Carbon Impact of Intra-Regional Transmission Congestion

Authored by Sarah Sofia, REsurety, and Yury Dvorkin, Johns Hopkins University with contributions from Devon Lukas, REsurety

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Executive Summary

Carbon accounting frameworks guide decision-making around investments in renewable energy, making them critical in the context of real-world grid operations. Research backing these policy designs currently overlooks a major factor by assuming intra-regional transmission congestion can be ignored, overestimating emissions reductions as a result. In this work, we test this assumption by quantifying the frequency and severity of intra-regional transmission congestion and its impacts on carbon emissions and prominent carbon accounting frameworks using nodal Locational Marginal Emissions (LMEs) data in PJM and ERCOT. Through several case studies, we find that load that is 100% hourly-matched to renewable generation within a grid-region will often still result in significant net operational emissions, and sometimes even increase net emissions relative to annual-matching [Figure 1]. Intra-regional transmission congestion proves to be a vital component of effective carbon accounting and hourly-matching frameworks, revealing the need for significant changes to load and generation siting and transmission development in order to reach the full decarbonization potential of renewable generation.

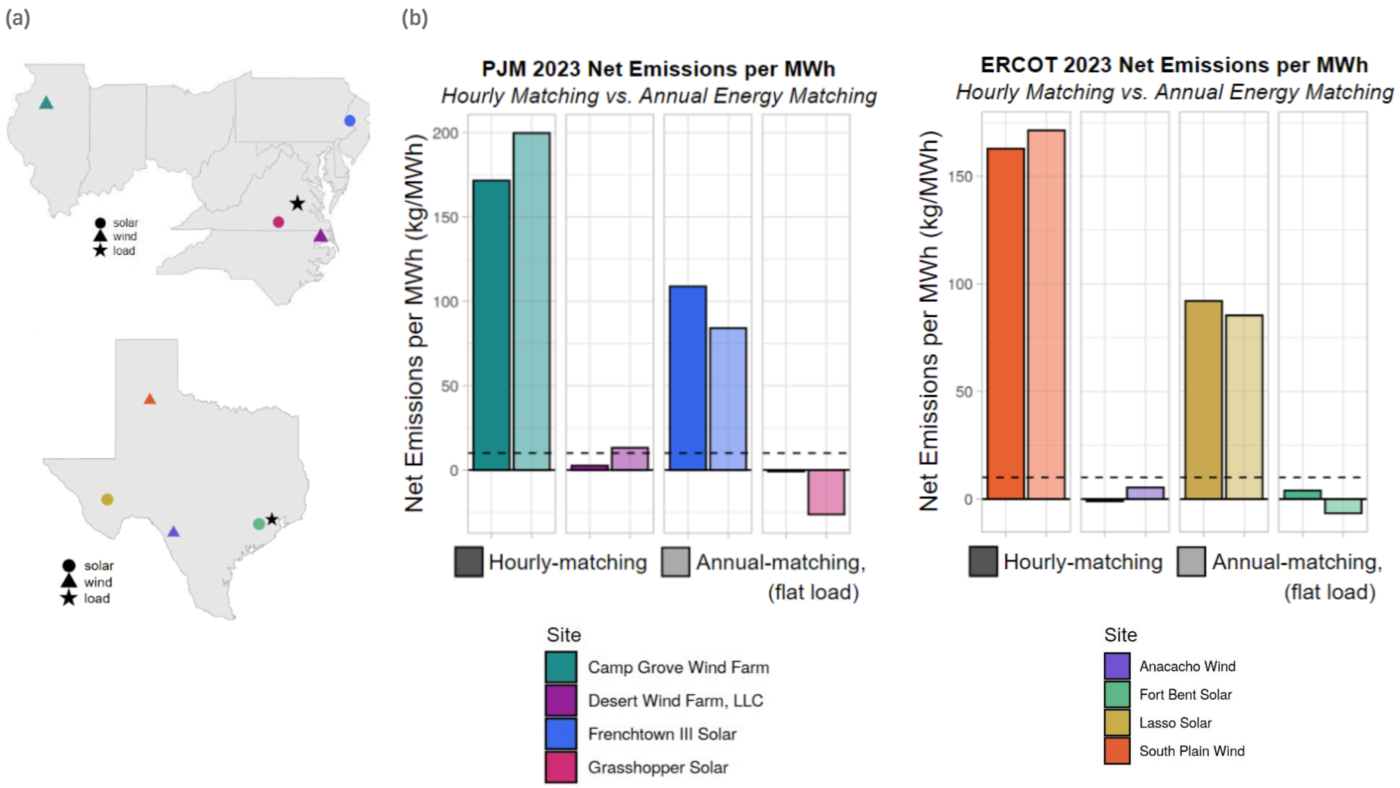

Figure 1: (a) Maps of case study renewable project and load locations; (b) total 2023 net emissions for hourly-matched and energy-matched scenarios.

Background

To address the urgent need for grid decarbonization, wind and solar generation have been deployed at record rates across the U.S. [1,2] However, the rising penetration of wind and solar power has led to transmission congestion and dampened emissions reductions as these resources are often located far from load centers, and generate power at similar times. These bottlenecks prevent clean energy from effectively displacing fossil fuels, making some renewable projects more valuable for emissions reduction than others.

Unfortunately, current incentives for project placement and greenhouse gas (GHG) protocols for carbon accounting often overlook the fact that these congestion impacts are variable over both time and location. Efforts are underway to revise these protocols [3], but recent proposals still assume uniform energy deliverability across large regions (e.g. one region for all of the 'Mid-Atlantic') [4-6]. Of the limited studies around decarbonization approaches, few acknowledge intra-regional transmission and deliverability limitations [7-9], despite the meaningful impact congestion has on system costs and operations in many regions [10,11]. This oversimplification highlights the need for more nuanced accounting methods as policies develop, especially with the recent interest and investment in renewable procurement for green hydrogen production through the Inflation Reduction Act '45V' production tax credit (PTC).

This paper demonstrates the frequency and impact of intra-regional congestion on the deliverability of renewable generation in ERCOT and PJM, quantifies its carbon impact using congestion-aware LME data, and examines how it impacts the effectiveness of emissions policies and frameworks. In this work, we look solely at operational emissions impact, which estimates the change in emissions due to a change in operation ("short-run emissions impact") rather than a change to built capacity, to determine the impacts of congestion specifically [12].

Findings

1. Congestion creates a significant system-wide increase in emissions.

Transmission congestion refers to transmission network restrictions that limit uniform power flow when lines reach their maximum allowed power flow. The grid must then compensate by dispatching additional, higher cost generators that can deliver power to the necessary locations along unconstrained lines. Both ERCOT and PJM have seen rising system costs associated with congestion, as shown in Figure 2(a), where congestion costs accounted for 8.3% and 2.2% of total system energy costs in 2023, respectively. The financial cost of congestion is reflected in the Locational Marginal Price (LMP), which comprises three components: energy, system loss, (for PJM only [13]), and congestion. When there is no congestion, the least-cost set of generators are able to be dispatched and LMPs are relatively uniform across the grid aside from losses.

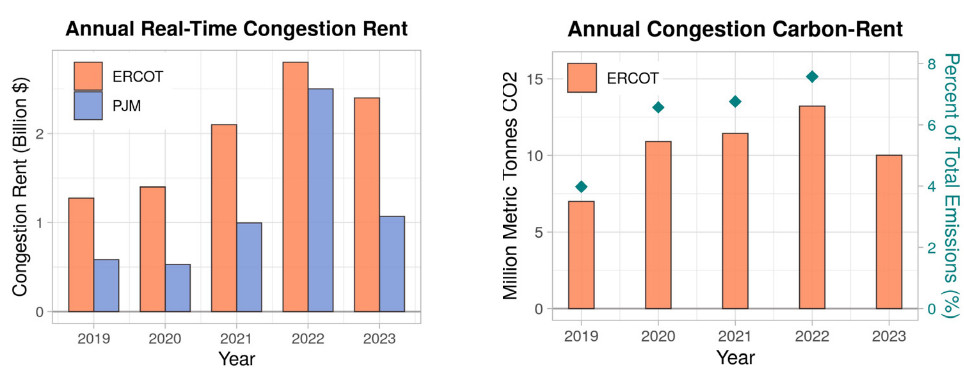

Figure 2: Annual system-wide (a) congestion rent, as reported by the Market Monitor reports [10,11,14–16], and (b) calculated ISO-wide congestion carbon-rent.

For both ERCOT and PJM, we quantify the overall impact that transmission congestion has had system-wide as 'congestion-rent' in Figure 2a. Analogous to this economic metric, the 'congestion carbon-rent' was calculated for ERCOT in Figure 2b, representing the total increase in emissions due to transmission congestion by summing the shadow carbon intensity of each constraint times the flow over the constraint (which are not publicly available for PJM). Transmission congestion creates a significant system-wide increase in emissions, nearly doubling from 2019 to 2022, suggesting that if congestion were alleviated, ERCOT emissions could drop on the order of 10 million tonnes CO_2e. This metric illustrates the scale and trend of the environmental challenge introduced by congestion and the potential opportunity for carbon reduction.

2. There is significant sub-regional variation in emissions impact.

Figure 3 shows contour maps of the significant variation in average county LME for 2023 across both ERCOT and PJM, with planned wind and solar capacity overlayed. LMEs are mapped onto counties using generator price node, county, and hub-level aggregate data. Areas with higher LME values mean that clean generation sited in those locations will reduce CO_2e emissions at an accelerated rate, while load sited in those locations will increase CO_2e emissions at an accelerated rate.

Congestion-driven spatial LME variation is obvious in PJM, where we see that there is nearly a 2x spread in LME across the region. The induced emissions of a newly built load could be reduced by hundreds of $kgCO_2e$/MWh by siting it in Eastern Pennsylvania instead of Virginia, for example, and a Virginian wind farm would have avoided 50% more carbon than an equivalent farm in Northern Illinois. Despite the low average LMEs (and LMPs) in regions like Northern Illinois and Western Texas, a large portion of planned wind and solar capacity of renewables are still planned in these sub-regions (depicted by the gray circles in Figure 3) and will further exacerbate congestion challenges if there are no significant changes to load siting patterns or transmission upgrades. As a result, it is critical that carbon accounting and related policies send a clear signal that prioritizes the development of projects in uncongested portions of the grid in order to meaningfully expedite grid decarbonization.

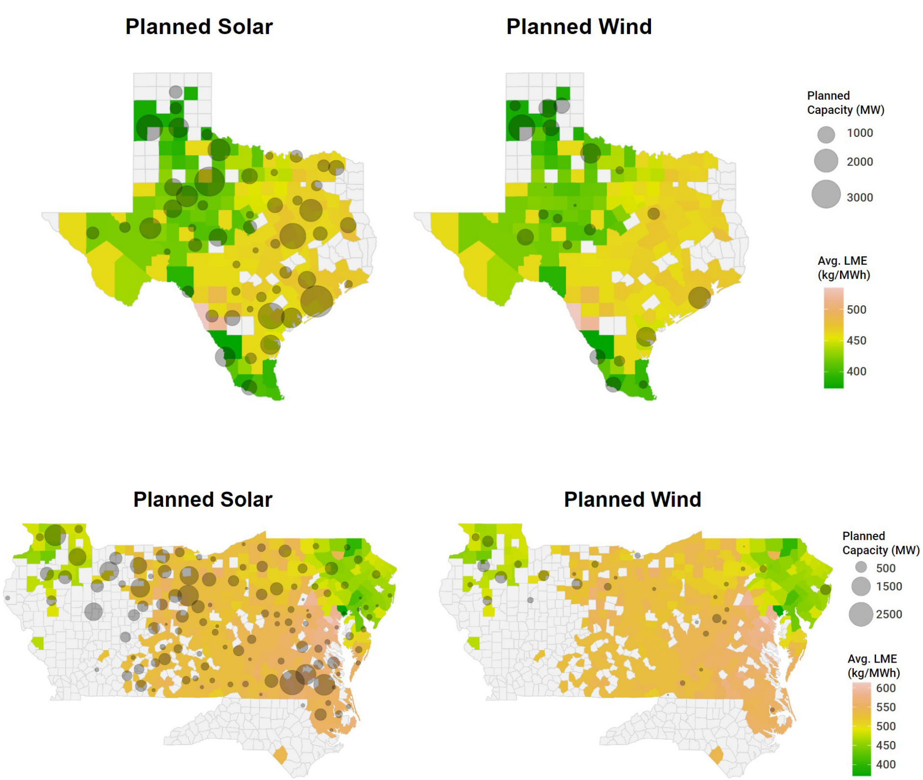

Figure 3: Contour map of 2023 average LME by county across (a) ERCOT and (b) PJM, with the capacity of solar (left) and wind (right) in the current interconnection queue for each county overlaid.

3. Congestion-driven intra-regional differences in marginal emissions are large and frequent.

To understand congestion's impact on policy, it's important to assess how often transmission constraints occur between renewable generation and load. Most existing and proposed carbon accounting methods assume that emissions induced by a load can be offset by an equal amount of clean generation within the same grid-region, but this is only the case when congestion does not impede the delivery of generation to the load. While various definitions of "deliverability" exist, we focus on the difference in LME, as it directly informs net emissions.

Figure 4 displays the total generation at each LME basis value for various load and generator locations across different hubs in ERCOT (a) and PJM (b) in 2023, where the 'LME basis' represents the difference in LME at the load and the generator during the same hour. This essentially represents net emissions each hour when load is matched with an equal quantity of clean generation. A positive value of LME basis indicates that emissions induced by the load are greater than the emissions avoided by the clean generation, leading to a net increase in emissions. We consider values of LME basis that are higher than 10 kg CO_2e/MWh to indicate "undeliverable" clean generation to load. This threshold was chosen as it reflects the LME basis that is roughly equivalent to the emissions cutoff defined by the proposed '45V' clean hydrogen production PTC of 0.45 kg CO_2e/kgH_2 [5].

In ERCOT, very high levels of LME basis are frequent, with the peak at around 500 kg CO_2e/MWh LME basis reflecting times when a gas plant is on the margin serving the load, but renewables are on the margin, and likely being curtailed, at the location of the renewable generation. Houston has the greatest deliverability challenges, with 49.6% of wind and solar generation across ERCOT being undeliverable to load in Houston, and more than half of the wind and solar generation produced in both South and West Texas being undeliverable to Houston load.

PJM has a less pronounced tail at extreme net emissions values, but we see a consistent trend of undeliverable renewable generation to loads across the grid-region. Over half of all clean generation produced cannot supply load behind transmission bottlenecks in any of the zones outside of Northern Illinois. Data center heavy Dominion hub has the greatest deliverability limitations, with almost 70% of wind and solar generation across PJM undeliverable to Dominion load.

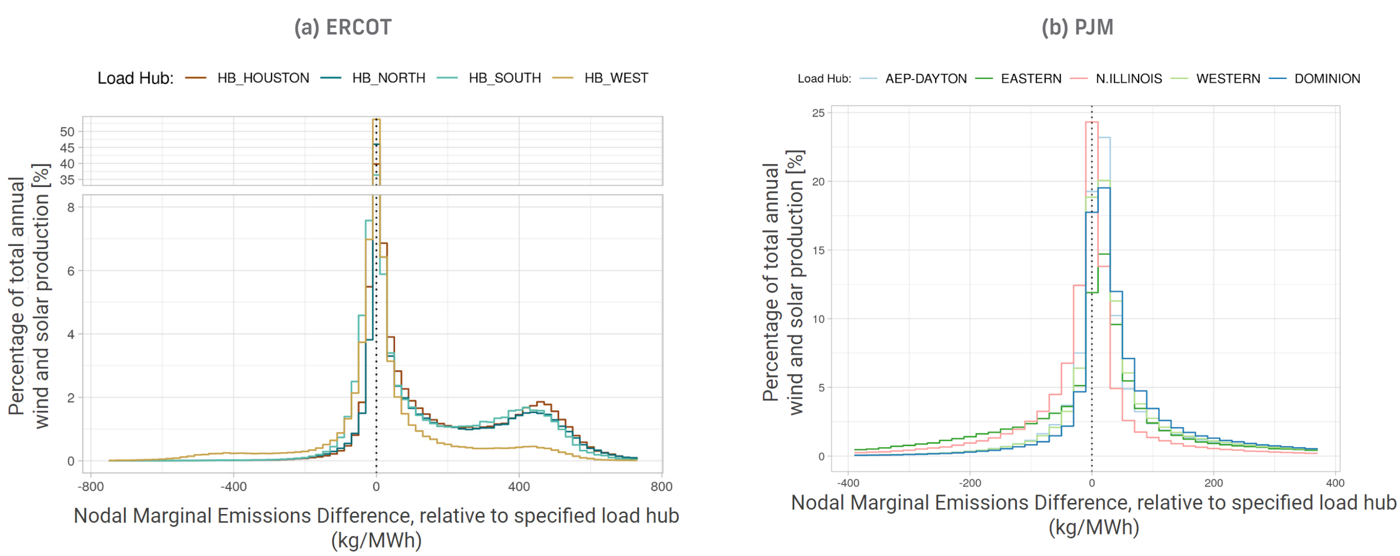

Figure 4: Percentage of total annual wind and solar generation in 2023 that is produced at a particular LME differential, or 'basis', between the point of generation and load, calculated as the LME difference ($LME_{load} - LME_{gen}$). The load hub-level LME is indicated by the line color.

The choice for where to site load and clean generation within a given grid-region can have a sizable effect on emissions on the order of 10s to 100s of kg CO_2e/MWh. With congestion-driven differences within the same grid-region occurring so often, a blanket assumption of deliverability within a single grid-region is not empirically defensible and will frequently result in significantly higher emissions in reality.

4. **Ignoring the impact of intra-regional transmission congestion severely reduces the efficacy of carbon accounting policy approaches.**

The previous section demonstrated that there are significant intra-regional deliverability challenges in both ERCOT and PJM due to transmission congestion. As a result, there are significant emissions implications for carbon accounting approaches like annual- and hourly-matching that do not take intra-regional congestion into account.

Most proposed implementations of hourly-matching carbon accounting frameworks assume grid-regions as a proxy for deliverability. As a result, the induced emissions from load are considered to be perfectly offset by the avoided emissions of carbon free energy so long as the quantity of load matches the quantity of clean generation in the same hour within the same grid-region. However, as shown in the previous section, the emissions impact of clean generation and load can vary significantly within a grid-region due to transmission congestion. As a result, an hourly-matching framework can, and often does, significantly increase real-world net emissions despite the effort made to comply with the hourly-matching constraint [Figure 1].

The impact of transmission congestion on deliverability is particularly relevant to the green hydrogen industry today given the pending guidance on compliance for 45V Production Tax Credits [5]. The currently proposed policy requires that load from hydrogen electrolyzers be met by renewable generation that is hourly-matched to load within the same grid-region [4,5]. As our results have demonstrated, clean generation is often not deliverable within a grid-region and hourly-matching will not necessarily result in low or zero net emissions. In fact, case studies analyzed in REsurety's research paper, *Carbon Impact of Intra-Regional Transmission Congestion*, found that introducing hourly-matching in some cases increased emissions relative to annual energy-matching [Figure 1]. Hourly-matching is not always the most suitable option for zero net emissions, as it's heavily impacted by congestion [17].

Summary

This paper demonstrates that in both ERCOT and PJM, there is significant and frequent intra-regional congestion occurring over the past five years, causing particularly large and variable impacts on renewable generation and marginal emissions rates across the same grid-region. Our analysis suggests that assuming equal emissions and perfect deliverability within a grid-region misses a major factor in determining the net carbon emissions of load and renewable generation. As a result, an hourly-matched load can still result in significant net induced emissions.

As potential new hydrogen production qualifies for the proposed hydrogen PTC, failure to recognize these impacts could lead to meaningful increases in net emissions despite abiding by the proposed hourly-matching requirements. Carbon accounting frameworks that require a tight definition of temporal matching (e.g., hourly) but allow for a loose definition of deliverability (e.g., grid-regions) will result in increased costs of operations without necessarily improving real-world emissions outcomes.

Looking to the future, the growth of renewables is expected to continue outpacing investment in transmission. Without accounting for intra-regional congestion, carbon accounting methods like hourly-matching or annual energy-matching significantly underestimate the net induced carbon emissions on the grid. It is essential to weigh the impact of transmission congestion on deliverability to accurately measure emissions and guide investment, development, and procurement decisions.

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