



Dynamic Line Rating for Enhancing Power System Reliability under High Wind Penetration

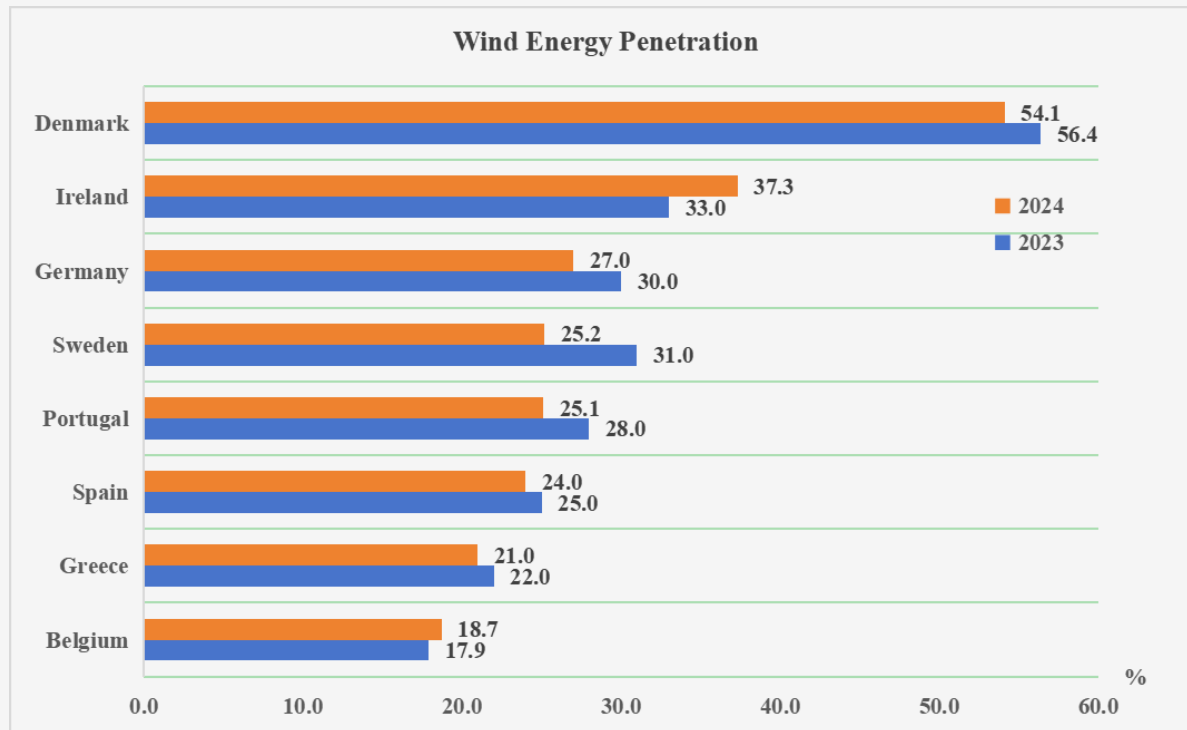


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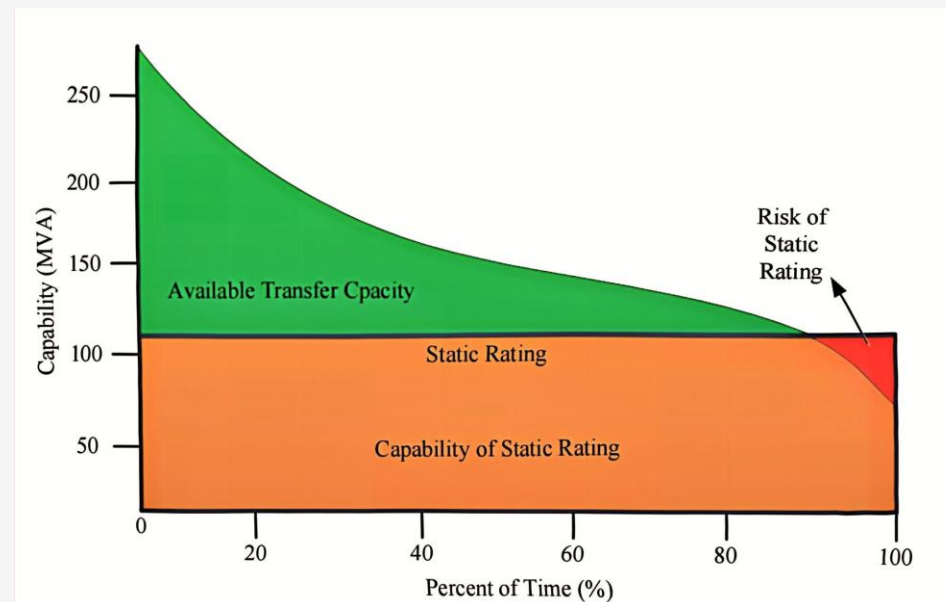
Wind power has become a cornerstone of modern power systems due to its near-zero operational emissions and merit-order effect, which jointly reduce market clearing prices and total production costs.

The rapid expansion of the wind industry has further increased renewable penetration worldwide.

However, its inherent intermittency poses challenges to system **reliability**.

Dynamic Thermal Rating (DTR) is an advanced transmission asset utilization technique that enables power lines and other components to operate closer to their **true thermal limits** by accounting for **real-time environmental conditions**.

In this paper, a coordinated modelling framework incorporating DTR is proposed to assess the reliability of power systems under high wind penetration scenarios.



$$P_w = \begin{cases} 0 & 0 \leq V < V_i \\ (A + BV + CV^2)P_r & V_i \leq V < V_r \\ P_r & V_r \leq V < V_o \\ 0 & V \geq V_o \end{cases}$$

$$A = \frac{1}{(V_i - V_r)^2} \left[V_i(V_i + V_r) - 4V_iV_r \left(\frac{V_i + V_r}{2V_r} \right)^3 \right]$$

$$B = \frac{1}{(V_i - V_r)^2} \left[4(V_iV_r) \left(\frac{V_i + V_r}{2V_r} \right)^3 - (3V_i + V_r) \right]$$

$$C = \frac{1}{(V_i - V_r)^2} \left[2 - 4 \left(\frac{V_i + V_r}{2V_r} \right)^3 \right]$$

- ✓ The power output of a wind turbine P_w as a function of wind velocity is commonly modelled using a piecewise-defined function.
- ✓ V_i and V_o represent the cut-in and cut-out wind speeds, respectively.
- ✓ The coefficients A, B, and C are determined through interpolation, ensuring a smooth transition from zero output to rated output.

In contrast to traditional Static Thermal Rating (STR), DTR dynamically updates the current-carrying capacity of transmission lines in real time by accounting for fluctuating meteorological conditions, including ambient temperature, wind velocity, and solar irradiance. For bare overhead conductors, the methodology underpinning DTR is formally specified in **IEEE Standard 738**. In this standard, the steady-state thermal behavior of a conductor is characterized by a heat balance equation, in which the sum of thermal gains and losses must remain in equilibrium

$$q_c + q_r = q_s + I^2 R(T_C)$$

The maximum transfer capacity of the conductor allowable can be expressed mathematically as:

$$I_{dtr} = \sqrt{\frac{q_c + q_r - q_s}{R(T_C)}}$$

The convective heat loss q_c from the conductor is calculated according to wind speed conditions.

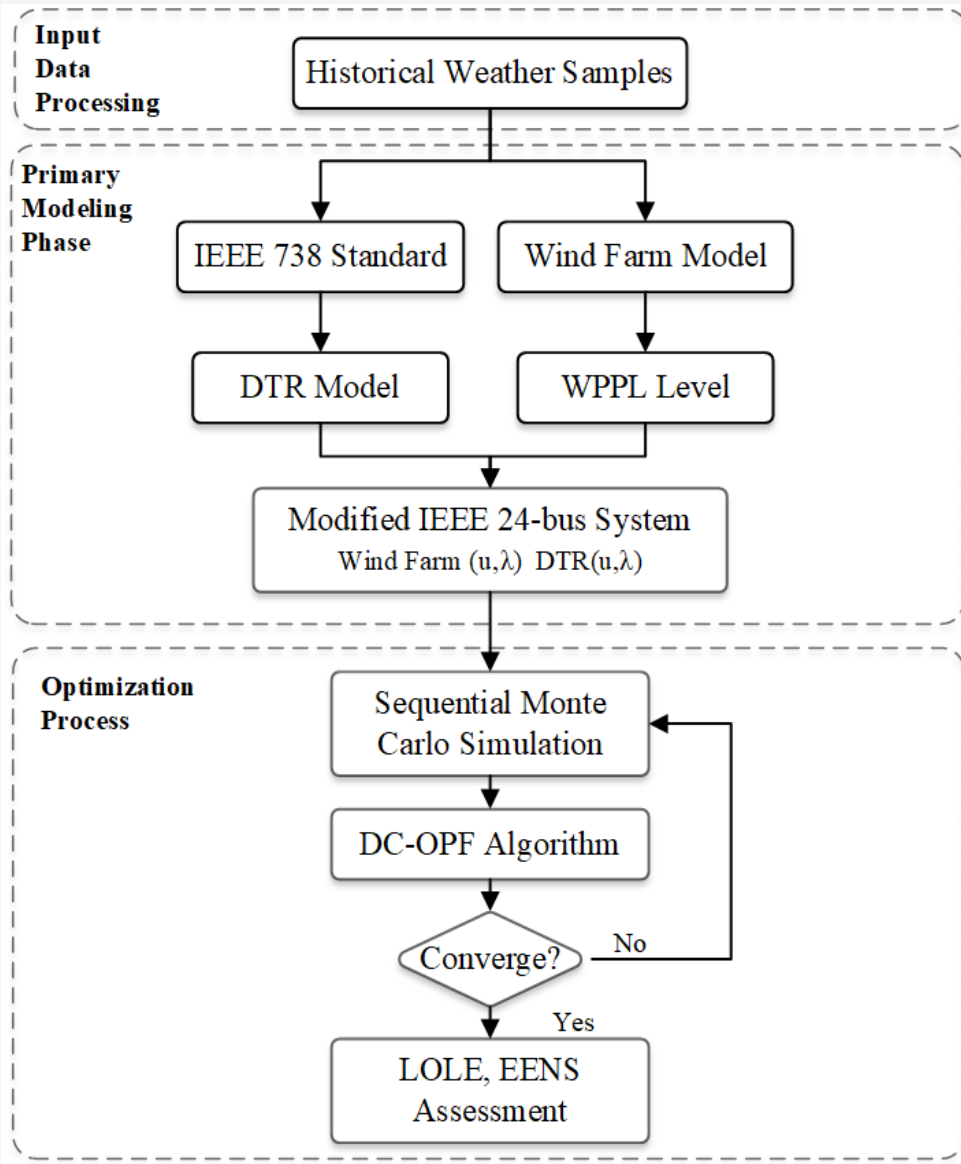
$$q_c = \begin{cases} \left[1.01 + 0.371 \left(\frac{D\rho_f v}{\mu_f} \right)^{0.52} \right] k_f (T_C - T_A) & V < 0.6 \text{ m/s} \\ 0.1695 \left(\frac{D\rho_f v_w}{\mu_f} \right)^{0.6} k_f (T_C - T_A) & V \geq 0.6 \text{ m/s} \end{cases}$$

The radiative heat loss from the conductor surface q_r is expressed as:

$$q_r = 0.138D\varepsilon \left[\left(\frac{T_C + 273}{100} \right)^4 - \left(\frac{T_{AC} + 273}{100} \right)^4 \right]$$

The solar heat gain q_s absorbed by the conductor is given by:

$$q_s = Q_s \sin(\theta) A'$$



- ✓ The framework employs a Sequential Monte Carlo Simulation (SMCS) scheme to accurately capture the temporal and stochastic characteristics of both wind generation and environmental conditions that affect line thermal capacity.
- ✓ The resulting system state is passed to a DC Optimal Power Flow (DC-OPF) algorithm.
- ✓ The SMCS process is deemed converged when the relative variation in EENS between successive iterations falls below 5%.

$$EENS = \sum_{i=1}^T P_{loss} \cdot \Delta t \quad LOLE = \sum_{i=1}^{8760} \sum_{j=1}^n p[X \geq (C_i - L_{i,j})]$$

- ✓ In this work, a modified version of the IEEE-24 RTS is employed.
- ✓ Each wind turbine is represented by a Doubly-Fed Induction Generator (DFIG) with a nominal capacity of 5 MW.
- ✓ The reliability parameters are defined by a mean time to failure (MTTF) of 2000 hours and a mean time to repair (MTTR) of 77 hours.
- ✓ The load profile is uniformly increased by 10%.
- ✓ The static STR of the original network are uniformly scaled by a factor of 0.7.

Under the conventional STR scheme, LOLE exhibits a steep upward trend as renewable integration increases, rising from approximately **1270 h/yr** at 20% penetration to **1895 h/yr** at 40%. When DTR is employed, LOLE is substantially reduced at all penetration levels due to the enhanced real-time transfer capability enabled by dynamic adjustment of line ratings. Specifically, LOLE decreases to approximately **549 h/yr** (a 57% reduction) at 20% penetration, **989 h/yr** (–29%) at 30%, and **1511 h/yr** (–20%) at 40%.

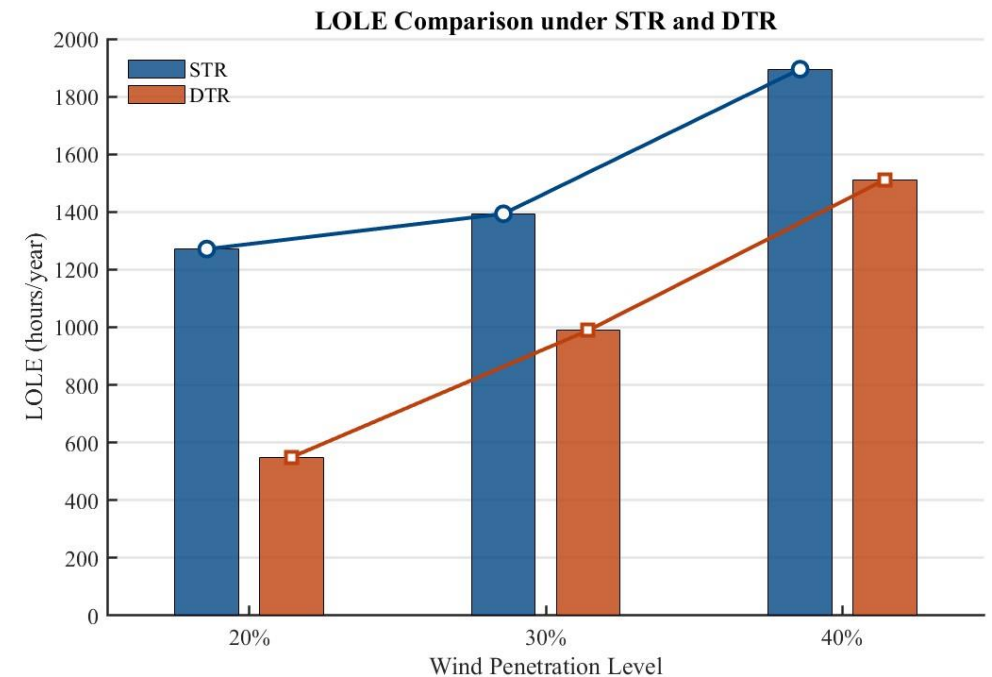


Figure 3. LOLE under STR and DTR across wind penetration levels 20 %, 30 %, and 40 %

Under STR, EENS increases steadily from **150.3 GWh/yr** at 20 % to **275.7 GWh/yr** at 30 %, and further to **588.8 GWh/yr** at 40 %. With DTR implemented, EENS shows a modest decrease to **146.4 GWh/yr** (–**2.6%**) at 20%, potentially reflecting improved dispatch efficiency under low-load conditions. More significant reductions are observed at higher wind shares, where EENS drops to **232.4 GWh/yr** (–**15.7 %**, **43.3 GWh**) at 30 %, and **514.2 GWh/yr** (–**12.7 %**, **74.6 GWh**) at 40 %.

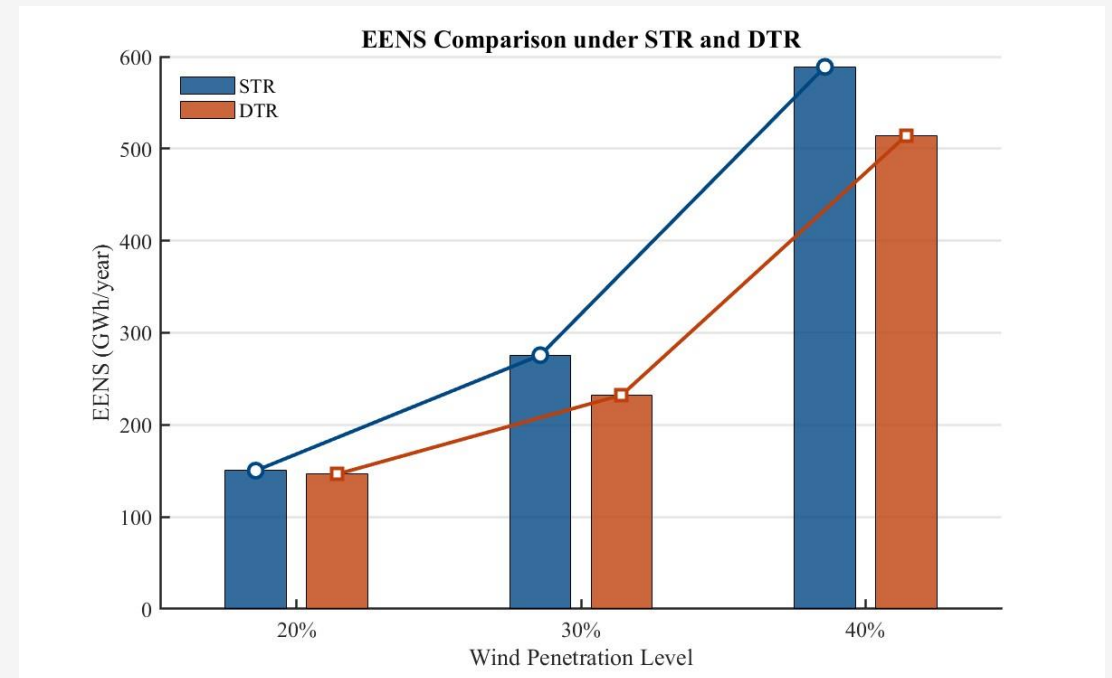


Figure 4. EENS under STR and DTR across wind penetration levels 20 %, 30 %, and 40 %

- ✓ This study presents a coordinated reliability assessment framework that integrates wind generation and DTR to evaluate power system performance under increasing renewable penetration.
- ✓ These findings illustrate that DTR substantially reduces reliability risk across a wide spectrum of renewable integration scenarios, with its most pronounced benefit observed in lowering LOLE at all penetration levels.
- ✓ Although the impact on EENS is limited at very low wind shares, DTR nonetheless achieves significant reductions in unsupplied energy once penetration reaches moderate and high levels.
- ✓ Overall, the implementation of DTR significantly improves power system reliability by reducing outage risks and maintaining operational adequacy under variable renewable generation.



THANKS

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