

Wind Farm Layout Optimization Considering Fatigue-induced Maintenance Costs to Drive Optimal Levelized Cost of Energy

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Abstract

Current wind farm layout optimization (WFLO) studies predominantly treat operation and maintenance (O&M) costs statically, neglecting the dynamic degradation of turbine components caused by complex wake-induced fatigue accumulation. To address this issue, this study aims to establish a novel WFLO framework optimized for the Levelized Cost of Energy (LCOE), utilizing turbine fatigue accumulation as the core engine driving O&M costs (OPEX) and downtime losses. First, a multi-condition fatigue load database is constructed via extensive aeroelastic simulations considering diverse inflow and wake interaction conditions, followed by the training of an Extreme Gradient Boosting (XGBoost) algorithm to efficiently predict Damage Equivalent Loads (DELs). Secondly, this advanced machine learning-based fatigue model is coupled with a refined LCOE economic model. Discarding traditional static cost assumptions, the framework leverages the fatigue prediction model to directly quantify structural damage, translating it into additional baseline-exceeding OPEX over the wind farm's lifecycle. Finally, the Random Search (RS) algorithm is employed to execute the fatigue-constrained layout optimization. Systematic evaluations indicate that XGBoost serves as the optimal fatigue prediction model, balancing high precision with computational efficiency, while the RS algorithm effectively navigates the complex nonlinear relationship between fatigue limits and spatial layout. Wind farm application tests confirm that, by imposing fatigue tolerance constraints to ensure operational safety, the optimized layout effectively mitigates severe wake superposition. Under full wind direction scenarios, while strictly limiting component fatigue and reducing OPEX, the framework still achieves an Annual Energy Production (AEP) increase of 0.39% to 3.89%. Cost-benefit analysis further validates that setting reasonable fatigue tolerance limits yields higher lifecycle economic returns compared to unconstrained designs. By deeply integrating fatigue assessment with LCOE, this study realizes the co-optimization of energy yield and lifecycle costs, providing a precise and novel paradigm for the cost-safety balanced design of wind farms.

Keywords

Fatigue Load, Wake Effect, Annual Energy Production, Wind Farm Optimization, Levelized Cost of Electricity