

Surrogate modeling of interconnector flows: A machine learning alternative to full-scale power system simulations with application to cross-border electricity exchange

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Abstract-

Cross-border electricity exchanges are crucial for operating and planning highly renewable power systems. Many studies reduce spatial granularity to keep models tractable and prescribe cross-border exchanges exogenously, often by reusing historical import/export time series. Such assumptions become inconsistent as renewable penetration changes the magnitude and timing of flows. The core contribution of this work is a machine-learning (ML) surrogate framework that maps nodal time-series data (e.g., hourly demand and renewable generation) to synthetic interconnector-level flow time series. The resulting flows serve as fixed boundary conditions in reduced power system optimization models (PSOMs). This addresses studies focused on a subset of an interconnected system, for which repeatedly solving the full model across multiple climate years or scenarios is computationally expensive. We demonstrate the framework on a pan-European single-node-per-country DC optimal power flow model. We benchmark k-nearest neighbors (KNN), ridge regression, random forests, Extra Trees, gradient boosting, XGBoost, and feedforward neural-network (SQU) surrogates. As an additional contribution, we introduce a novel custom neural-network loss that softly penalizes physically implausible flow patterns. This soft penalty is not a guarantee of full power-flow feasibility. Across benchmarks, the SQU variants provide the most consistent out-of-sample and downstream optimization performance while substantially outperforming scaled historical profiles. The ML-generated flows closely reproduce country-level results of the full European model while greatly reducing computation time (up to $\sim 500\times$). The proposed framework enables scenario-consistent reduced PSOM studies across climate years after a single full-model run, eliminating repeated pan-European simulations and supporting more robust climate-year analyses under fixed system assumptions.

Index Terms- Surrogate modeling; Machine learning; Power system optimization; DC optimal power flow; Renewable integration; Energy system modeling

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