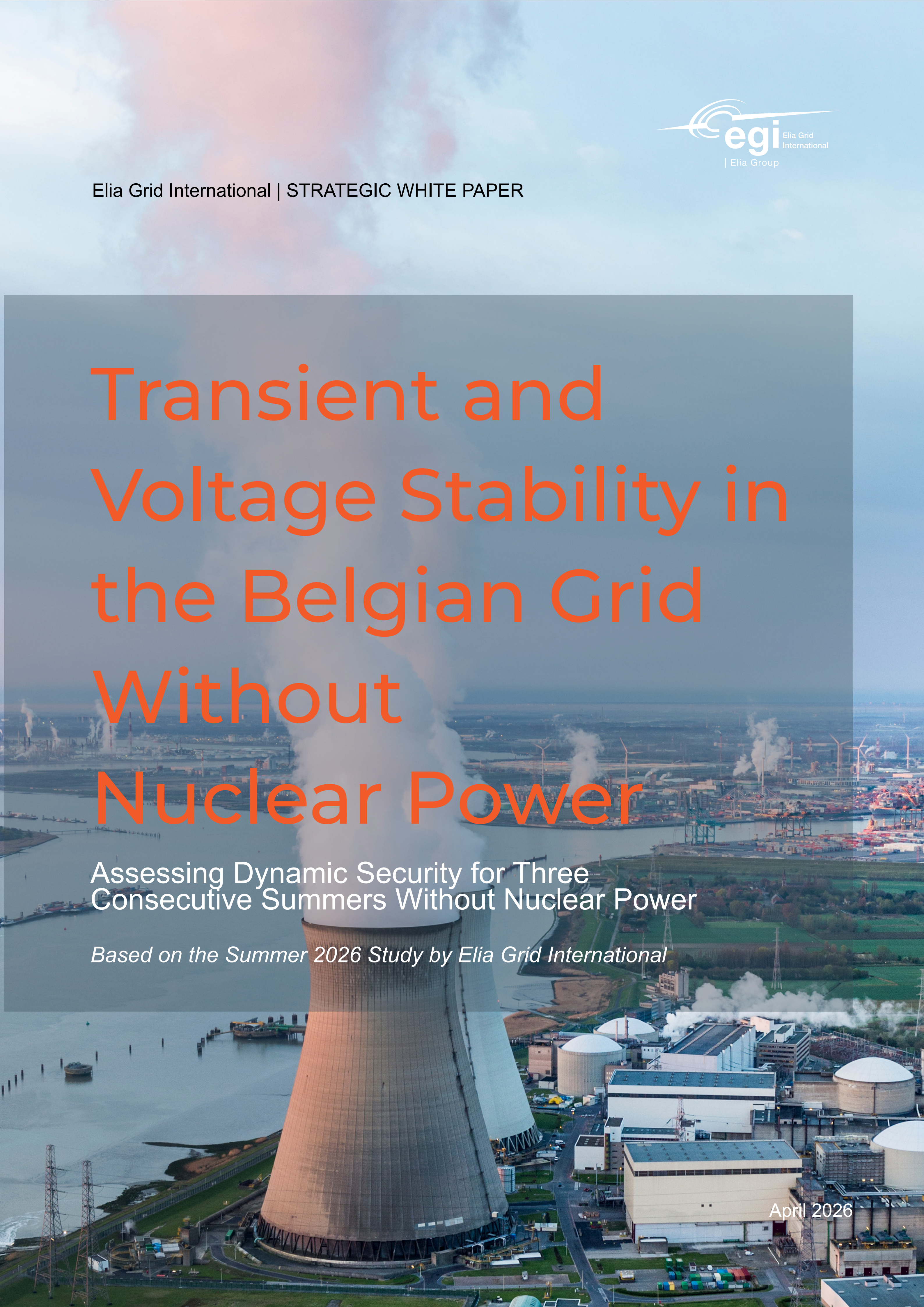


Elia Grid International | STRATEGIC WHITE PAPER

Transient and Voltage Stability in the Belgian Grid Without Nuclear Power

Assessing Dynamic Security for Three Consecutive Summers Without Nuclear Power

Based on the Summer 2026 Study by Elia Grid International

April 2026

Executive Summary

Belgium's Nuclear-Free Summers (2026–2028): Is the Grid Ready?

From 2026 to 2028, Belgium will spend three consecutive summers without nuclear power as Doel 4 and Tihange 3 undergo refurbishment from April to November. In the wake of the 2025 Iberian blackout, Elia's National Control Center commissioned a comprehensive grid security assessment. This white paper, prepared by Elia Grid International (EGI), presents the findings on transient and voltage stability.

The verdict is reassuring. The absence of nuclear power introduces no additional transient or voltage stability risks. Short-circuit power drops by up to 20% at the Mercator 380 kV substation and voltage dips propagate more deeply, yet all dynamic security indicators — MW at risk, multi-infeed equivalent short-circuit ratio (MIESCR), and cross-border exchange capacity — stay within safe limits. EMT simulations with OEM converter models confirm no instability risks for large converters on the Belgian coast. Cross-border stability margins hold under N-1 and N-2 contingencies, narrowing only at the N-3 extreme.

The trade-off is strategic. Belgium's strong interconnections — France above all — carry the grid through the nuclear gap, but this dependency makes the Belgium–France corridor a critical operational asset requiring enhanced monitoring and tighter TSO coordination.

What this paper delivers

- A definitive answer on whether a low-inertia, nuclear-free system can hold stable across extended summer periods
- Quantified impact on short-circuit power, voltage dip propagation, and MIESCR at critical nodes
- A replicable three-stream methodology for TSOs navigating similar transitions
- Strategic insight into how interconnection strength substitutes for synchronous generation — and the operational exposures this creates
- Iberian blackout lessons applied to a live planning case
- Clear identification of where margins narrow, so operators know where to act

The energy transition is rewriting the rules of grid stability. EGI helps clients stay ahead of them, combining the operational expertise of a leading TSO with the strategic perspective to turn technical findings into decisions leadership can act on.

Executive Outcome

Europe's energy transition demands that transmission system operators (TSOs) ensure reliable electricity supply while accommodating fundamental shifts in the generation mix. For Belgium, this challenge is particularly acute: the country must navigate three consecutive summers without nuclear power while simultaneously integrating increasing volumes of power electronic-based assets (e.g., RES (renewable energy sources), BESS (battery energy storage systems), data centers, etc.)

The ideal end-state is a power system that holds the same level of transient and voltage stability without nuclear as with it. Following any credible disturbance, such as a three-phase fault on the 380 kV network, the system must recover without cascading disconnections of generators, industrial loads, or critical infrastructure. Cross-border exchange margins must hold, and the growing fleet of converter-connected generation on the coast must remain stable under all credible contingencies.

Why now? The refurbishment of Doel 4 (D4) and Tihange 3 (T3) is essential to prepare these units for continued operation until 2035. However, both reactors will be taken offline for approximately seven months each year – from 1 April to 1 November – during the summers of 2026, 2027, and 2028. Belgium's five other nuclear units (Doel 1, 2, 3, Tihange 1, and Tihange 2) have already been permanently shut down between 2022 and 2025. The result is an unprecedented situation: **for three consecutive summers, Belgium will operate with zero nuclear generation.**

Summer conditions are particularly challenging for transient stability because they combine high renewable production with low conventional demand, resulting in fewer synchronous generators online and therefore lower system inertia and short-circuit power. In the most extreme scenario studied, the percentage of synchronous generation drops from 24% (with nuclear) to just 10% (without nuclear) – a dramatic reduction that fundamentally alters the grid's dynamic behaviour.
This situation is not unique to Belgium. A similar reduction in system strength is being observed in the south of the Netherlands and the west of Germany due to the replacement of synchronous machines with power converters.

Grid stability has thus become a broad challenge requiring analysis and cooperation beyond national borders. The April 2025 Iberian blackout – where oscillations, voltage instability, and loss of synchronism combined to cause a major disruption – served as a stark reminder of what can go wrong in weakened systems, directly motivating the depth of this study.

Achieving this outcome requires rigorous, scenario-based dynamic security assessment supported by advanced simulation tools, novel stability indicators, and validated operational measures – exactly the type of analysis that EGI's transient and voltage stability stream delivers.

The Problem

Without nuclear, Belgium's grid loses short-circuit power, inertia, and voltage support, with consequences that extend across borders.

Removing nuclear units fundamentally weakens the Belgian grid. Nuclear plants are large synchronous machines that provide short-circuit power, reactive support, and rotational inertia. Take them offline, and the network becomes electrically weaker: voltage dips propagate further, fault currents fall, and voltage recovery slows.
The numbers are concrete. At the pivotal Mercator 380 kV node, short-circuit power drops by roughly 20% in the high-RES scenario (from 19.7 to 16.5 GVA) and 13% in the low-RES case (from 25.9 to 23.1 GVA). As Belgium's domestic contribution falls, France's share rises from 33% to 42%, signalling a growing dependence on foreign synchronous generation for core stability services.

What Risks Emerge

- Voltage dips during faults become deeper and reach further across the network, affecting more components.
- Converter-connected assets, including the Nemo and Alegro HVDC links and offshore wind in the coastal zone, may face stability challenges where MIESCR falls below critical thresholds.
- The maximum safe power exchange between Belgium, the Netherlands, and continental Europe contracts, compressing margins against flow-based market coupling outcomes.

Why this Problem is being critical

The convergence of several trends makes this problem increasingly urgent:

The accelerating retirement of synchronous generation across the Central Western Europe region, the rapid growth of inverter-based resources that do not inherently provide system strength, the increasing complexity of cross-border power flows through flow-based market coupling, and – for Belgium specifically – the unprecedented duration of the nuclear-free period (three full summers).

The Iberian blackout demonstrated that when multiple stability phenomena interact in a weakened system, the consequences can be severe and difficult to predict with traditional methods alone.

This is precisely why Elia's broader Summer 2026 study was organised around three complementary streams, and why EGI's transient and voltage stability stream deployed both classical and novel analytical approaches.

A weakening grid, a tightening regional context, and a recent blackout make the case unmistakable: stability must now be engineered, not assumed.

Content and Complexity

The Broader Summer 2026 Study

Elia structured its Summer 2026 assessment around three complementary streams, each addressing phenomena seen in the Iberian blackout. The oscillations stream found minimal impact from the absence of nuclear, except where it combines with the loss of critical Belgium–France lines. The steady-state voltage stream identified a risk of voltages reaching 422 kV without intervention, and validated countermeasures to hold the 370–420 kV band until new shunt reactors come online in early 2027.

Each stream followed the same process: internal simulation, exchange with neighbouring TSOs (TenneT NL, RTE, Amprion, NESO), and recommendation assessment. All converged on one conclusion: nuclear absence does not threaten stability thanks to Belgium's interconnections, but margins narrow and dependency on France grows.

This white paper covers the third and technically complex stream: transient and voltage stability, led by EGI.

EGI Study Framework

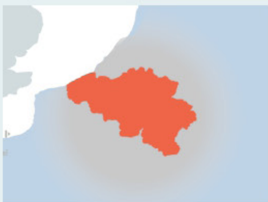
EGI deployed a multi-scenario framework anchored in two cases: High-RES (10–24% synchronous share) and Low-RES (56–68% synchronous share), each tested with and without Belgian nuclear. Network configurations covered a base case, a critical maintenance week, and a stressed scenario considering the unavailability of Gravelines units in northern France.

Methodology to asses dynamic stability

Classical methods to identify risks for dynamic security are looking at transient stability of synchronous machines. However, power systems are evolving with the integration of inverter-based resources and the decommissioning of large synchronous power plants. As a consequence, new methods need to be developed to properly assess dynamic security.

This study relies on classical and recent methods to identify risks for the dynamic security of the Belgian grid but also developed new indices to better capture risks for system stability with less and less synchronous generators.

1 Generation of different grid models based on scenarios



NUCLEAR; With and without Belgian nuclear

TOPOLOGY; Several maintenances options

GENERATION MIX

High synchronous machines, low RES

2 Dynamic security assessment through indicators

- Short circuit level (SCL)
- Aggregate SCR
- MW at risk
- Maximum flow exchange

LOW →

2 bis

If aggregate SCR is below a threshold, more detailed dynamic simulations are performed to assess the risk of converter instability

Although no risks have been identified, the system without nuclear is operated closer to its stability limits.

Concept Clarification: The Indicators

Short circuit level (SCL)

Short-circuit level computed at one of 400 kV substation, MERCATOR, during a fault. It gives an estimation of the grid strength and its ability to maintain stable voltage during and after a grid disturbance (fault, loss of generator/load,....).

It also gives a view on the contribution from Belgium compared to adjacent countries.

Aggregate SCR

Aggregate SCR is the short-circuit power at an electrical node divided by the capacity of the inverter-based injectors around that node weighted by their voltage sensitivity. It estimates the system strength in areas **with high penetration of inverter-based resources.**

1. Aggregate SCR → 2.5 → Dynamic studies
2. Dynamic studies → 1.5 → Stability limit reached

MW at risk

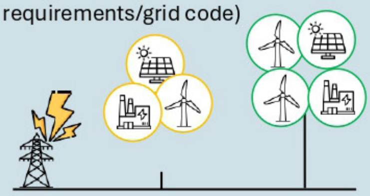
The index monitors the **loss of injected power after a short-circuit** event. It is based on RMS simulations.

Direct indicator

- MW of synchronous generators at risk after a short-circuit
- Based on **accurate protection schemes.**

Indirect indicator

- MW of PPMs[1] type B,C,D, and SPGMs type B, C, D at risk after a short-circuit
- Based on **assumed protection schemes** (following Belgian technical requirements/grid code)

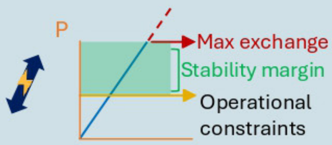


LIMITS:

1. **1000 MW** = warning for balancing of BE control areal
2. **3000 MW** = Continental Europe dimensioning incident

Maximum flow exchange

1. **Active power transfer** between BE-NL and continental EU is increased **until dynamic instability** occurs
2. The **maximum exchange** is determined in both directions, BE-NL ⇔ continental EU and **compared with static flow** based on flow based limits domain
3. Provide a **stability margin** relative to **operational constraints**



From Uncertainty to Assurance

EGI's Five-Part Resilience Assessment

Dynamic Security Assessment: Confirmed Resilience

The comprehensive simulation campaign delivered reassuring results across all scenario combinations. For PPMs and SPGMs of types B, C, and D, the maximum MW at risk remained below 250 MW in every scenario – well under both the 1,000 MW Belgian limit (which serves as a warning threshold for balancing of the Belgian control area) and the 3,000 MW Continental European dimensioning incident threshold. No synchronous generators lost synchronism in any base case or outage scenario, and the impact of removing nuclear generation on these indicators was consistently small.

Converter Stability: MIESCR Screening and EMT Validation

The Belgian coastal area hosts significant converter-connected infrastructure: the Nemo HVDC link to the UK and large offshore wind farms. In the High-RES scenario without nuclear, MIESCR values in the coastal area dropped below the 2.5 threshold triggering detailed EMT analysis. Notably, MIESCR values also fell below 2.5 in this area even with nuclear generation, indicating that this is a structural characteristic of the coastal area's electrical topology rather than a consequence of nuclear absence alone.

To address these findings, EGI developed a large-scale EMT model in PSCAD following a rigorous six-step process: full system modelling in PowerFactory, extraction of the Elia study area, export in PSSE and matching with PSSE load flow, import of PSSE raw file into PSCAD with network equivalent representations, addition of OEM-specific dynamic models for converters, model validation and fault simulation. The worst-case scenario combined maximum wind infeed, maximum Nemo HVDC import, and critical N-1 contingencies in the coastal area.

The EMT results were unequivocal: no risks of large converter instability were identified. Both the Nemo HVDC and the MOG1 offshore wind farm demonstrated stable fault ride-through behaviour, with active and reactive power recovering to pre-fault values and voltages stabilising within acceptable timeframes. This provides significant confidence that the MIESCR values, while below theoretical warning thresholds, do not translate into actual operational risk under the studied conditions.

Cross-Border Exchange Margins

The maximum BE+NL exchange analysis – a new indicator developed for this study – revealed important insights. Load in the Netherlands was progressively increased (or decreased) while compensating in France and Germany, until dynamic instability occurred. In the High-RES scenario under N-1 conditions, the maximum exportable volume (NL+BE to EU) decreased from 16.88 GW with nuclear to 14.27 GW without – a reduction of approximately 2.6 GW. However, both values remained comfortably above the maximum CORE market coupling exchange of 10.28 GW, a representative value for High RES/Low Load scenario, providing adequate stability margins.

The critical scenario emerged under N-3 conditions (three major BE-FR cross-border lines simultaneously out of service): the import capacity (EU to NL+BE) dropped to 5.54 GW without nuclear in the High-RES case and to 5.71 GW in the Low-RES case, both falling below the respective maximum CORE exchange values. While N-3 conditions are extremely unlikely, this result highlights the reduced resilience and the direct link between interconnection availability and dynamic security – reinforcing the recommendation to avoid simultaneous maintenance of two or more FR–BE 380 kV lines during the nuclear-free period.

The Gravelines Sensitivity

Given France's dominant contribution to short-circuit power in the no-nuclear scenario, EGI assessed the additional impact of losing the Gravelines nuclear units (located in northern France near the Belgian border). The results showed that the loss of Gravelines has limited impact on direct and indirect indicators, with total MW at risk remaining below 250 MW. However, MIESCR in the coastal area dropped further and EMT analysis confirmed the absence of converter instability. The maximum exchange capacity for NL+BE to EU decreased from 14.27 GW to 11.43 GW under N-1 – still above the 10.28 GW CORE limit, but with compressed margins. This scenario, though improbable, starkly illustrates Belgium's growing dependency on French synchronous generation.

High Voltage Scenario: No Self-Excitation Risk

Complementing the steady-state voltage stream's findings, EGI assessed the dynamic dimension of high-voltage scenarios through time-domain simulations. Starting from an initial operating point with voltages above 420 kV, a sequence of contingencies was simulated (loss of shunt Champion at t=0s, Nemo disconnection at t=40s, Coo 4–5–6 disconnection at t=60s). The results confirmed that, unlike during the Iberian blackout, no self-excitation mechanisms leading to overvoltage instability were detected in Belgium. Voltages at synchronous unit terminals remained within acceptable limits, reactive power outputs stayed within normal ranges, and the system settled to new stable operating points after each contingency.

Takeaways

Key findings and implications

The findings of this study extend beyond Belgium. They define a new operating reality for any grid losing synchronous generation, carry strategic implications for policy-makers and TSOs alike, and point to the kind of expertise needed to manage that reality.

1. The absence of nuclear power does not introduce additional transient or voltage stability risks to the Belgian grid. All dynamic security indicators – MW at risk, MIESCR, and maximum cross-border exchange – remain within safety thresholds across every scenario studied. No synchronous generators lost synchronism, no converter instabilities were detected. This is consistent with the broader study's conclusion that Belgium's strong interconnections, especially with France, underpin continued grid resilience.

2. System strength decreases measurably but manageably. The 13–20% reduction in short-circuit power and deeper voltage dip propagation represent real physical changes. France becomes the dominant contributor to system strength at Mercator (42% without nuclear). The grid operates closer to its stability limits than before – but does not cross them even with conservative/ pessimistic assumptions.

3. Converter stability in the coastal area is confirmed through rigorous EMT analysis. Despite MIESCR values falling below literature-based warning thresholds– both with and without nuclear – detailed electromagnetic transient simulations with OEM models found no instability risks for HVDC converters and large offshore wind farms.

4. Cross-border exchange margins remain positive but narrower, and the France dependency is critical. Under N-1 and N-2 conditions, margins remain comfortable. Under N-3 conditions, margins compress to or below market coupling levels. Avoiding simultaneous maintenance of two FR–BE 380 kV lines during the nuclear-free period is a key operational recommendation endorsed by all neighbouring TSOs.

Conclusion

Strategic Implications

For policy-makers, these findings provide evidence-based reassurance that Belgium's nuclear refurbishment programme does not create unmanageable dynamic security risks during summer conditions. The system's resilience depends on the availability of French synchronous generation and intact cross-border interconnections – a dependency that warrants continued attention in energy security planning.

For TSOs and system operators, the study validates the importance of maintaining and expanding the operational toolkit – from network topology management to enhanced monitoring. The indicators used by EGI for stability assessment (MIESCR screening with EMT validation, maximum exchange stability margin) are directly implementable in operational processes. The recommendation to dedicate an expert to analyse these indicators during the nuclear-free period reflects the increased operational demands. Cross-border collaboration on outage planning and methodology exchange – including quarterly stability assessment meetings and improved cross-border models – is a critical enabler.

How EGI Adds Value

Elia Grid International brings a unique combination of operational expertise, advanced modelling capabilities, and real-world system knowledge to the challenge of managing dynamic security during energy transition. The methodology presented in this paper – combining RMS dynamic security assessment with multi-layered indicators, MIESCR screening, EMT validation with OEM models, and progressive exchange analysis – represents a comprehensive framework that can be adapted and applied to any power system facing the integration challenge of high inverter-based resource penetration with declining synchronous generation.

EGI's work was conducted within the broader three-stream structure of the Summer 2026 study, benefiting from cross-stream insights (notably the steady-state voltage stream's identification of high-voltage scenarios and the oscillation stream's confirmation of the France interconnection's critical importance) and enriched by structured dialogue with four neighbouring TSOs. This integrated, collaborative approach demonstrates that rigorous analysis not only identifies risks but – equally importantly – confirms when risks are manageable, providing the evidence base that decision-makers need to move forward with confidence during unprecedented operational situations.

About Elia Grid International

Elia Grid International (EGI) is a leading consultancy specializing in addressing complex power system challenges. Drawing expertise and innovative solutions from two of Europe's top transmission system operators, EGI delivers strategic, technical, and regulatory guidance across all aspects of power transmission.

Over the past 10 years, EGI has grown into a truly global player, built on a fantastic human journey. What started as a team of 10 experts who broke a new strategic ground to establish a consulting company has evolved into a trusted partner worldwide.

Today, EGI has successfully delivered more than 320 projects in over 20 countries, extending its reach across all seven continents.

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