Study Area Selection Tool to Enhance System Impact Analysis of Generator Interconnections

Sanjana Kunkolienkar, Thomas J. Overbye
Department of Electrical and Computer Engineering
Texas A&M University
College Station, TX
{sanjanakunkolienkar; overbye}@tamu.edu

Gabriela Cabrera, Hanyue Li
Electric Power Engineers, LLC.
Austin, TX
{gcabrera; hli}@epeconsulting.com

***Abstract*—This paper introduces a study area selection tool that identifies relevant network segments/facilities affected by interconnection of generators into a power grid. Case studies are shown using the actual Texas grid model where the tool captures essential network facilities to see the impact of generator integration at different Points of Interconnection (POI). The tool's compatibility with existing power system analysis software make it valuable for reliable generator integration studies, minimizing iterative exchanges between generator owners and grid regulators.**

***Index Terms*—Study area selection, generator interconnection, transmission planning**

I. Introduction

The power grid network must have sufficient generation capacity to meet consumer demand. To achieve this balance, generation resources must match the required load. As consumer demand has steadily increased over the years, the grid must continually expand its generation capacity. However, adding new generation is more complex than merely manufacturing a generator and connecting it wherever demand exists. Because the laws of physics govern power flow, it's essential to assess the impact of each new generator interconnection carefully.

Before a new generator can be connected to the grid, a series of studies—both steady-state and dynamic—are conducted. Key factors in this decision include the Point of Interconnection (POI), the voltage level, generator capacity, and the potential impact on system behavior under various contingency events. Generator developers or interconnection customers submit an interconnection request that includes technical details about the proposed facility. Each Independent System Operator (ISO) (or regulatory authority) has specific guidelines for performing these studies. Once submitted, the interconnection request enters a queue managed by the ISO/ regulatory authority, alongside other pending requests, for a system impact study.

Assessing the impact of such interconnections on system stability and reliability poses significant challenges, particularly in large-scale networks. Various ISOs and regulatory authorities follow different guidelines for performing generator interconnection studies, which is summarized in Section II. For large power grid networks, it's often necessary to define a "study area" as the sink and treat the rest of the system as a source or slack area. Each network is unique, with distinct characteristics; for instance, ERCOT uses Generic Transmission Constraints (GTC) [1], while other ISOs establish custom transmission line limits.

Currently, the determination of study areas for generator interconnection lacks a standardized manual or guideline. ISOs and RTOs provide guidelines to transmission system owners or generator owners on the types of studies and the procedure with the liberty to make study assumptions. These assumptions are typically made by transmission system owners or generator owners, relying heavily on their expertise. This expertise often stems from years of experience in power engineering, which has led to the common practice of assessing impacts based on the distance of "n buses away." This method has worked in the past; however, as the workforce shifts, with seasoned engineers retiring and new professionals stepping in, reliance on individual judgment becomes less feasible.

To address this, a tool is needed—one that is grounded in the physics of power flow and based on the generator's POI, aligning with the engineering judgments traditionally employed. Such a tool would consolidate the various rules of thumb used by different ISOs, providing a consistent approach. In this paper, we propose a tool for identifying and extracting relevant subsets of the power grid based on generator POI, voltage level, power flow and voltage sensitivities in steady state as well as contingency scenarios. This tool is seamlessly compatible with standard power system simulation tools such as PSS®E, TARA and PYPOWER.

The remainder of this paper is structured as follows: Section II explores requirements for generator interconnection studies in different regions of the United States, Section III describes the approach used to develop the tool, Section IV presents three case studies, Section V concludes the study with future directions.

II. Background

The Federal Energy Regulatory Commission (FERC) has issued key orders over the years to improve U.S. electric power markets in response to technological advances and policy shifts. Order No. 888 (1996) [2] opened transmission lines

Principle	Description
Electrical Proximity	Facilities electrically close to the POI, often defined by the number of transmission buses away from the POI.
Impact Thresholds	Facilities where the new generator causes power flow changes exceeding a certain percentage are included. Common thresholds range from 3% to 5% change in line loading.
Voltage Levels	Facilities operating at certain voltage levels (e.g., 100 kV and above) are often included due to their significance in bulk power transfer.
Stability Considerations	Areas where the new generator could impact system stability, such as oscillations or voltage collapse, are part of the study.
Affected Systems	Adjacent systems or neighboring ISOs/RTOs are included if cross-border impacts are possible.

TABLE I: General Principles for Selecting Study Areas

to third-party access, promoting market competition. This was followed by Order No. 2000 (1999) [3], which encouraged forming Regional Transmission Organizations (RTOs) to enhance grid efficiency.

Order No. 2003 (2003) [4] introduced standardized generator interconnection procedures, simplifying grid access for new generators. Similarly, Order No. 2006 (2006) [5] established guidelines for small generator connections, facilitating grid entry for smaller renewable sources. Order No. 845 (2018) [6] improved transparency and flexibility in the interconnection process. On the other hand, FERC orders and guidelines from several ISOs allow for certain assumptions. It is represented in FERC Order 2023 [7] as follows,

> *"Consequently, some or many of the details of a particular transmission provider's generator interconnection procedures may vary considerably from the broad description provided here."*

This flexibility may lead to iterative back-and-forth communication or even penalties for generator owners who lack adequate visibility into their interconnection's system impact.

Generator interconnection studies help ensure system reliability, identify necessary upgrades, and maintain compliance with regulatory standards. A critical component of these studies is the selection of the study area, which encompasses the portion of the grid analyzed for potential impacts due to the new generator. Different ISOs and RTOs have specific methodologies for selecting study areas, although they share common principles.

One of the primary considerations in selecting a study area is electrical proximity. This typically includes facilities that are electrically close to the POI, often defined by the number of transmission buses away from the POI. Another factor is impact thresholds, where facilities are included if the new generator causes power flow changes that exceed a certain percentage, commonly ranging from 3% to 5%. Additionally, voltage levels play a role, with facilities operating at certain voltage levels (e.g., 100 kV and above) often included due to their importance in bulk power transfer. Stability considerations are also critical, including areas where the new generator could affect system stability, such as oscillations or voltage collapse. Finally, affected systems such as adjacent or neighboring ISOs/RTOs may be included if cross-border impacts are possible.

In PJM Interconnection, the study methodology is based on Distribution Factor (DFAX) analysis, where facilities contributing more than 5% to the flow are included in the study area [8]. Midcontinent ISO (MISO) conducts a Definitive Planning Phase study, which includes facilities that experience a 3% or greater change in power flow [9]. MISO's study area focuses on regional transmission facilities and may extend to neighboring systems if the impacts exceed thresholds.

In California ISO (CAISO), Phase I and Phase II interconnection studies are performed, and facilities within a certain electrical distance, along with those affected beyond established thresholds, are included [10]. CAISO's study area may extend across multiple voltage levels and neighboring utilities if significant impacts are detected. ISO New England (ISO-NE) uses a combination of power flow and stability analyses, including facilities that experience a 5% or greater change in power flow [11]. Their study area encompasses affected transmission lines, transformers, and sometimes includes neighboring control areas.

In New York ISO (NYISO), the Class Year Study process identifies facilities affected by significant thermal, voltage, or stability impacts, focusing primarily on the New York State transmission system, but may also involve adjacent ISOs if necessary [12]. Electric Reliability Council of Texas (ERCOT) conducts a Full Interconnection Study, which includes facilities where the new generator impacts thermal limits, voltage profiles, or stability margins [13], [14]. Due to ERCOT's isolated grid, the study area is limited to the Texas Interconnection but is comprehensive within that scope. Finally, Southwest Power Pool (SPP) performs coordinated Impact Studies, including facilities that experience a 3% or more change in loading [15]. SPP's study area includes regional facilities and may extend to neighboring systems for a thorough analysis.

These tailored approaches reflect each region's specific needs and configurations while focusing on grid reliability and system stability. The general principles followed in different regions are compiled together in Table I. The power grid has evolved from a collection of localized networks into a complex, interconnected system spanning multiple voltage levels. Due to the physical laws governing power flow, actions in one area can affect distant parts of the grid. Despite some control mechanisms, our ability to direct power flow remains limited. This interconnectedness has made defining an effective study area crucial for all analyses, especially with the increased emphasis on cluster studies [7].

Identifying "affected systems" in generator interconnection studies, which assess the impact of queued projects on neighboring systems, illustrates the importance of careful study area selection. These studies often reveal the affected systems, or adjacent networks influenced by the addition of new generation. They are conducted with differing assumptions and modeling approaches between host transmission providers and affected systems. This lack of coordination introduces procedural uncertainty, additional costs, and delays—particularly in regions like MISO, PJM, and SPP, where interconnection customers have noted that the uncertainty surrounding timelines can be more disruptive than the study duration itself [16]. Effective coordination and sequencing of these affected system studies become critical to maintaining queue progress, especially for projects near commercial operation or requiring restudies. While ERCOT and CAISO manage this process efficiently, MISO, PJM, and SPP regions have faced challenges [16].

A dedicated tool for study area selection is essential in a system with diverse stakeholders and varying interconnection guidelines. Such a tool would provide consistency across different requirements, reduce procedural uncertainty, and improve coordination—ultimately helping the grid adapt to its increasingly interconnected structure and the demands of modern power markets.

III. Methodology

Algorithm 1 presents a structured process for managing data through a series of scripts. Importantly, the county notation used in this paper is adopted to safeguard Critical Energy Infrastructure Information (CEII). All underlying network data and analyses presented are based on the actual ERCOT planning cases. However, for aiding reader understanding, a demonstration of the algorithm is shown on a synthetic Texas case. The code for this tool is published at [17].

In the United States, a county is a geographic subdivision of a state or territory, typically governed by local authorities. While most states use the term ”county,” Louisiana and Alaska use ”parishes” and ”boroughs,” respectively, as equivalent terms. With over 3,000 counties and equivalents nationwide, these units vary widely in population size and area. Texas, for instance, has 254 counties. Given that power grids span large geographic regions, counties serve as a practical spatial representation for analyzing the spread of power grid networks in this study.

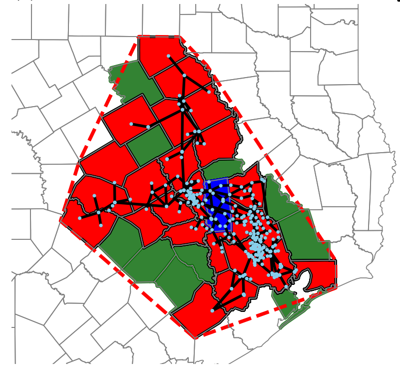
A. Algorithm Overview

Using a breadth-first search approach, the algorithm identifies buses that are n levels away from a specified starting bus. This method explores the network, marks each visited bus, and compiles a list of those that are exactly n levels away. This initial step is pivotal in pinpointing network sections potentially affected by disturbances originating from the starting bus.

Initially, a conservative selection for the value of n is adopted—typically starting with a broader scope to encompass a larger network area. This scope is then refined through power flow studies to identify the truly impacted subset. Based on practices observed across various ISOs, RTOs, and generator owners, selecting up to 8 levels, determined by ”engineer experience” based on the voltage level, is used as a benchmark. The ultimate objective is to extract a relevant segment of the more extensive network that is directly impacted. The counties containing these identified buses are then highlighted in red, signifying their direct connection to the starting bus across n levels of separation. This visual representation helps understand the geographical spread and impact of the electrical network. Next, the algorithm focuses on the geographical aspect by creating a convex hull around the counties identified in the first step. This convex shape encompasses all the selected counties and is then used to determine which other counties intersect with this shape, highlighting them in green. For this step, counties with an area of 50% or greater intersecting with the convex hull are included. These intersecting counties are important as they might be affected indirectly by issues within the convex hull.

Following this, the algorithm incorporates an analysis phase that scrutinizes power system facilities for operational strain under N-1 contingency scenarios through sensitivity analysis using power factor distribution factors and high-loading con-

(a) Subnetwork with buses 8 levels away.



(b) Subnetwork with intersecting counties.

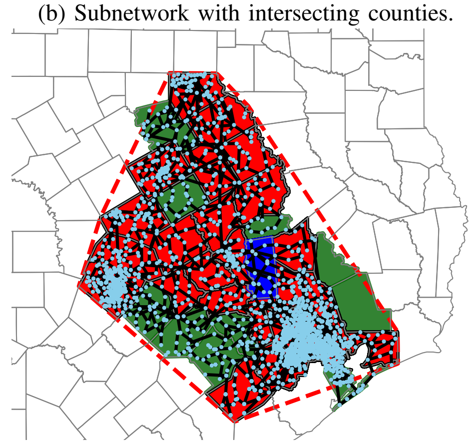


Fig. 1: Demonstration of the tool to determine study area for POI in Grimes County for the synthetic test case on the footprint of Texas.

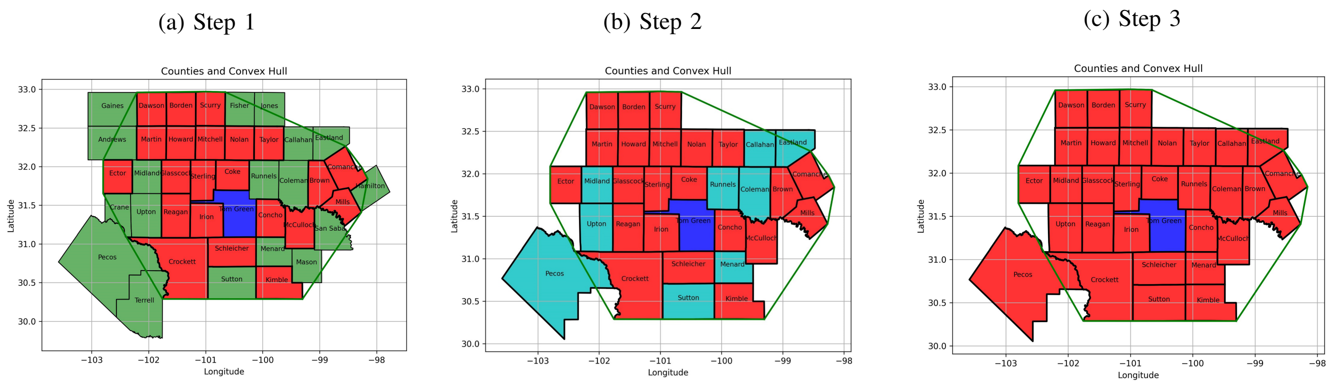


Fig. 2: Study area determination process

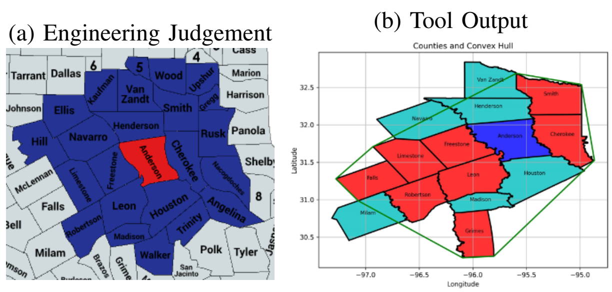


Fig. 3: Study area determination for POI in Anderson county

ditions. Facilities strained beyond 80% of their line limits or where generator injection impacts distribution factors by more than 3% are identified and extracted using TARA [18] flowgate screening. This analysis helps pinpoint facilities needing attention due to their critical operational parameters.

Then the voltage sensitivity of buses connected to the previously identified facilities, both with and without the influence of a study generator are assessed. Buses exhibiting significant changes in voltage sensitivity (defined as changes greater than 0.05%) are flagged. Subsequently, counties containing all the buses identified through various stages of the algorithm are marked in blue, creating a comprehensive map highlighting potentially vulnerable facilities within the power network.

This entire analytical cycle is repeated for various loading scenarios, reflected in the planning cases released by ISOs/RTOs because the identified affected facilities can vary depending on the loading conditions. This multi-layered approach prepares the network for immediate impact and identifies potential risk areas within a broader operational context considering N-1 contingencies. Such analysis leverages critical analytical tools like Power Transfer Distribution Factors (PTDFs) and Generator Shift Factors (GSFs) to manage congestion and ensure system reliability alongside power flow sensitivities, which are indispensable for contingency planning and maintaining voltage stability under various operational conditions.

B. Example with the synthetic Texas case

An example case is demonstrated using a synthetic power grid model based on the Texas footprint, developed following the methodology in [19], [20] and available at [21]. The Point of Interconnection (POI) is bus 230080 at 345kV, located in Grimes County, Texas, highlighted in blue in Fig. 1a. Fig. 1a also illustrates a subnetwork of the Texas grid, comprising buses within eight levels of connectivity from the POI, with the corresponding counties highlighted in red. The convex hull of these counties' borders, shown with red dashed lines, is then computed. Counties intersecting this convex hull are identified as the preliminary study area. Fig. 1b depicts the power grid subnetwork within this study area. Next, power flow analysis can be conducted to evaluate steady-state sensitivities and N-1 contingency scenarios, identifying the network components affected by disturbances originating at the POI, further reducing the study area.

Algorithm 1: Study Area Determination

Data: System data; Point of Interconnection, Generator information (Ratings)

Result: Study area information with county mapped to substations

$X \leftarrow$ Get all the buses that are n-levels away from the POI bus;
$C \leftarrow$ Find the counties that these buses belong to;
Create a convex hull around the counties listed in C;
$C \leftarrow$ Add the counties that intersect the convex hull;
Run TARA Flowgate screening and get monitored facilities with DFAX>3% and line loading>80% (steady state, N-1 and N-1-1 contingency scenarios);
$X \leftarrow$ Get all the buses from these monitored facilities;
Calculate the voltage sensitivity of buses with and without the study generator in the system. Get buses with voltage sensitivity>0.05% $\rightarrow$ Get bus numbers.;
$C \leftarrow$ Add the counties with the additional buses;

IV. Results

This section presents three different cases, each with a POI in three different counties: Anderson (Fig. 3), Tom Green (Fig. 4(top)), and McMullen (Fig. 4(bottom)). Using engineering judgment, the selection is made as shown in Fig. 3(top) and Fig. 4(left).

Fig. 2 visualizes the three steps involved in determining a study area for a generator interconnection at a POI in Tom Green County, where the voltage level is 138kV. In step 1, the algorithm identifies all buses connected to the POI within an 8-level network radius (corresponding counties shown in red). For this example, facilities in 22 counties are added to the list. Subsequently, a convex hull is constructed around these initially selected counties. Any additional county intersected more than 50% by this convex hull is also included in the study area to ensure a conservatively large area that might be refined based on detailed power system parameters later. For this example, 18 counties are again added to the list.

The analysis employs TARA to analyse power flow and voltage sensitivities results, adjusting the generator's output to various levels of its maximum capacity. For conventional generators, power flow scenarios simulate the generator operating at full capacity or 100%. Conversely, simulations for battery storage systems include scenarios where the battery is charging at -100% and discharging at +100%. This analysis is essential for identifying two types of critical facilities:

- Transmission lines that exceed 80% of their loading limit under both steady state and N-1 contingency conditions.
- Buses with voltage sensitivities greater than 0.05% due to generator dynamics.

Counties containing these affected facilities are then highlighted in blue in Fig. 2c. From the initial set of 18 counties included based on the convex hull and direct connections, only 9 contain facilities impacted under the specified conditions. These steps determine relevant facilities, i.e., counties, that should be included in the study area for generator interconnection studies at the POI in Tom Green County.

In this manner, another case is shown for a generator interconnection with a POI in McMullen County. For this interconnection, the voltage level is 345kV. In Fig. 4a, the counties selected based on engineering judgment are two counties away from McMullen County, indicated in green. However, based on the tool developed in this paper, the visualization of the underlying power network chosen as a study area is shown in Fig 4b. A logical explanation of a larger footprint is that since this is a 345kV network it spans further than just a few counties away. Cases like these underscore the importance of a tool based method rather than reliance on engineering judgement.

V. Conclusion and Future Work

Integrating new generators into power grids requires impact assessments to ensure stability and reliability. Traditionally, experienced engineers define study areas for these assessments, but their expertise is being lost as the workforce shifts. To address this, we propose a tool to optimize system observability during generator interconnections.

This tool offers several key advantages. It unifies diverse ISO requirements. The tool considers a variety of scenarios, accounts for different loading conditions, and reflects system-specific factors, including GTCs and other unique characteristics, ensuring a comprehensive assessment. The tool eliminates reliance on workforce expertise and reduces the need for back-and-forth communication between generator owners and ISO/RTOs or TSOs over insufficient study requirements. This tool will improve efficiency in handling large queues and improve the precision of planning studies. This avoids over-analyzing the system while ensuring that none of the critical elements that should be considered in a study are missed. The broader objective of the project is to enhance the tool's capabilities by integrating features for conducting dynamic stability studies. These enhancements will allow for a detailed assessment of the impact of generator interconnections on the power grid. Such advancements are for future development efforts.

Acknowledgment

This work was conducted as part of the 'Electric Grid Resilience' Project (60NANB24D210), funded by the National Institute of Standards and Technology (NIST) of the U.S. Department of Commerce. Additional support for this work was provided by Electric Power Engineers as an internship opportunity.

References

[1] Electric Reliability Council of Texas (ERCOT), *Use of Generic Transmission Constraints in ERCOT*, ERCOT, July 2020.

[2] Federal Energy Regulatory Commission (FERC), *Promoting Wholesale Competition Through Open Access Non-discriminatory Transmission Services by Public Utilities; Recovery of Stranded Costs by Public Utilities and Transmitting Utilities*, Federal Energy Regulatory Commission, Washington, DC, April 1996, docket Nos. RM95-8-000 and RM94-7-001, Issued on April 24, 1996.

[3] ——, *Order No. 2000, 89 FERC ¶ 61,285*, Federal Energy Regulatory Commission, Washington, DC, December 1999, docket No. RM99-2-000, Issued on December 20, 1999.

[4] ——, *Standardization of Generator Interconnection Agreements and Procedures*, Federal Energy Regulatory Commission, Washington, DC, July 2003, docket No. RM02-1-000, Issued on July 24, 2003.

[5] ——, *Standardization of Small Generator Interconnection Agreements and Procedures*, Federal Energy Regulatory Commission, Washington, DC, July 2006, docket No. RM02-12-002, Issued on July 20, 2006.

[6] ——, *Reform of Generator Interconnection Procedures and Agreements*, Federal Energy Regulatory Commission, Washington, DC, April 2018, docket No. RM17-8-000, Issued on April 19, 2018.

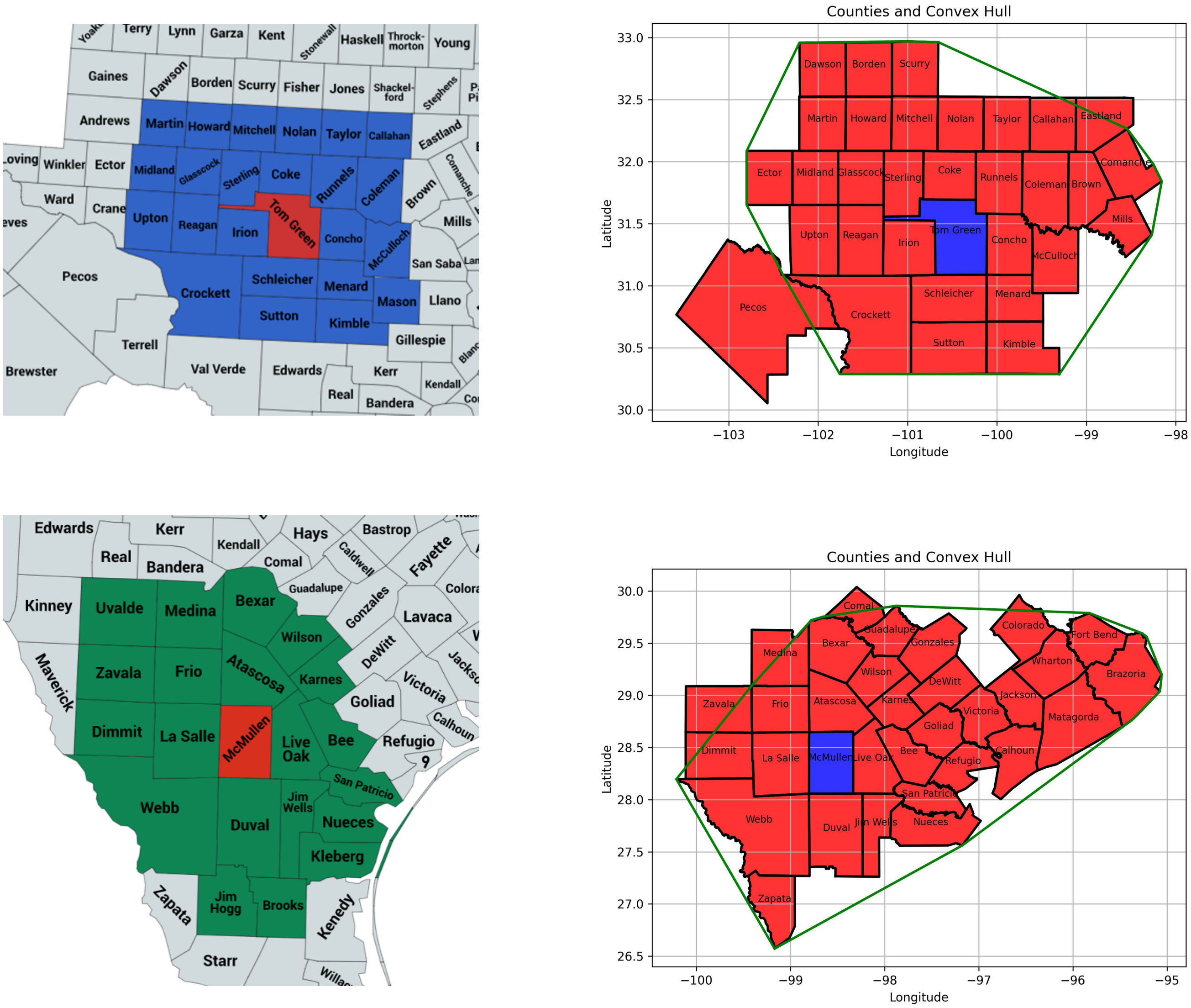
[7] ——, *Improvements to Generator Interconnection Procedures and Agreements*, Federal Energy Regulatory Commission, Washington, DC, July 2023, docket No. RM22-14-000, Issued on July 28, 2023.

[8] PJM Interconnection Projects Department, *PJM Manual 14A: New Services Request Process*, 30th ed., PJM, July 2023, effective Date: July 26, 2023.

[9] OPS-12 Public, *Generation Interconnection Business Practices Manual*, 28th ed., MISO, January 2024, effective Date: Jan 22, 2024.

[10] California Independent System Operator Corporation, *Fifth Replacement Tariff Appendix DD: Generator Interconnection and Deliverability Allocation Procedures (GIDAP)*, 5th ed., CAISO, March 2024.

[11] ISO New England, *ISO New England Planning Procedure PP5-3: Guidelines For Conducting And Evaluating Proposed Plan Application Analyses*, ISO New England, December 2023, effective Date: December 8, 2023.



(a) Engineering Judgment

(b) Algorithm Output

Fig. 4: Study area for generator interconnection POI in county Tom Green (top) and McMullen (bottom) based on engineering judgment (on left) and based on proposed algorithm output (on right).

[12] New York Independent System Operator (NYISO), *Manual 23: Transmission Expansion and Interconnection Manual*, NYISO, January 2023, version 4.2, Effective Date: January 4, 2023. Committee Acceptance: December 14, 2022 (BIC) and December 15, 2022 (OC). Revisions filed on May 1, 2024, with FERC Docket No. ER24-1915.

[13] Electric Reliability Council of Texas (ERCOT), *ERCOT Planning Guide*, October 2024, effective Date: October 1, 2024. [Online]. Available: https://www.ercot.com/mktrules/guides/planning/library

[14] ——, *Resource Interconnection Handbook*, ERCOT, March 2023, effective Date: March 1, 2023.

[15] Generator Interconnection Department, *Generator Interconnection Manual (DISIS Manual)*, Generator Interconnection Department, April 2024.

[16] J. D. Wilson, R. Seide, R. Gramlich, and J. M. Hagerty, "Generator Interconnection Scorecard: Ranking Interconnection Outcomes and Processes of the Seven U.S. Regional Transmission System Operators," February 2024, prepared with funding from the Advanced Energy Institute.

[17] S. Kunkolienkar, "Study Area Selection Tool Github Repository," 2024, accessed: 2025-01-09. [Online]. Available: https://github.com/SanjanaKunkolienkar/InternSanj-StudyAreaAutomation.git

[18] PowerGEM, LLC, *Transmission and Reliability Analysis (TARA)*, PowerGEM, LLC, Power Grid Engineering & Markets, September 2024, released on September 23, 2024.

[19] K. M. Gegner, A. B. Birchfield, T. Xu, K. S. Shetye, and T. J. Overbye, "A methodology for the creation of geographically realistic synthetic power flow models," in *2016 IEEE Power and Energy Conference at Illinois (PECI)*. IEEE, 2016, pp. 1–6.

[20] A. B. Birchfield, T. Xu, K. M. Gegner, K. S. Shetye, and T. J. Overbye, "Grid structural characteristics as validation criteria for synthetic networks," *IEEE Transactions on power systems*, vol. 32, no. 4, pp. 3258–3265, 2016.

[21] S. Kunkolienkar, F. Safdarian, J. Snodgrass, A. Birchfield, and T. Overbye, "A Description of the Texas A&M University Electric Grid Test Case Repository for Power System Studies," in *2024 Texas Power and Energy Conference*. IEEE, Conference Proceedings.