Comparative Reliability Assessment of Subsea Cables and Overhead Lines for Large-Scale Offshore Wind Integration: A Dutch Case Study

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***Abstract*—This paper assesses and compares two alternative transmission options between the Borssele and Maasvlakte regions: an HVDC subsea cable with converter and switching station, and an AC overhead line over the conventional transmission route. Such a study is needed to support the integration of large-scale offshore wind generation requiring reliable transmission solutions to maintain grid security and support the Netherlands' 2035 future grid vision. The analysis focuses on system-level reliability indicators, mainly, system unavailability, Expected Energy Not Supplied and Probability of Load Curtailment, in order to quantify performance under realistic operational conditions. The study aims to identify the most reliable transmission option and provide evidence-based recommendations for TenneT's grid-expansion planning. By linking reliability evaluation with offshore wind integration, this work supports the development of a robust hybrid AC/DC transmission system for the future Dutch electricity grid.**

***Index Terms*—AC overhead line, HVDC, offshore wind farms, probabilistic analysis, reliability assessment.**

I. Introduction

Offshore wind integration comes with some operational challenges within the electricity grid. As the location of demand centers and offshore wind farms (OWFs) are not always close by, the non-dispatchable sources cannot be easily managed or curtailed. This spatial dispersion imposes a burden on the Transmission System Operators (TSOs) who have to operate the existing infrastructure with uncertainty from both ends, i.e. demand and generation. To accommodate the growing penetration of wind power within the existing electrical grid, TSOs are facing challenges due to delayed or stranded transmission expansion. As a result, they are investing both knowledge and resources to safeguard grid reliability and ensure the required security of supply. The Dutch transmission grid is also anticipating challenges due to the planned integration of large-scale offshore wind energy and a new nuclear generation facility [1]. Moreover, the stress on the transmission grid has increased in the past two decades due to congestion. The same applies for TenneT, the Dutch TSO, as it is facing considerable challenge of allowing new connections to the existing grid due to an increase in network congestion [2].

The Netherlands has set ambitious goals to scale up installed capacity of offshore wind from approximately 4.5 GW in 2023 to 35 GW by 2035, and 70 GW by 2050 [3]. Achieving these targets will require a stable and supportive framework for long-term offshore wind development. The massive integration of wind power cannot be answered by fast grid development activities in terms of transmission system expansion. Such a need should be carefully assessed against a possible overinvestment in expansion planning, resulting from an uncertain forecast of wind power generation and load respectively. The dilemma with system planners is that construction of OWF takes 4-5 years while it may take 8-10 years to plan, execute and construct a transmission corridor.

As part of TenneT's Target Grid initiative [4], a large volume of OWFs is planned to be connected to the mainland transmission network. Specifically, 4 GW of offshore wind capacity will be connected to the Borssele region and another 6 GW to the Maasvlakte region [5]. Borssele is already hosting power generation, including an existing 1.4 GW of OWF and additional plan for 3.2 GW of new nuclear units. Given this substantial concentration of both renewable and conventional generation, it is foreseeable that the network in the Borssele and Maasvlakte region may face congestion issues due to the massive influx of power. As a result, the expected increase in power flows from offshore wind farms and new nuclear power plant will place significant stress on the transmission network in this region. The circuits in this region are expected to face congestion and potential overloads in the future, which could negatively impact the reliability of the Dutch power grid.

A. Problem Statement

Fig. 1 shows the OWF programs at North Sea [6]. Currently, the Borssele Alpha and Beta (each 700 MW) are connected to the Borssele substation, and by 2031 additional projects such as IJver Alpha and Nederwiek 1 (each 2 GW), together with new nuclear power, will also connect to Borssele substation. At Maasvlakte, the Hollandse Kust Alpha and Beta (each 700 MW) are already connected, and after 2031, further offshore projects, namely IJver Beta, IJver Gamma, and Nederwiek 2

979-8-3315-8138-1

(each 2GW), will follow [7]. Fig. 2 shows the future OWFs connected to both the substations.

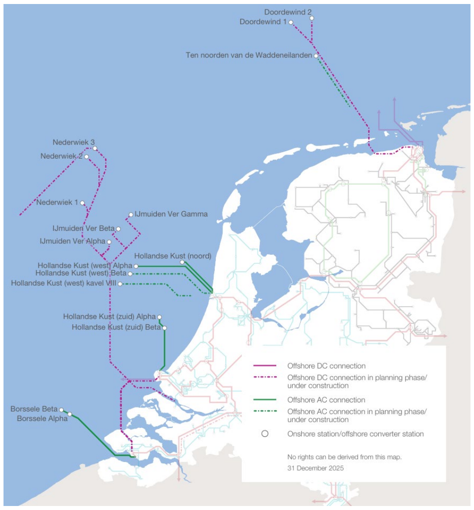

Figure 1. OWF programs at North Sea (current and future)

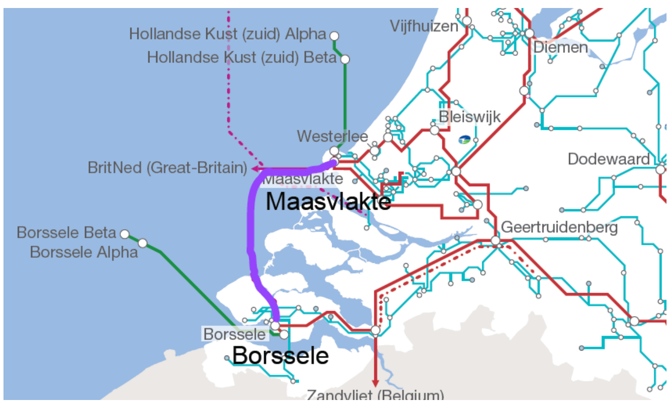

Figure 2. OWF project in scope of this paper [6]

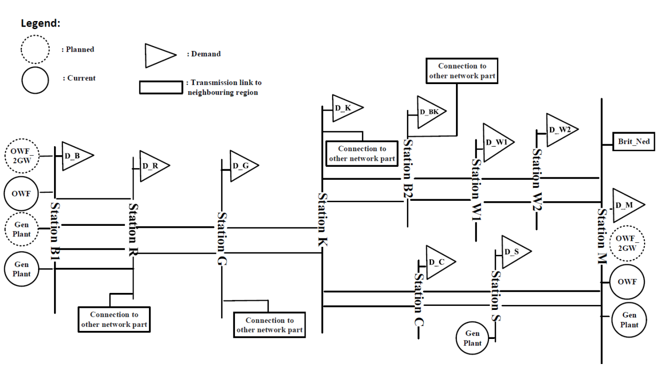

Figure 3. Single line diagram of network under study

The connection between the substations can be visualized via two paths as shown in Fig. 3. For naming purposes, Borssele is B1 and Maasvlakte is M, and all the other intermediate stations are named as shown in Fig. 3. For substation M-K transmission, there are two parallel transmission paths: M→W2→W1→B2→K and M→S→C→K. For substation B1-K transmission, there is only one transmission path B1→R→G→K. Between B1 and R, the path consists of four 380 kV AC overhead lines (OHLs), while the sections between R–G and G–K each contain two 380kV AC OHLs [8].

To address this challenge, this paper focuses on two potential solutions via three scenarios for transporting electricity between the substations B1 and M: Subsea high voltage DC (HVDC) cable between B1 and M (includes HVDC switching station) or new 380kV AC OHLs. Each solution has its own technical characteristics in terms of complexity and operation. One of the important factors when choosing between them is reliability. Therefore, it is necessary to compare the reliability of both options to find out which one is more suitable for TenneT's future power grid in the long term.

B. *Research Questions and Scope*

To achieve the study objectives, the following research questions were formulated:

1. How can the reliability of the Dutch transmission grid be quantitatively assessed and compared for two potential solutions?
2. Which reliability indicators and modelling approaches (e.g., power-flow simulations and reliability block diagram) best capture differences in system performance in terms of unavailability, Expected Energy Not Supplied (EENS), and Probability of Load Curtailment (PLC)?
3. Based on the comparative reliability outcomes, which grid expansion option demonstrates superior robustness under normal and contingency conditions, and how can these findings inform TenneT's 2035 grid development strategy?

The reliability assessment methods and system under study are explained in Section II. Section III explains the three scenarios as well as data, and section IV analyses as well as discusses the results for the two potential solutions. Finally, section V concludes this work.

II. Methods and System under Study

A. *Reliability Assessment Methodology under Study*

This paper uses two main approaches to study the reliability of grid expansion between substations B1 and M: Power Flow Analysis (PFA) and Reliability Block Diagram (RBD) [9]. The two approaches give different but complementary insights. While PFA shows how the system performs under demand and generation conditions, RBD analysis shows the structural reliability of the network. Together, they give a more complete picture of system reliability.

B. *Justification of the Method*

The choice of methods is based on both the literature and the project requirements. RBDs are well established in reliability studies and provide clear insights into how system topology and redundancy affect the grid. However, RBDs cannot capture operational conditions such as power demand, generation variability, and circuit loading. For this reason, power flow analysis is also adopted. PFA with contingency analysis are widely used in transmission planning to evaluate overloads and to quantify energy not supplied under failure conditions. Simulation-based reliability assessment is not chosen, because topics such as cable aging and time-to-failure are outside the scope of this project. Instead, fixed failure rate

979-8-3315-8138-1

data from TenneT's reports are used. Combining both methods ensures that the study covers both structural reliability (via RBD) and operational reliability (via PFA). This dual approach is also chosen because of the practical needs of the project. TenneT requires a comparison between subsea HVDC cables and OHLs, not only in terms of component reliability but also in terms of their ability to solve congestion problems.

C. *Transmission Routes for Substations B1-M*

For the HVDC connection between B1 and M, the selected route follows a path close to the existing HVDC cables that connect offshore wind farms in the North Sea to the Borssele and Maasvlakte substations. This route is chosen because the seabed studies and environmental assessments have already been carried out by TenneT for previous projects along this corridor. Therefore, using the same route for future grid expansion reduces both time and cost for TenneT. The new AC OHLs follow the existing 380kV grid corridor, which simplifies the licensing and permitting process. TenneT has already implemented grid expansion between substations B1 and R, and is planning further expansion between substations R and G. Adding new OHL circuits along this established route is therefore more practical and easier to approve [10]. There are two routes between substations K and M. The selected route: M→S→C→K is chosen because it provides better grid flexibility and connection balance. The alternative route via substation B2 is not selected, as the substation B2 already has interconnections with other 380kV substations, whereas substations S and C have fewer connections.

III. Scenarios under Study and Data

For reliability assessment, three possible scenarios are defined and explained in Table I. In this scope, the studied network is connected to the rest of the Dutch and UK grid from five substations. These interconnections are shown as rectangular boxes. They represent the interfaces through which power can either be imported from, or exported to, the studied grid section. The direction of power flow at these interconnections depends on the balance between local generation and load. For example, in the 2035 scenario that is used for analysis, there are hours when substation R imports power from the other network part while in other hours R exports power to the same.

The generator and load data used in this study are based on the 2035 National Drivers (ND) scenario developed by TenneT where long-term energy system simulations are performed using national statistics and studies (e.g., CBS, PBL), European modelling frameworks (e.g., ENTSO-E, ERAA), and weather-based hourly profiles. Given the uncertainty of such future data, caused by factors such as changing CO_2 prices, market developments, and technology costs, TenneT updates the scenario every two years to ensure more realistic projections for 2035. In this paper, the most recent update from the 2025 ND scenario is used [11].

For the RBD analysis, the network is divided into its subsystems and it follows the series/parallel schema as shown in Figs. 3-5. Table II shows the failure rate and repair time for the components. While disconnectors and circuit breakers are included in the substation design, their failure rates are relatively low, and repairs can be managed directly by TenneT. In contrast, failures in the overhead line or subsea cable require external permits, coordination with stakeholders, and longer repair times. For this reason, the paper focuses on the OHL and the HVDC cable circuits. The exact length of cable and OHL will be assessed in project realization phase and an approximated length was considered for this study.

TABLE I. Three Scenarios under Study

Scenario A	Scenario B	Scenario C
No Grid Expansion (Fig. 3): The base case without any additional OHL or subsea HVDC cables. The number of circuits in this scenario is 22.	Grid Expansion via Subsea HVDC Cables (Fig. 4): Two sets of subsea HVDC cables connect substation M and B1 (Two set of independent cable with the capacity of each of them 250MW is chosen by request of TenneT). The total length of cables in this scenario is approx. 160 km.	Grid Expansion via Overhead Line (Fig.5): 5 new 380 kV OHL AC circuits with total length of 181 km are added to reinforce the network in this region. These new OHL with the colour of red is shown in Fig. 5

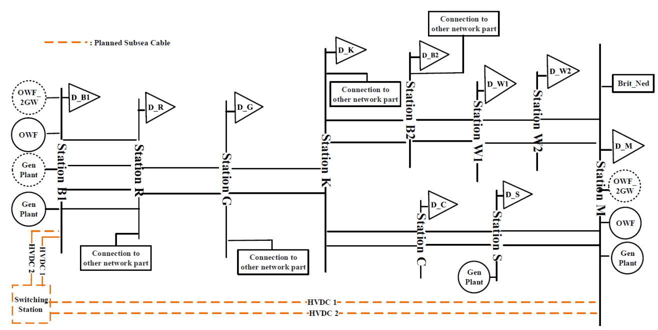

Figure 4. Single line diagram of network in scenario B

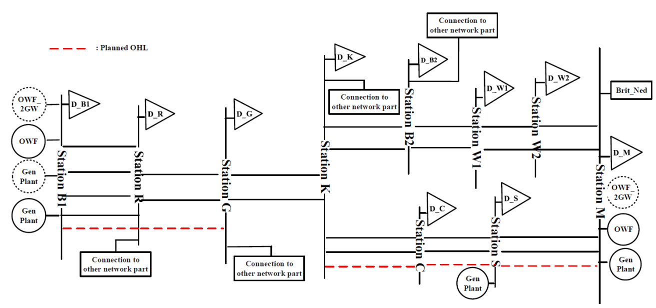

Figure 5. Single line diagram of network in scenario C

TABLE II. Failure Rate and Repair Time

Component	Failure rate	Repair time
Cable	0.047 failures/year 100 cct.km	60 days
Joint	0.02 failures/year 100 components	9.7 days
OHL AC circuit	0.19 failures/year 100 cct.km	2 days
Disconnector	0.0022 failures/year	-
AC circuit breaker	0.0098 failures/year	-

979-8-3315-8138-1

IV. Results

A. Power Flow Analysis Method

1) Loading and congestion behavior

Hourly load-flow simulations, using Pandapower, were conducted for 8736 hours to account for seasonal and diurnal variability in wind generation and demand. Based on expert advice within TenneT, each circuit's utilization was classified into four loading bands (0–50%, 50–80%, 80–100%, > 100%) as shown in Table III. N-1 contingency analyses were used to calculate the EENS and PLC [12]. While EENS is used to quantify the energy that is expected to be unserved (or curtailed) due to insufficient generation or circuit capacity, PLC is the probability that the demand load cannot be supplied (partially or completely).

$$EENS = \sum_{i \in N} P_i \times E_i \tag{1}$$

where P_i is the probability of contingency i, E_i is the total curtailed energy in the study period (1 year) if contingency i happens (in MWh) and N is the set of considered contingencies.

$$PLC = \sum_{i \in N} \frac{t_i}{T} \times P_i \tag{2}$$

where t_i is the total duration of load curtailment during the study period T given that contingency i occurs.

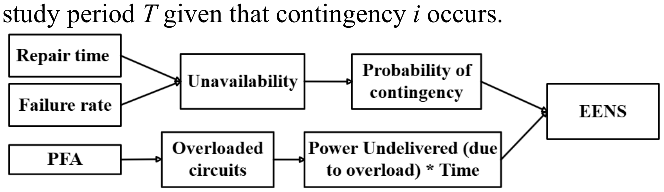

Figure 6. Calculation of EENS

TABLE III. Circuit Loading for Different Scenarios

Scenario \ Loading	0–50 %	50–80 %	80–100 %	> 100 %
A	88.1 %	11.7 %	0.17 %	0.003 %
B	89.3 %	10.5 %	0.22 %	0.002 %
C	96.9 %	3.0 %	0.10 %	0.0017 %

Scenario C therefore maintains most circuits below 50 % loading for > 96 % of the year and nearly eliminates overloads. High-loading corridors persist only in G–K and R–G, which approach rated limits during peak export from substation B.

2) Reliability indices

Under the N-1 criterion, reliability indices were computed as shown in Table IV.

TABLE IV. EENS and PLC for Different Contingencies

Scenario with EENS (MWH) / PLC (%)		Contingency: R–G	Contingency: G–K	Contingency: B1–R
	A	420.4 / 0.237	427.4 / 0.158	0.56 / 0.0006
	B	1 038.9 / 0.019	189.4 / 0.0043	1.80 / 0.00007
	C	0.10 / 0.0004	426.6 / 0.196	0.06 / 0.0002

The OHL expansion (Scenario C) yields the lowest EENS, while Scenario B introduces a single-point risk of large EENS when the R–G path is stressed.

3) Probability of load curtailment

The PLC distribution over all contingencies shows that overload probabilities above 0.2% occur only in Scenario A. Scenario C lowers PLC for 90% of circuits below 10^{-3}%, indicating robust redundancy and balanced power sharing between parallel paths.

4) Contingency analysis

Figs. 7-8 (EENS/PLC comparison) highlights that G–K and R–G dominate reliability performance.

- **Scenario A:** Two major contingencies cause most EENS (≈ 850 MWh combined).
- **Scenario B:** The HVDC link offloads B1–M flow but shifts congestion to R–G, doubling its curtailment impact.
- **Scenario C:** Grid reinforcement effectively confines energy not supplied to a single corridor (G–K), with all other outages yielding negligible curtailment. Thus, OHL expansion ensures operational resilience and minimizes risk concentration.

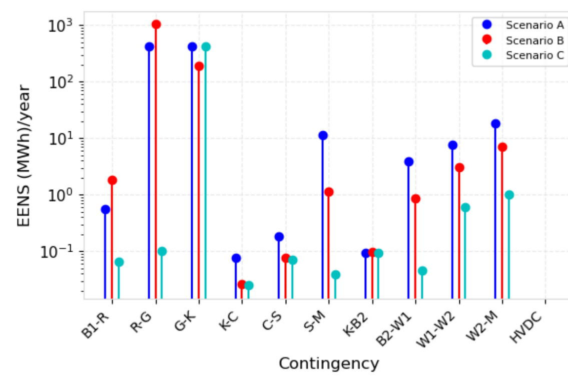

Figure 7. Comparison of EENS for different scenarios

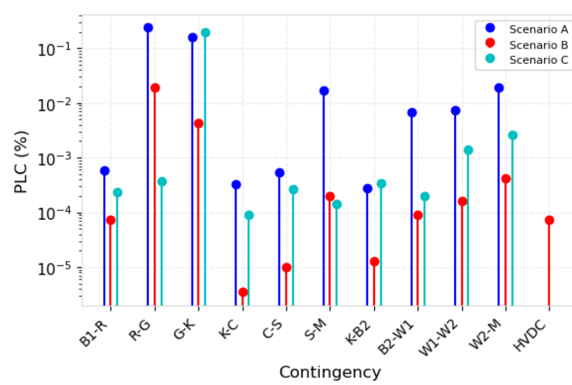

Figure 8. Comparison of PLC for different scenarios

B. Reliability Block Diagram Method

1) System-level results

The RBD approach complements the power-flow results by quantifying structural reliability based on component failure and repair data. Each transmission path between substations is represented as a series–parallel network, and combined unavailabilities are derived for the three scenarios.

TABLE V. UVAVAILABILITY AND AVAILABILITY

Scenario	Unavailability (%)	Availability (%)	Downtime (s yr⁻¹)
A	5.47×10^{-5}	99.999945	17.2 s
B	2.12×10^{-9}	99.999999998	0.0007 s
C	1.25×10^{-5}	99.999987	3.95 s

Scenario B provides the mathematically highest availability, as indicated by the lower values of PLC in every contingency except R-G, the lower unavailability and downtime in Table V, and the lower unavailability in Fig. 9, but Scenario C offers better redundancy and maintainability because repairs on OHLs are faster and less complex than subsea interventions, factors that are not reflected in the repair time assumptions in Table II.

2) Node-level insights

- Node 1 (B1–K): Highest criticality; unavailability ≈ 5.47×10^{-5} % in A, reduced to 1.26×10^{-5} % in C.
- Node 2 (K–M via C–S): Least critical; unavailability ≈ 1.0×10^{-8} % in C.
- Node 3 (K–M via B2–W2–W1): Unavailability ≈ 4.2×10^{-5} % in C.

3) Comparative interpretation

The RBD analysis supports the PFA results: the G–K and R–G circuits dominate reliability performance, and additional parallel paths dramatically reduce overall unavailability.

4) Contingency analysis

Structural N-1 analyses, shown in Table VI and Fig. 9, quantify how loss of a single branch increases total system unavailability.

TABLE VI. N-1 CONTINGENCY RESULTS AGAINST BASE CASE

Scenario	Base U (s/yr)	Most Critical Branch	U(N-1) (s/yr)	Increase Factor
A	17.26	R–G	20 476	× 1186
A	–	G–K	11 204	× 650
B	6.7×10^{-4}	R–G	0.79	× 1180
C	3.95	G–K	11 191	× 2830

While the absolute values differ by method, both frameworks consistently identify the same critical corridors and confirm that OHL reinforcement distributes reliability risk more evenly.

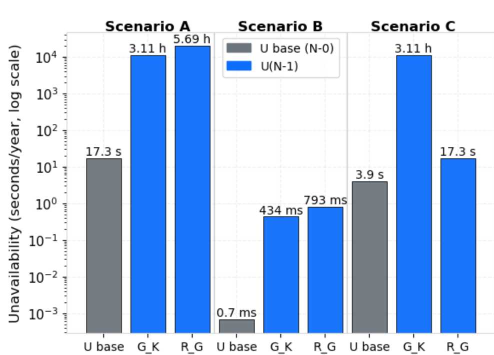

Figure 9. Comparison of N-1 contingency in RBD

C. *Verification of the two methods*

Two cross-checks were conducted to validate the reliability modelling:

- **PFA method:** Pandapower simulation outputs were compared with reference cases and historical TenneT data. Maximum line-loading deviation < 1.8%, and PLC/EENS indices varied < 3% under alternative hourly generation profiles, thus confirming numerical robustness.
- **RBD method:** Analytical formulations were recalculated in MATLAB; differences in system unavailability were < 0.2%. Sensitivity tests with alternative repair times reproduced proportional trends, confirming internal consistency.

V. CONCLUSION

This study compared the reliability of two grid expansion options between Borssele and Maasvlakte in addition to no grid expansion. Using static power-flow simulations and Reliability Block Diagram (RBD) modelling, system reliability was assessed through unavailability, Expected Energy Not Supplied (EENS), and Probability of Load Curtailment (PLC). Results show that the AC overhead-line expansion (Scenario C) performs best in both reliability and congestion management. Over 96% of circuit-hours remain below 50% loading, and only the G–K corridor reaches 80–100% utilization for brief periods. Scenario C yields the lowest EENS, while Scenario B, though highly reliable in theory, is more sensitive to single-corridor outages and repair times. The study concludes that OHL reinforcement is the most operationally robust solution for large-scale offshore-wind integration. As this is a static reliability analysis, future work should include voltage-stability and economic assessments, and explore hybrid AC/DC solutions and energy storage to further enhance grid resilience.

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REFERENCES

[1] IEA (2025), The Netherlands 2024, IEA, Paris https://www.iea.org/reports/the-netherlands-2024.
[2] TenneT half-year report 2022. Available from: https://www.tennet.eu/nl/nieuws/tennet-zet-cruciale-stappen-deenergietransitie-met-een-record-aan-groene-financiering-0
[3] Available online: https://www.rijksoverheid.nl/documenten/kamerstukken/2022/09/16/kamerbrief-windenergie-op-zee-2030-2050
[4] TenneT Target Grid: https://www.tennet.eu/nl/target-grid
[5] TenneT: https://www.tennet.eu/nl/projecten/provincies/offshore
[6] TenneT grid maps: https://www.tennet.eu/grids-and-markets/grid-maps
[7] TenneT, Het 2GW Program: https://www.tennet.eu/nl/over-tennet/innovatie-en-partnerships/het-2gw-program
[8] “Nederlands Transportnet,” TenneT, Arnhem, Internal Report, 2024.
[9] J. Setreus and L. Bertling, “Introduction to HVDC technology for reliable electrical power systems”, IEEE PMAPS 2008.
[10] “Analyze grid integration,” TenneT, Arnhem, Internal Report, 2024
[11] “Investment Plan 2035,” TenneT, Internal Report, 2025
[12] R. Billinton and R. N. Allan, *Reliability Evaluation of Power Systems*, New York: Plenum Press, 2nd ed., 1996.

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