SYNTHESIZING REALISTIC ELECTRIC POWER TRANSMISSION NETWORKS FOR EXPEDITING INTERCONNECTION STUDIES

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Overview

The shift toward high-electrification scenarios is fundamentally transforming power system planning, investment decisions, and operational strategies. A key obstacle impeding progress is the lengthy process of interconnecting zero-carbon generators to the transmission network, which has become a critical bottleneck in advancing U.S. decarbonization goals and addressing rising electricity demand. Between 2010 and 2023, the total generation capacity in U.S. interconnection queues quadrupled to nearly 2.6 TW, with grid interconnection delays becoming the leading cause of project cancellations for utility-scale solar developers. The median time from interconnection request to commercial operation has doubled, interconnection costs—driven by network upgrades—have escalated, and the available transmission capacity continues to shrink. These trends underscore an urgent need for innovative interconnection strategies to facilitate renewable energy integration and grid modernization. The U.S. Department of Energy's Transmission Interconnection Roadmap has proposed expedited approaches, such as the Energy Resource Interconnection Service (ERIS), highlighting that their impacts on grid stability and operational performance warrant further exploration.

Addressing these interconnection challenges demands an accurate and granular representation of the transmission network, including nodal-level hourly profiles of historical and forecasted generation and consumption. Such representations are essential for quantifying system reliability risks, assessing curtailment rates, and evaluating the economic outcomes of interconnection policies like ERIS. Key areas of analysis include (i) thermal reliability risks, (ii) congestion-induced curtailment risks, and (iii) non-thermal reliability risks. Current expedited interconnection studies often overlook real-time operational flexibility for curtailing ERIS generators, leaving gaps in reliability assessments. Stochastic unit commitment models, which incorporate probabilistic forecasts, can provide operators greater flexibility, particularly in systems with significant storage capacity. However, the main obstacle to proposing any approaches for expedited analyses is the confidentiality of the power network information, which, for the US, is mandated by the Critical Energy Infrastructure Information (CEII) regulations. While recent efforts in open-data transmission network modeling have yielded valuable tools, they primarily offer static snapshots of load and generation profiles [1], [2] or employ testbeds disconnected from real-world scenarios [3], [4]. Therefore, open-source, realistic transmission networks equipped with nodal-level historical and forecasts of load and variable renewable energy (VRE) generation are needed to support advanced interconnection studies.

We have developed the GridSynth protocol, a comprehensive framework for synthesizing realistic transmission networks and supporting data essential for advanced interconnection analyses to meet the abovementioned needs. As illustrated in the green box of Figure 1, GridSynth outputs a set of data products that enable researchers to evaluate curtailment rates and reliability risks under stochastic unit commitment paradigms, contrasting sharply with traditional models reliant on deterministic forecasts. Central to the framework is its Probabilistic Forecast Generator (PFG) [5], which produces scenarios of nodal hourly profiles of demand and VRE generation and their corresponding probabilities of occurrence. These multivariable time series capture the variability and uncertainty of renewable energy production and load dynamics, reflecting plausible trajectories across a week-long planning horizon. GridSynth preserves inter-regional and cross-variable correlations, enabling robust grid planning and operational simulations. To demonstrate its capabilities, we apply GridSynth to a case study of Duke Energy's territory—one of the largest vertically integrated utilities in the U.S.—which includes 2.1 GW of pump-hydro storage power. The findings offer actionable insights for refining interconnection policies and optimizing network upgrade decisions.

Methods

The GridSynth protocol, summarized in Figure 1, integrates diverse data sources, including historical load-generation profiles (eGRID, EIA), weather data (ERA5), and local energy consumption patterns (OEDI) as follows:

1. **Input Data Processing**: Nodal-level VRE generation and demand profiles are synthesized using the PFG model. These profiles capture historical variations and future uncertainties, forming a robust foundation for stochastic unit commitment studies. City- and county-level electricity consumption is disaggregated into industrial, commercial, and residential sectors to represent demand variability and reflect real-world consumption patterns accurately.
2. **Network Topology Extraction**: The protocol employs HIFLD and supplementary data sources, including street-view information, to estimate line lengths, tower configurations, and conductor parameters. This ensures that synthesized networks align with the physical and operational constraints of actual transmission systems.

3. **Parameter Estimation**: Synthesized networks include impedance, reactance, and thermal capacity parameters for transmission lines, as well as generator locations and capacities. Historical and forecasted nodal-level load and VRE generation profiles are integrated for use in AC power flow and stochastic unit commitment analyses.
4. **Validation and Case Study**: The GridSynth framework is validated using a case study of Duke Energy's territory, highlighting the role of long-duration energy storage assets in interconnection studies. By incorporating probabilistic forecasts and realistic network parameters, the framework ensures that interconnection strategies are thoroughly evaluated in terms of technical feasibility and economic viability.

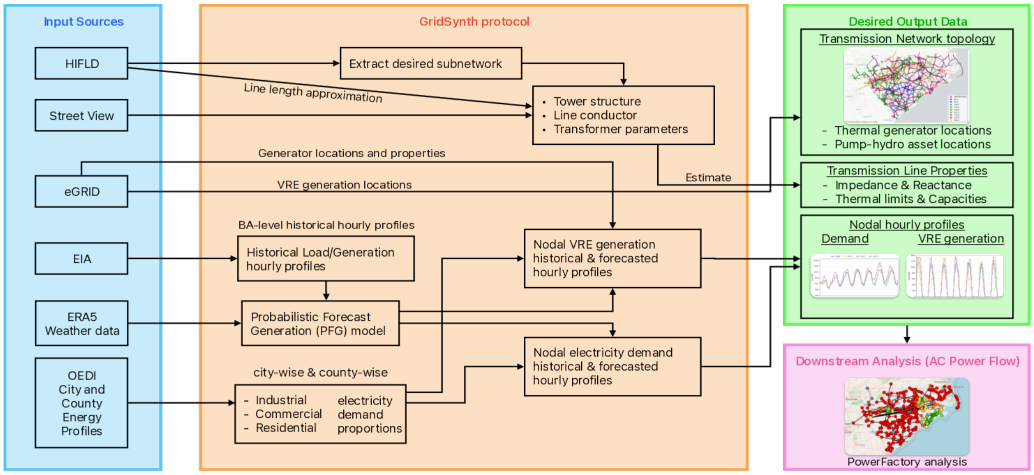

Figure 1: The GridSynth architecture integrates datasets such as historical load-generation profiles (eGRID, EIA), weather data (ERA5), and regional energy consumption patterns (OEDI). The GridSynth protocol, summarized in the orange block, generates nodal demand and VRE profiles via the Probabilistic Forecast Generator (PFG), and estimates network parameters. The resulting network outputs, shown in the green block, support downstream analyses essential for interconnection studies, including AC power flow, stochastic unit commitment, and steady-state analysis.

Results

The synthesized network accurately captures the spatial distribution of thermal generators, pump-hydro storage assets, and nodal hourly profiles of historical and forecasted VRE generation and demand. The network's quality and realism are validated using topological metrics commonly applied in transmission system analyses [6]. In the Duke Energy case study, GridSynth demonstrates its capacity to assess stability, thermal performance, and economic curtailment rates under various interconnection scenarios. Key findings highlight the pivotal role of integrated storage systems in mitigating variability impacts, reducing curtailment, and enhancing grid flexibility and reliability.

Conclusions

The GridSynth protocol addresses critical gaps in interconnection studies by providing high-resolution, realistic transmission network models. These models support detailed evaluations of curtailment rates, reliability risks, and economic outcomes under stochastic unit commitment frameworks. GridSynth equips researchers and policymakers with tools to develop effective strategies for optimizing interconnection processes and minimizing network upgrade costs by integrating nodal hourly profiles of historical and forecasted load and VRE generation. This comprehensive framework ensures that future interconnection studies are technically rigorous, paving the way for scalable renewable energy integration while maintaining grid stability.

References

[1] T. Banze and T. M. Kneiske, "Open data for energy networks: Introducing DAVE—a data fusion tool for automated network generation," *Sci Rep*, vol. 14, no. 1, p. 1938, Jan. 2024.
[2] A. B. Birchfield and T. J. Overbye, "A Review on Providing Realistic Electric Grid Simulations for Academia and Industry," *Curr Sustainable Renewable Energy Rep*, Jun. 2023.
[3] I. Peña, C. B. Martinez-Anido, and B.-M. Hodge, "An Extended IEEE 118-Bus Test System With High Renewable Penetration," *IEEE Transactions on Power Systems*, vol. 33, no. 1, pp. 281–289, Jan. 2018.
[4] G. Tricarico, R. Wagle, M. Dicorato, G. Forte, F. Gonzalez-Longatt, and J. L. Rueda, "Zonal Day-Ahead Energy Market: A Modified Version of the IEEE 39-bus Test System," in *2022 IEEE ISGT Asia,* Nov. 2022, pp. 86–90.
[5] D. Floros, W. Wang, M. Hernandez, J. Kern, and D. Patino-Echeverri, "Generating Probabilistic Scenario Ensembles for Stochastic Unit Commitment," in *Proceedings of the 45th IAEE conference*, 2024.
[6] J. Li, L. Dueñas-Osorio, C. Chen, B. Berryhill, and A. Yazdani, "Characterizing the topological and controllability features of U.S. Power transmission networks," *Physica A*, vol. 453, pp. 84–98, Jul. 2016.