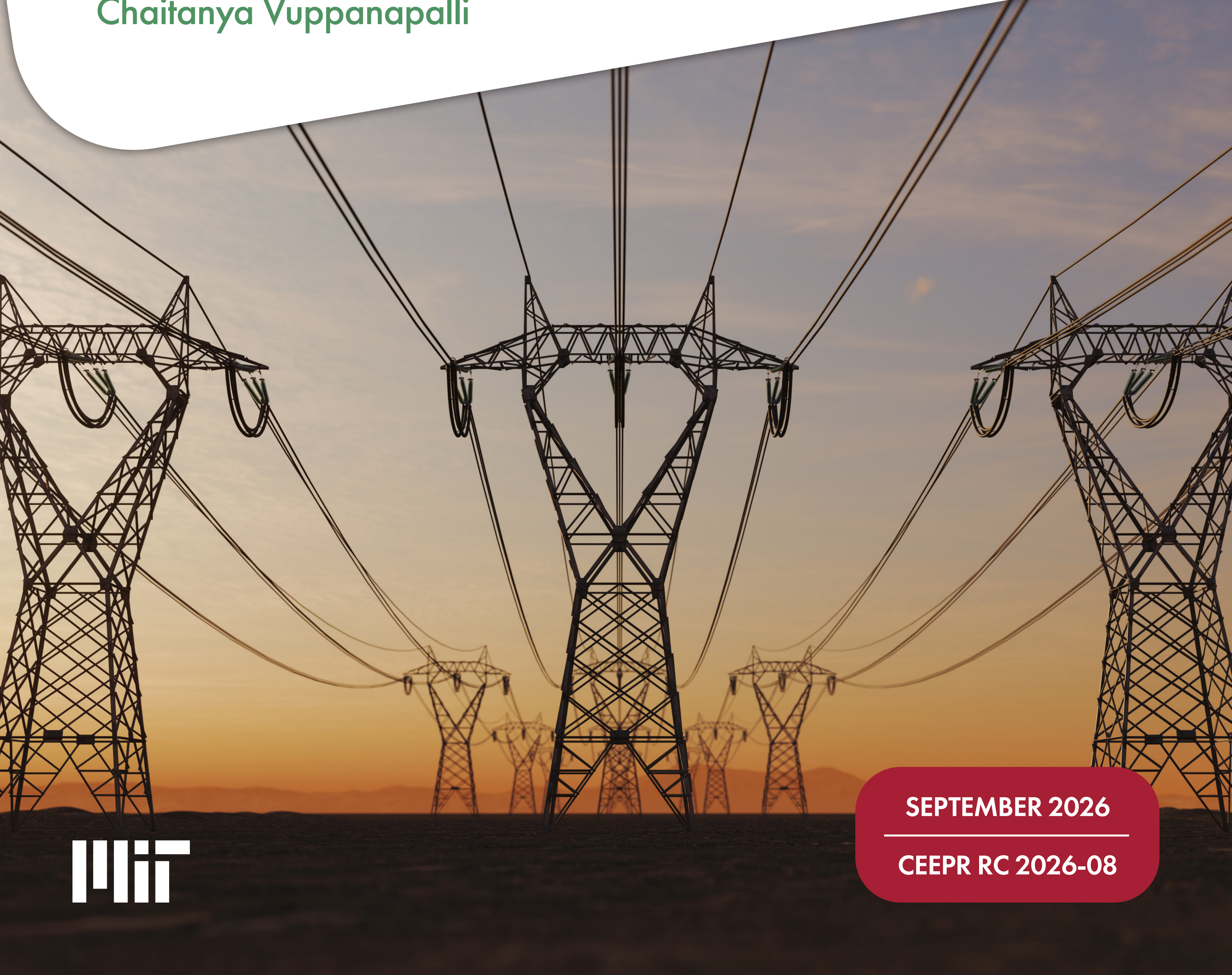
MIT CEEPR
Center for Energy and Environmental Policy Research

Research Commentary

The System Value of Grid-Enhancing Technologies under Alternative Transmission Deployment Strategies

Christopher R. Knittel, Juan Ramon L. Senga, and Chaitanya Vuppanapalli



SEPTEMBER 2026

CEEPR RC 2026-08

Research Commentary Series.

Since 1977, the Center for Energy and Environmental Policy Research (CEEPR) has been a focal point for research on energy and environmental policy at MIT. CEEPR promotes rigorous, objective research for improved decision making in government and the private sector, and secures the relevance of its work through close cooperation with industry partners from around the globe. Drawing on the unparalleled resources available at MIT, affiliated faculty and research staff as well as international research associates contribute to the empirical study of a wide range of policy issues related to energy supply, energy demand, and the environment.

The System Value of Grid-Enhancing Technologies under Alternative Transmission Deployment Strategies

Christopher R. Knittel, Juan Ramon L. Senga, Chaitanya Vuppanapalli *

September 16, 2026

1 Introduction

The United States' electric grid faces pressure from the growing electricity demands of an increasingly electrified economy and the influx of large loads such as data centers. Meeting these challenges requires not only new generation but also a transmission system capable of moving power efficiently across regions [1, 2]. Yet transmission infrastructure investment remains costly, slow, and politically challenging [3, 4]. The projected timeline of major projects often takes a decade or more from planning to operation. These constraints create a need for solutions that can increase the utilization of existing transmission infrastructure while new transmission projects are being planned and developed. In the interim, Grid Enhancing Technologies (GETs) offer a near-term, cost-effective alternative [5].

GETs are a suite of hardware and software tools that increase the capacity and efficiency of existing transmission infrastructure. These encompass a range of technologies including dynamic line ratings (DLR), which adjust the allowable power-transfer capacity of transmission lines in real time based on weather conditions; advanced power flow control (APFC) devices, which redirect electricity flows away from congested lines; and topology optimization software, which reconfigures the network to reduce bottlenecks[1]. Unlike conventional transmission expansion, GETs can be deployed on existing infrastructure at a fraction of the cost and in a fraction of the time, increasing grid capacity without the permitting delays and capital expenditure associated with new transmission lines. Despite their technical promise, GETs remain underdeployed across the U.S. grid. Regulatory frameworks designed for traditional capital investment have been slow to accommodate technologies that deliver value through software and operational improvements rather than physical assets. As electricity demand continues to

*As is standard in Economics, authors are currently listed in alphabetical order. *Knittel:* Sloan School of Management, Massachusetts Institute of Technology, Cambridge, MA, USA. Center for Energy and Environmental Policy Research, Massachusetts Institute of Technology, Cambridge, MA, USA. MIT Climate Policy Center, Massachusetts Institute of Technology, Cambridge, MA, USA. National Bureau of Economic Research, Cambridge, MA, USA. knittel@mit.edu. *Senga:* Center for Energy and Environmental Policy Research, Massachusetts Institute of Technology, Cambridge, MA, USA. MIT Climate Policy Center, Massachusetts Institute of Technology, Cambridge, MA, USA. jsenga@mit.edu. *Vuppanapalli:* Center for Energy and Environmental Policy Research, Massachusetts Institute of Technology, Cambridge, MA, USA. Correspondence: chaitu@mit.edu.

[1] Among many other technologies. See Appendix A for more information on the technologies.

grow, understanding how these technologies can be deployed strategically becomes increasingly important.

The value of GETs, however, depends not only on the amount of additional transmission capacity they provide but also on where that capacity is made available. The U.S. transmission network contains numerous corridors with different levels of congestion, power flows, and interactions with generation and demand. Increasing the capacity of one corridor may therefore produce substantially different system-wide benefits from increasing the capacity of another. Moreover, the lines that appear most important can depend on how transmission needs are measured. A deployment strategy based on the economic value of relieving constraints may identify different corridors than one based on the frequency with which those corridors become congested.

This raises a central question for grid planning: how does the strategy used to target GETs affect their system-wide benefits? Rather than focusing on a single deployment criterion, this study examines multiple approaches for identifying transmission corridors and evaluates how the resulting deployment patterns translate into changes in system cost, generation, and emissions. This perspective is particularly relevant for policymakers and system planners because GETs deployment is not simply a question of how much additional transmission capacity can be obtained, but also of where that capacity should be provided.

This research commentary quantifies the system-wide and economy-wide implications of alternative GETs deployment strategies in a 2035 representation of the U.S. electricity system. Using the capacity expansion model GenX [6], the analysis evaluates GETs deployment across four transmission-targeting approaches, with deployment varied from 0 to 100% of eligible transmission lines and the capacity of selected lines increased by 5%, 10%, 20%, or 30%. The analysis compares which transmission corridors are selected under each approach and examines the resulting impacts on system costs, generation, and CO2 emissions.

This study evaluates four approaches for selecting transmission lines for GETs deployment. The first is the economic-based approach, which selects lines according to the economic value of additional transmission capacity obtained from the optimization model. The second is a congestion-frequency-based approach, which prioritizes lines that are persistently close to their transmission limits. The third is a weighted-random approach, in which congestion determines the probability that a line is selected, allowing highly congested lines to receive greater consideration while retaining diversity in the selected transmission corridors. The fourth is a uniform-random approach, which assigns equal selection probability across all transmission lines and serves as a control case for assessing the importance of targeted deployment.

The results show that the mechanism used to select transmission lines materially changes the geographic pattern of GETs deployment. Economic-based deployment initially concentrates deployment in Central, whereas congestion-frequency-based deployment initially deploys the Northeast and New York and subsequently follows different transmission corridors. The stochastic approaches produce broader and more variable transmission deployment patterns, with weighted-random selection maintaining a relationship between congestion and deployment while uniform-random selection removes this targeting mechanism.

Despite these differences in transmission deployment, the resulting system-level effects are less sensitive. GETs deployment reduces annual system costs by up to approximately $1.34 billion, with the magnitude depending on deployment level and the increase in transmission capacity. Although the economic-based and congestion-frequency-based approaches identify different transmission corridors for GETs deployment, they produce broadly similar system-level cost savings across adoption levels, suggesting that the overall value of GETs is relatively robust to the specific locations selected for deployment. For the stochastic approaches, weighted-random selection produces lower system costs than uniform-random selection at adoption levels up to approximately 40%, although differences in system cost at a given adoption level are relatively small.

The generation response is more sensitive to where GETs is deployed. GETs deployment increases wind generation and generally reduces natural gas generation, while coal generation can increase relative to the no-GETs case. The resulting emissions response therefore depends on the resources enabled by additional transmission capacity. The comparison of weighted- and uniform-random deployment further shows that congestion-informed selection produces a more consistently declining emissions trajectory as deployment increases.

These findings demonstrate that the system value of GETs depends on both how much additional transmission capability is created and where that capability is deployed. Economic-based selection provides a direct system-cost signal, whereas congestion-based and stochastic approaches provide alternative mechanisms for identifying transmission needs. Comparing these strategies provides a basis for assessing the robustness of GETs valuation and for understanding the extent to which transmission targeting should be incorporated into policies for GETs deployment.

2 Modeling Framework

2.1 Capacity Expansion Modeling

We use the capacity expansion model, GenX, to model a 2035 U.S. grid [6]. GenX is a large linear programming model that simulates a least-cost future grid given a representative year of demand and renewable availability. It assumes cost and technology availability projections and accounts for investments and retirements of new and existing generators. It has been used in a variety of studies that examine transmission and policy deployment. In our case, we use GenX to simulate GETs deployment by a central planner who minimizes total annual cost for the U.S. grid. We use the same zones, regions, and transmission topology as [7] and [8]. The zones and regional maps can be found in the Supplementary Material. Full details of the modeling will be included in the main paper following this research commentary.

GETs are represented as an increase in the effective capacity of existing transmission lines. The analysis therefore abstracts from the physical technology used to achieve the additional capacity and instead evaluates the system value of increasing the usable capacity of selected existing transmission connections. Two dimensions characterize GETs deployment. The first is the Deployment Level, defined as the fraction of eligible transmission lines receiving GETs. Deployment is evaluated from 0 to 100% in 5-percentage-point increments. The second is the Increase in Capacity, defined as the percentage increase in capacity applied to each selected line. Capacity increases of 5%, 10%, 20%, and 30% are evaluated. Transmission lines receiving GETs are selected using four alternative deployment strategies, allowing the effects of different approaches to transmission targeting to be evaluated within a common modeling framework. The strategies differ only in the mechanism used to identify the lines to be reinforced; the underlying GenX optimization problem and the capacity increase applied to selected lines remain unchanged.

2.2 Transmission Reinforcement Strategies

2.2.1 Economic-based selection

Following the solution of the GenX optimization, the marginal economic value of increasing the capacity of each eligible transmission line is obtained from the dual value associated with its transmission capacity constraint. Let D_l denote the dual value associated with transmission line l. The line with the most negative dual is selected for reinforcement:

$$l^* = \arg\min_{l \in L} D_l$$

The capacity of the selected line is then increased according to

$$R_{l^*}^{\text{new}} = R_{l^*}^{\text{old}} + \min\left(\Delta R_{\max}, \Delta_l\right)$$

where R_l represents GETs-enabled transmission capacity and ΔR_l represents the allowable reinforcement for line l. The model is subsequently re-optimized, and the process is repeated until the specified deployment level is reached. This approach prioritizes transmission investments according to their marginal contribution to system-wide economic value.

2.2.2 Congestion-frequency-based selection

An alternative approach prioritizes transmission lines according to the persistence of congestion rather than their marginal economic value. For each line l, a congestion score is calculated as the number of modeled hours during which the line operates at or above a specified fraction of its capacity:

$$CS_l = \sum_t \mathbf{1}\left(\frac{F_{l,t}}{C_l} \geq \alpha\right)$$

where $F_{l,t}$ is the power flow on line l during hour t, C_l is the transmission capacity of line l, and $\alpha = 0.9$ is the congestion threshold used in the analysis. The transmission line with the highest congestion score is selected:

$$l^* = \arg\max_{l \in L} CS_l$$

Unlike the economic-based approach, this strategy explicitly measures persistent physical congestion rather than marginal economic value.

2.2.3 Weighted-random selection

The weighted-random strategy introduces stochasticity while retaining information about congestion. Each eligible transmission line receives a weight based on its congestion score:

$$w_l = CS_l + \epsilon$$

where ϵ is a small positive value that ensures that lines with low congestion retain a nonzero probability of selection. The probability of selecting line l is given by

$$P_l = \frac{CS_l + \epsilon}{\sum\limits_{j \in L} (CS_j + \epsilon)}$$

Thus, highly congested lines are more likely to receive GETs, but the selection mechanism does not deterministically select the most congested line. The weighted-random strategy therefore provides a compromise between targeted congestion relief and line-selection diversity.

2.2.4 Uniform-random selection

The uniform-random approach serves as a control case in which transmission selection is not informed by either economic value or congestion. Each eligible line is assigned equal probability:

$$P_l = \frac{1}{|L|}$$

The selected line is reinforced and the process is repeated until the desired deployment level is reached. This approach does not represent a proposed planning rule. Rather, it provides a benchmark for determining whether system-level GETs benefits depend primarily on the quantity of additional transmission capacity or on the specific corridors receiving that capacity.

2.3 Analysis dimensions

For each reinforcement strategy, GETs deployment is evaluated across deployment levels from 0 to 100% and capacity increases of 5%, 10%, 20%, and 30%. For the stochastic strategies, multiple realizations are generated for each deployment level to characterize variability in transmission selection and system outcomes. The analysis evaluates four categories of outcomes:

1. **Transmission deployment:** Number, location, and magnitude of reinforced lines;
2. **Economic outcomes:** Total annual system cost and cost-component changes;
3. **Generation and environmental outcomes:** Changes in generation by technology and annual CO2 emissions;
4. **Robustness:** Variation across stochastic realizations and differences between congestion-informed and uninformed random selection.

3 Where are GETs deployed?

3.1 Economic-based versus congestion-frequency-based deployment

The spatial distribution of GET deployment differs between the economic-based and congestion-frequency-based strategies, particularly at low adoption rates (Figure 1). At a 5% adoption rate, the two approaches prioritize largely different transmission corridors. The economic-based strategy concentrates deployment on a limited set of economically valuable corridors, primarily across the central and eastern United States, whereas the congestion-frequency-based strategy emphasizes a different set of corridors, including connections in the Northeast and New York. This divergence indicates that corridors with high economic value in the system-level optimization are not necessarily those experiencing the most frequent congestion.

The number of transmission lines receiving GETs also differs between the two strategies for a given system-wide capacity increase (Figure 2 in the Supporting Information). The congestion-frequency-based strategy consistently requires fewer lines to achieve the same overall increase in transmission capacity than the economic-based strategy. This indicates that the congestion-frequency criterion tends to prioritize lines with higher existing transmission capacity, allowing a larger amount of capacity to be enhanced through modifications to a smaller number of corridors. From a deployment perspective, this distinction may be important because reinforcing fewer transmission lines could reduce the number of individual projects requiring permitting and other regulatory approvals, potentially facilitating faster deployment of GETs. Thus, although the two strategies may provide comparable system-level value, they can differ in the number of transmission projects that must be modified to realize that value

As the adoption rate increases, the spatial patterns produced by the two approaches progressively converge. At 30% adoption, deployment under both approaches expands across a substantially larger portion of the transmission network, with several corridors selected by both strategies. At 60% and 80% adoption, most of the deployed corridors are common to the two approaches, as indicated by the increasing prevalence of red lines in Figure 1. The remaining approach-specific selections are concentrated in a smaller number of corridors, particularly at the edges of the network.

These results suggest that the distinction between economic value and congestion frequency is most consequential when GET deployment is limited. At low adoption rates, the two metrics identify different priorities because only a small fraction of the network can receive GETs, making the choice of prioritization criterion important. As deployment expands, the two strategies increasingly identify the same transmission corridors, suggesting that many of the corridors that provide economic value to the system are also associated with recurring congestion. Thus, the value of the deployment criterion depends on the scale of GET deployment: the choice between economic-based and congestion-frequency-based prioritization has a greater influence on deployment location when GET availability is constrained, whereas the spatial patterns become increasingly similar at higher adoption rates.

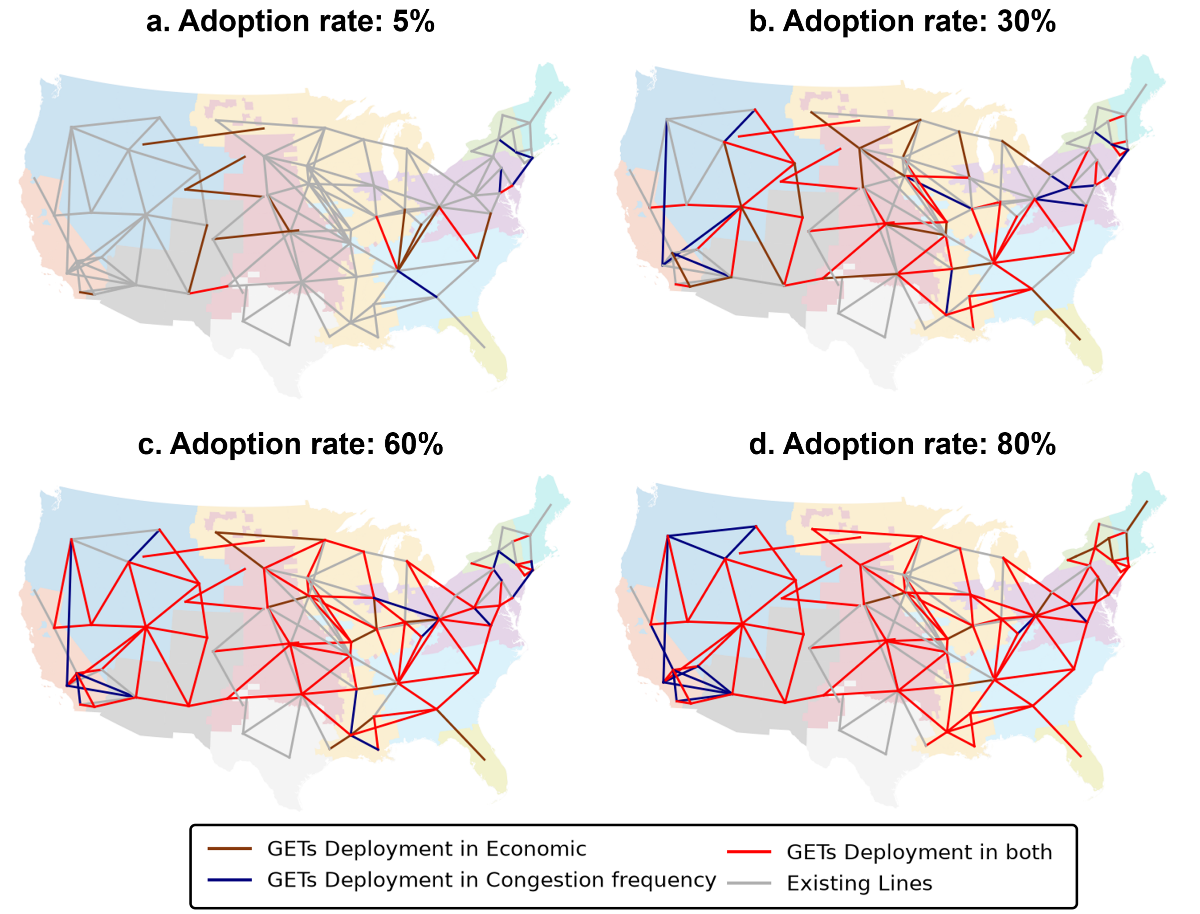


Figure 1: **Spatial distribution of GET deployment under economic- and congestion-frequency-based strategies.** Transmission corridors selected for GET deployment at adoption rates of (a) 5%, (b) 30%, (c) 60%, and (d) 80%, assuming a 10% increase in transmission capacity. Brown lines indicate corridors selected only by the economic-based strategy, blue lines indicate corridors selected only by the congestion-frequency-based strategy, red lines indicate corridors selected by both strategies, and grey lines indicate existing transmission lines. The increasing prevalence of red corridors with adoption rate indicates increasing convergence between the two deployment strategies as GET deployment expands.

3.2 Stochastic deployment patterns

The stochastic approaches provide a complementary perspective on the spatial allocation of GETs. Figure 2 compares weighted-random and uniform-random selection across multiple realizations at a 10% adoption level. Both approaches produce geographically distributed GET deployments across the U.S., but the specific transmission corridors selected vary substantially across realizations. This variation is a direct consequence of the different selection mechanisms: weighted-random selection assigns a higher probability of selection to more congested lines, whereas uniform-random selection assigns equal probability to all eligible lines.

The realized selections illustrate the diversity of transmission corridors that can result from stochastic deployment. Under weighted-random selection, no individual corridor is selected in more than three of the ten realizations. The corridors selected most frequently are generally those with higher congestion scores, consistent with the congestion-based weighting. Under uniform-random selection, only one corridor is selected in five of the ten realizations, and one additional corridor is selected in four realizations, with the remaining selections distributed across a broad set of corridors. Thus, neither stochastic approach consistently identifies the same transmission corridors across realizations, although weighted-random selection retains a systematic preference for more congested lines.

The number of transmission lines receiving GETs increases approximately with the specified adoption level for both approaches, as shown in Figure 2c. The average number of selected lines is broadly similar between weighted-random and uniform-random selection, indicating that the stochastic mechanisms primarily affect which lines are selected rather than the overall extent of deployment. However, the variation in the number of selected lines increases with the capacity reinforcement applied to individual lines. Once a selected line receives the specified capacity increase, it is no longer eligible for additional reinforcement, and the selection process proceeds to the next line in the ranking. Consequently, the capacity of the selected corridors influences how many lines are required to achieve a given deployment level.

Taken together, these results distinguish the robustness of the aggregate GETs deployment level from the diversity of the specific transmission corridors selected. Although weighted-random and uniform-random approaches deploy GETs across similar numbers of lines on average, they can produce substantially different spatial deployment patterns across realizations. This distinction is important when assessing GETs because similar aggregate deployment levels do not necessarily imply identical transmission-system effects when the reinforced corridors differ.

4 System Cost Impacts

4.1 Economic-based and congestion-frequency-based approaches

GETs deployment reduces annual system costs across both the economic-based and congestion-frequency-based strategies, with larger savings obtained as either the adoption level or capacity increase rises (Figure 3). At a 30% capacity increase, for example, full deployment reduces annual system cost from \$169.13 billion to \$167.79 billion, a reduction of approximately \$1.34 billion per year. At 50% adoption, the corresponding reduction is approximately \$1.06 billion for the economic-based strategy and \$1.06 billion for the congestion-frequency-based strategy.

Despite selecting different transmission corridors, the two strategies produce closely aligned system-cost trajectories. At 50% adoption and a 10% capacity increase, the annual system costs differ by only approximately \$10 million, while at 100% adoption the results are identical because all eligible transmission lines receive GETs. The close agreement across the two strategies indicates that the aggregate value of GETs is relatively robust to the criterion used to identify deployment locations, even though the spatial patterns of deployment differ substantially (Figure 1).

The source of these savings is primarily reduced fuel expenditure (Figure 4). Additional transmission capacity enables greater utilization of lower-cost wind generation and reduces reliance on natural gas generation. These fuel savings are partially offset by changes in generation investment and operating costs associated with the resulting generation mix. Thus, the value of

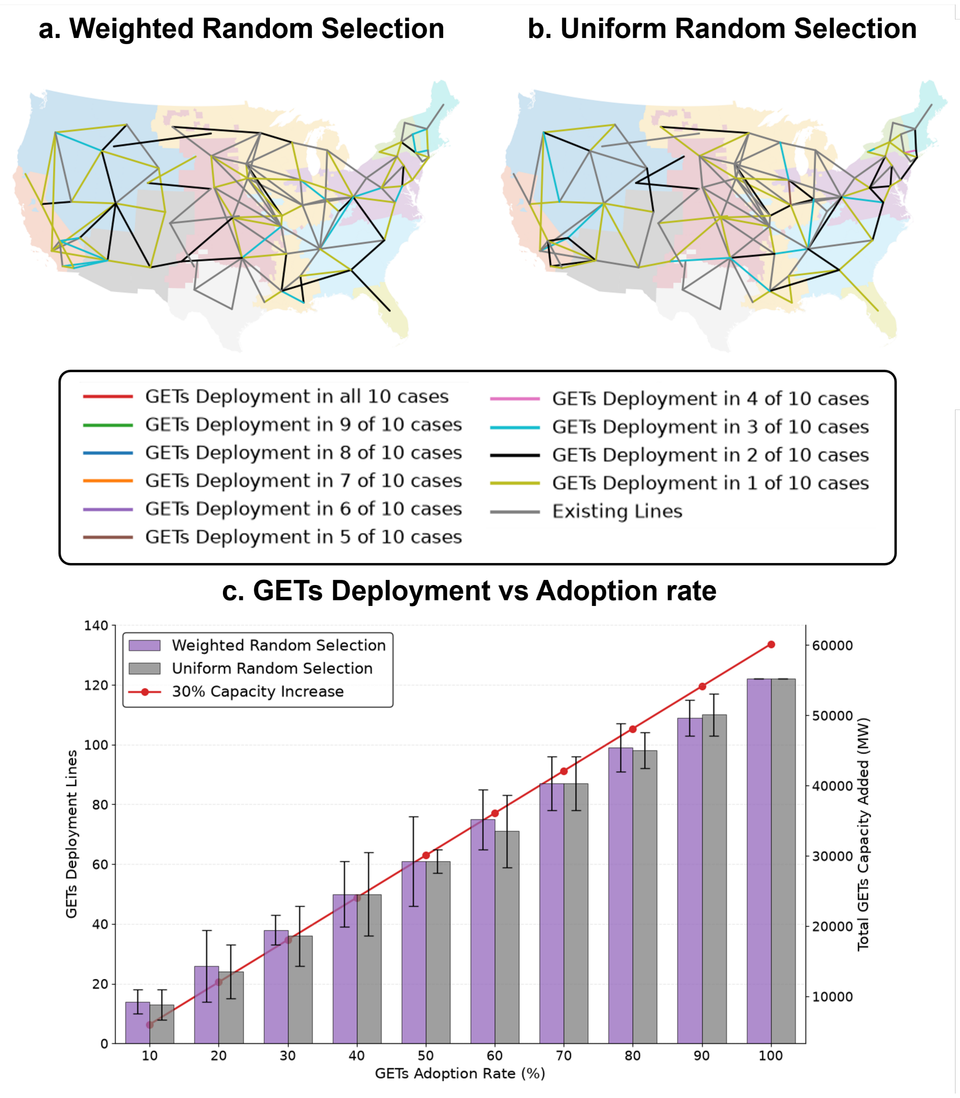


Figure 2: **Stochastic GETs deployment under weighted-random and uniform-random selection.** Transmission deployment patterns at 10% GETs adoption across multiple stochastic realizations for (a) weighted-random and (b) uniform-random selection. Each realization represents a different set of transmission corridors selected for GET deployment. Weighted-random selection assigns higher selection probabilities to more congested corridors, whereas uniform-random selection assigns equal probabilities to eligible corridors. (c) Number of transmission lines receiving GETs as a function of adoption rate; points and error bars represent the mean and variation across stochastic realizations. The similar average number of selected lines but substantial variation in individual corridor selections illustrates the diversity of spatial deployment generated by the two stochastic approaches.

GETs extends beyond improving utilization of the existing transmission network: by relaxing transmission constraints, GETs can also change the economically preferred generation portfolio and facilitate greater utilization of low-cost renewable resources.

4.2 Weighted-random versus uniform-random system cost

The two stochastic strategies produce closely similar system costs across the full range of GETs adoption, despite differences in the transmission corridors selected. Figure 5 shows that

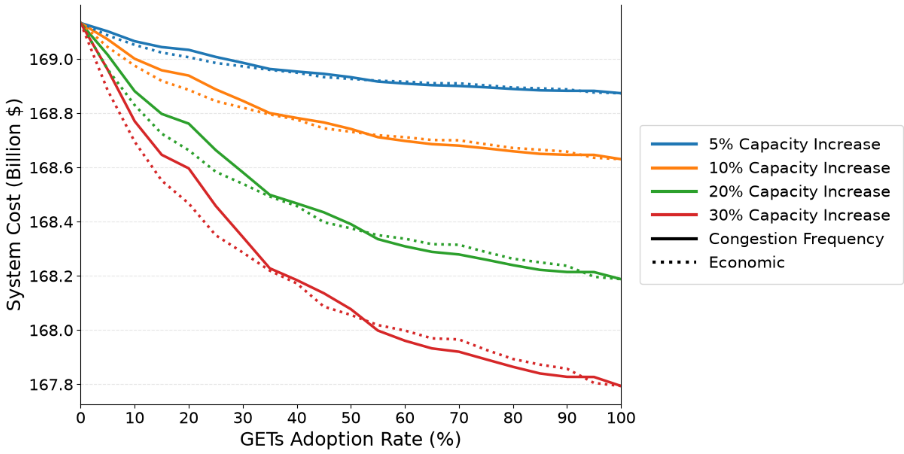


Figure 3: **System-cost effects.** Annual electricity-system cost as a function of GETs adoption level for the economic-based (dotted lines) and congestion-frequency-based (solid lines) deployment strategies. Results are shown for 5%, 10%, 20%, and 30% increases in the capacity of selected transmission corridors. System costs decline with increasing GETs deployment and capacity reinforcement, with savings of up to approximately $1.34 billion per year at full adoption and a 30% capacity increase.

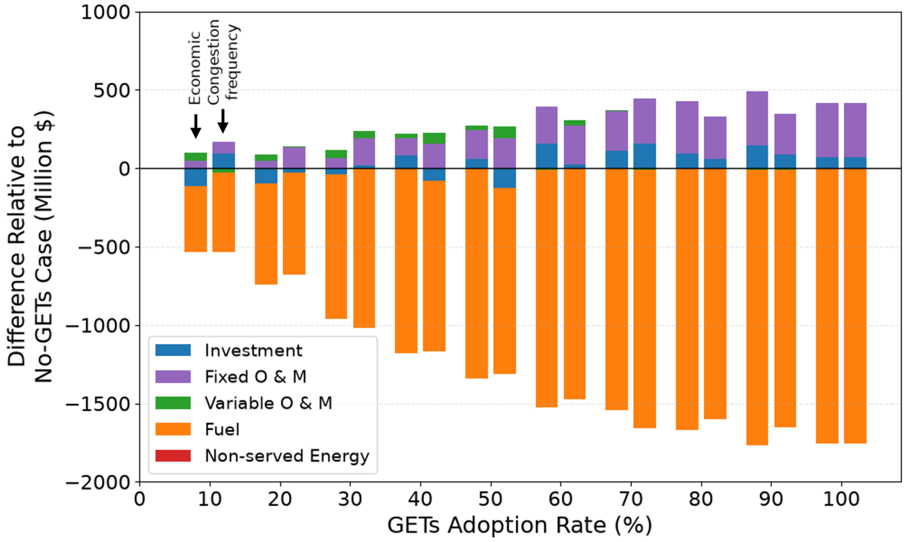


Figure 4: **Sources of GETs benefits.** Contribution of major system-cost components to the change in annual system cost relative to the no-GETs case for a 30% capacity increase. Negative values indicate a reduction in the corresponding cost component and positive values indicate an increase. Reduced fuel expenditure is the principal contributor to system-cost savings, while increases in generation investment and other operating costs partially offset these savings.

weighted-random selection generally provides a modest cost advantage at low adoption levels, with the largest difference occurring at 20% adoption: mean system cost is $168.83 billion compared with $168.89 billion for uniform-random selection, corresponding to a difference of approximately $56 million per year. The advantage is smaller at 10–40% adoption, ranging from approximately $9 to $21 million per year.

At higher adoption levels, the relative performance of the two strategies exhibits some variation, with neither strategy consistently yielding the lowest system cost. By 90% adoption, the difference in mean annual system cost is less than $7 million, and both strategies converge to the same system cost at 100% adoption. This variation arises in part from the ex-ante ranking of transmission lines used to determine the GET deployment sequence. The rankings are established prior to solving the GET-GenX model and are therefore not updated as transmission capacity is added. Reinforcing one corridor can alter power flows, congestion patterns, and the marginal value of capacity on other corridors, such that the initial ranking may no longer reflect the system-optimal deployment order. Because the analysis considers a static deployment sequence rather than iteratively re-optimizing line selection after each GET installation, changes in system cost can therefore exhibit non-monotonic behavior across adoption levels. Under an adaptive deployment framework in which the transmission-line ranking is updated following each reinforcement, the economic-based strategy would be expected to more consistently identify the sequence that minimizes system cost.

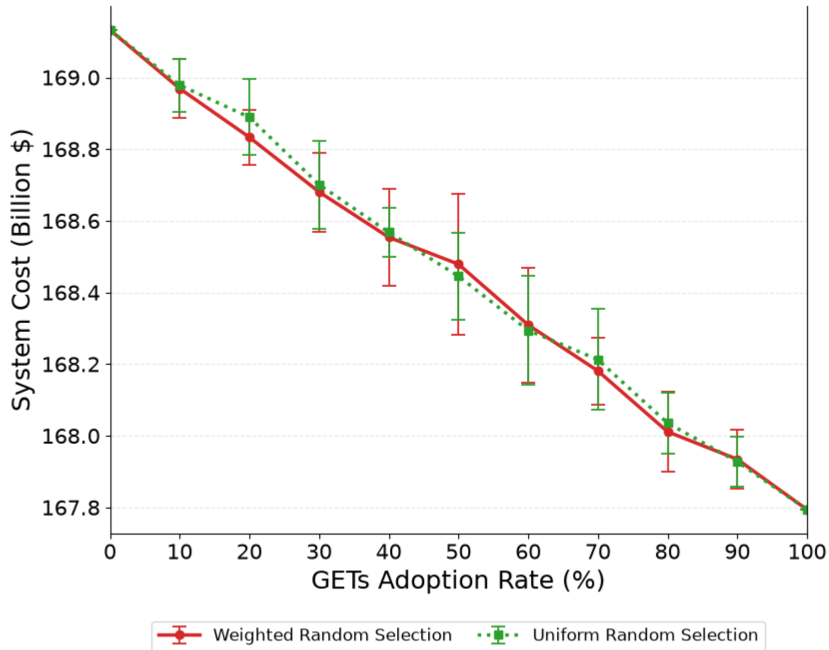


Figure 5: **System cost under stochastic GETs deployment.** Mean system cost as a function of GETs adoption for weighted-random (red solid line) and uniform-random (green dotted line) selection with a 30% transmission-capacity increase. Error bars represent variability across 10 stochastic realizations. The two strategies exhibit similar system-cost trajectories, with the largest difference occurring at 20% adoption and convergence at full deployment.

5 Generation and CO2 emissions

GETs deployment changes the generation mix by altering which resources can access additional transmission capacity. Figure 6 shows changes in annual generation relative to the no-GETs case for a 5% and 30% increase in transmission capacity. The response differs substantially between deployment strategies, particularly at low adoption levels. Under the congestion-frequency-based strategy, initial GETs deployment is concentrated in New York and the Northeast, where the reinforced corridors provide greater access to wind and solar generation and reduce coal generation. This effect is most pronounced for the 5% capacity-increase case. In contrast, the economic-based strategy initially prioritizes corridors in the Central, where coal generation is economically competitive; consequently, early GETs deployment can increase coal generation while providing a smaller shift towards renewable generation. As adoption increases, these differences diminish, and the generation trajectories become more similar.

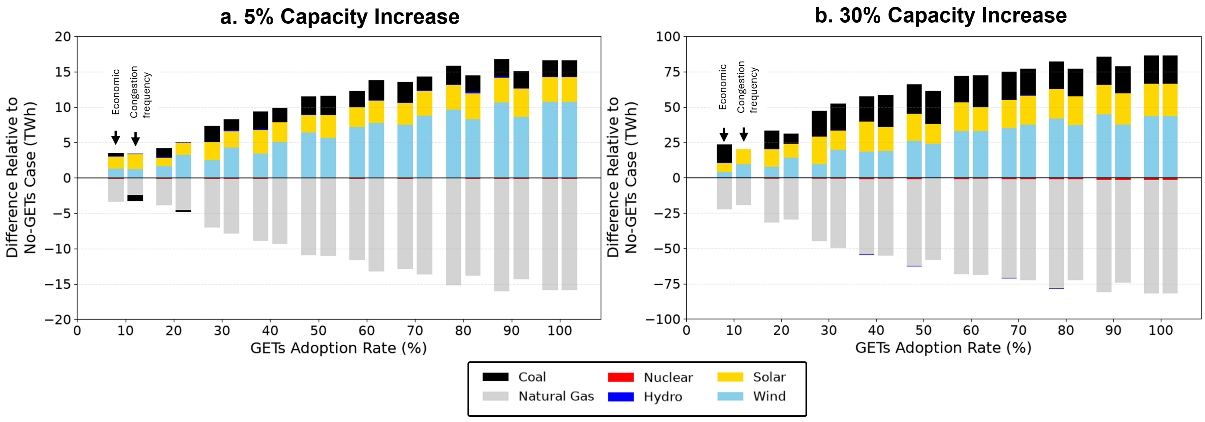


Figure 6: **Changes in annual generation following GETs deployment.** Change in annual generation relative to the no-GETs case for (a) a 5% and (b) a 30% increase in the capacity of selected transmission corridors. Results are shown for the economic-based and congestion-frequency-based deployment strategies across GETs adoption levels. Positive and negative values indicate increases and decreases in generation, respectively. At low adoption levels, congestion-frequency-based deployment shifts generation towards wind and solar and away from coal more strongly than economic-based deployment, particularly for the 5% capacity-increase case.

These changes in the generation mix translate into distinct emissions responses (Figure 7a). Under the congestion-frequency-based strategy with a 30% capacity increase, CO_2 emissions at 10% GET adoption are nearly identical to those at 100% adoption, despite the substantially lower level of deployment. At intermediate adoption levels, emissions increase as greater transmission capacity enables additional coal generation, before declining again at higher adoption levels as the generation mix shifts toward lower-emitting resources. Notably, the 10% adoption case with a 30% capacity increase also reduces annual system cost by approximately $25 million relative to the no-GETs case (Figure 3), while requiring GETs on fewer transmission lines than the economic-based strategy for the same system-wide capacity increase. This combination of lower system cost, comparable emissions performance to substantially higher adoption levels, and a smaller number of transmission corridors requiring modification highlights the potential policy value of congestion-frequency-based deployment, particularly when rapid or targeted GET deployment is prioritized. Thus, the emissions benefits of GETs depend not only on the amount of additional transmission capacity but also on the corridors selected and the generation resources that the resulting network configuration enables.

The stochastic strategies further demonstrate the importance of deployment targeting when it comes to emissions. For a 30% capacity increase, weighted-random selection produces a generally declining mean CO2 emissions trajectory with increasing adoption, whereas uniform-random selection exhibits greater variability and does not follow the same trend (Figure 7b).

Retaining congestion information in the weighted-random strategy therefore provides a more consistent pathway towards emissions reductions than untargeted random deployment.

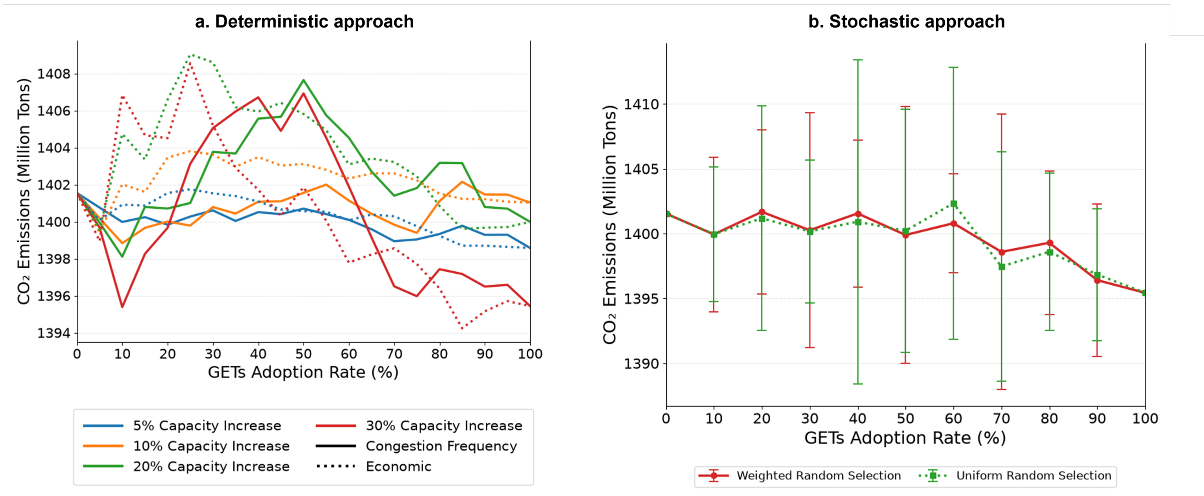


Figure 7: **CO2 emissions under deterministic and stochastic GETs deployment.** (a) Annual CO2 emissions as a function of GETs adoption for economic-based (dotted lines) and congestion-frequency-based (solid lines) deployment strategies, shown for 5%, 10%, 20% and 30% increases in the capacity of selected transmission corridors. (b) Mean annual CO2 emissions for weighted-random (red solid line) and uniform-random (green dotted line) selection with a 30% transmission-capacity increase. Error bars represent variability across 10 stochastic realizations. Emissions are reported relative to the corresponding no-GETs case.

6 Discussion

6.1 Economic value versus congestion persistence

The comparison demonstrates that transmission importance can be defined in multiple ways. Economic-based selection identifies lines with the greatest marginal contribution to reducing system cost, whereas congestion-frequency-based selection identifies lines that repeatedly approach their capacity limits. These signals are related but not equivalent.

The different transmission deployment patterns demonstrate that a line's importance cannot be inferred from congestion alone or from a single economic signal. Transmission constraints are embedded within a network, meaning that reinforcing one line can change power flows and the value of reinforcing other lines. Consequently, reinforcement strategies should be interpreted as sequential network interventions rather than independent line-level decisions.

6.2 Targeting versus deployment quantity

An important result is that differences in individual transmission-line selection do not necessarily translate into proportionally large differences in system-level outcomes.

The stochastic analysis illustrates this particularly clearly. Weighted-random and uniform-random selection produce substantially different transmission corridors, yet their system costs at a given adoption level are relatively close. This suggests that multiple transmission configurations may provide similar system value once sufficient additional capacity is distributed across the network.

At lower deployment levels, however, targeting becomes more important. Weighted-random selection performs better than uniform-random selection, indicating that congestion information is particularly valuable when the number of lines receiving GETs is limited.

6.3 Implications for GETs deployment

These results have an important implication for GETs deployment policy. If GETs are inexpensive relative to conventional transmission expansion, maximizing the number of lines receiving GETs may not be the only relevant planning objective. The selection mechanism can determine which generation resources gain access to the additional transmission capability and therefore influence both system cost and emissions.

Economic-based selection provides a direct mechanism for identifying system-value opportunities. Congestion-frequency-based selection offers a more physically interpretable measure of persistent transmission bottlenecks. Weighted-random selection provides a middle ground that incorporates congestion information while allowing exploration of alternative network configurations.

The appropriate deployment strategy may therefore depend on the objective of the planner: minimizing short-run system costs, relieving persistent congestion, increasing renewable access, or maintaining flexibility in transmission deployment.

7 Conclusion

GETs can provide substantial system value by increasing the effective capacity of existing transmission infrastructure, but realizing this value depends critically on where and how GETs are deployed. This study evaluates four alternative deployment strategies—economic-based selection, congestion-frequency-based selection, weighted-random selection and uniform-random selection—and demonstrates that the choice of deployment mechanism affects not only the economic value of GETs, but also the geographic distribution, number of transmission corridors modified and resulting generation mix.

The results show that economic-based and congestion-frequency-based strategies identify different transmission priorities when GET deployment is constrained. Economic-based deployment initially concentrates on economically valuable corridors in the central and eastern United States, whereas congestion-frequency-based deployment emphasizes corridors with recurring congestion, including those in the Northeast and New York. Importantly, the congestion-frequency-based strategy achieves a given system-wide capacity increase by modifying fewer transmission lines than the economic-based strategy, indicating a tendency to prioritize higher-capacity corridors. This distinction has practical implications: targeting fewer corridors could reduce the number of projects requiring permitting and regulatory approval, potentially enabling faster deployment of GETs where transmission expansion is otherwise constrained by long development timelines.

Despite these differences in deployment location and scale, GETs provide substantial system-level economic benefits. Annual system-cost savings reach approximately \$1.34 billion in the most favorable scenarios. A particularly policy-relevant result is observed for the congestion-frequency-based strategy with a 30% capacity increase: at only 10% GET adoption, annual system costs are approximately \$25 million lower than in the no-GETs case, while CO_2 emissions are nearly identical to those at 100% adoption. This result illustrates that substantial economic and environmental benefits can be obtained without deploying GETs across a large fraction of the transmission network. For policymakers seeking near-term transmission solutions, targeted deployment on a limited number of highly congested corridors may therefore offer a relatively rapid pathway to improving network utilization while avoiding the scale and timelines associated with widespread transmission construction.

The generation results further demonstrate that the environmental consequences of GET deployment cannot be inferred from additional transmission capacity alone. GETs generally increase wind generation and reduce natural gas generation, but can also increase coal generation depending on the corridors selected. Consequently, emissions can increase over intermediate adoption levels even when system costs decline, before decreasing as additional transmission capability enables greater substitution toward lower-emitting resources. The stochastic analysis similarly shows that congestion-informed weighting provides greater economic value than untargeted random deployment at lower adoption levels, while these differences diminish as GET deployment expands.

The comparison of deployment strategies also highlights an important methodological and policy consideration. The economic-based ranking is determined ex ante, before the GET-GenX model is solved, and is not updated as transmission capacity is added. Because reinforcing one corridor changes power flows, congestion patterns, and the marginal value of capacity elsewhere in the network, the initial ranking may no longer represent the system-optimal deployment sequence after successive GET installations. The observed variation in system costs across adoption levels therefore reflects, in part, the use of a static deployment sequence. An adaptive framework that re-evaluates transmission priorities as GETs are deployed could further improve system outcomes and may provide a useful direction for future planning studies.

Taken together, these findings position GETs as a potentially important near-term complement to conventional transmission expansion. Their value does not arise simply from increasing transmission capacity, but from strategically increasing capacity where it can most effectively relieve network constraints and alter the generation mix. The results suggest that deployment strategies based on congestion can be particularly attractive when the objective is to achieve meaningful system and emissions benefits with a limited number of transmission modifications. Such targeted deployment could be especially valuable in the near term, when permitting constraints, project lead times, and institutional capacity limit the rate at which new transmission can be built. More broadly, the results indicate that GETs policy should move beyond questions of how much additional transmission capacity is needed to also consider which existing corridors can be upgraded most efficiently, how many projects must be modified, and how deployment choices affect both system costs and emissions.

References

[1] J. R. L. Senga, A. Botterud, J. E. Parsons, S. D. Story, C. R. Knittel, Interregional transmission can increase reliability while reducing costs and emissions in the US. *Nature Energy* **11** (2), 163–164 (2026), doi:10.1038/s41560-025-01914-6, https://www.nature.com/articles/s41560-025-01914-6.

[2] J. R. L. Senga, C. R. Knittel, The frequency of extreme events determines the value of grid integration: a welfare framework for transmission investment under climate uncertainty (7074121) (2026), doi:10.2139/ssrn.7074121, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=7074121.

[3] L. Armstrong, A. Canaan, C. Knittel, G. Metcalf, T. Schittekatte, Can federal grid reforms solve the interconnection problem? *Science* **385** (6704), 31–33 (2024), doi:10.1126/science.ado9254, https://www.science.org/doi/abs/10.1126/science.ado9254.

[4] S. Ansolabehere, *et al.*, *Crossed Wires: A Salata Institute-Roosevelt Project Study of The Development of High-Voltage Transmission Lines in the United States*, Tech. rep., Salata Institute for Climate and Sustainability, Harvard University (2024), https://salatainstitute.harvard.edu/grid-report/.

[5] B. Deese, R. Gramlich, A. Pasnau, A Roadmap for Advanced Transmission Technology Adoption (2024-06) (2024), https://ceepr.mit.edu/wp-content/uploads/2024/09/MIT-CEEPR-RC-2024-06.pdf.

[6] J. D. Jenkins, N. A. Sepulveda, Enhanced decision support for a changing electricity landscape: The GenX configurable electricity resource capacity expansion model (2017), https://energy.mit.edu/wp-content/uploads/2017/10/Enhanced-Decision-Support-for-a-Changing-Electricity-Landscape.pdf.

[7] J. R. L. Senga, A. Botterud, J. E. Parsons, S. D. Story, C. R. Knittel, Implications of policy-driven transmission expansion for costs, emissions and reliability in the USA. *Nature Energy* (2026), doi:10.1038/s41560-025-01921-7, https://www.nature.com/articles/s41560-025-01921-7.

[8] N. Shi, *The Role for Electricity Transmission in Net-Zero Energy Systems: A Spatially Resolved Analysis of the Continental US*, Master's thesis, Massachusetts Institute of Technology (2023), https://hdl.handle.net/1721.1/151926.

Supplementary Materials for The System Value of Grid-Enhancing Technologies under Alternative Transmission Deployment Strategies

Christopher R. Knittel, Juan Ramon L. Senga, Chaitanya Vuppanapalli

A What are GETs?

GETs are a suite of hardware and software tools that increase the capacity and efficiency of existing transmission infrastructure without requiring the construction of new transmission lines. Rather than expanding the physical grid, GETs optimize the use of transmission assets that are already in place, utilizing capacity that is routinely left unused due to conservative static operating limits and inefficient power flows. Three categories of GETs are most widely considered:

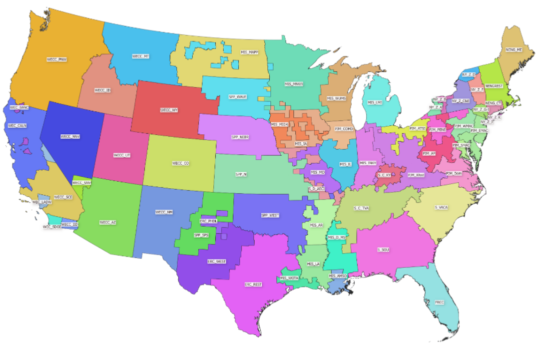
Dynamic Line Ratings (DLR): Transmission lines are assigned capacity limits that determine how much power can flow through them at any given time. Traditionally, these limits are set statically based on worst-case ambient conditions such as peak summer temperatures and low wind speeds, to ensure the line does not overheat and sag into unsafe proximity with the ground. In practice, actual conditions are almost always more favorable than the worst case, meaning the true capacity of the line is higher than its rating. DLR systems replace these fixed limits with real-time ratings derived from continuous measurements of weather conditions (e.g. wind speed, ambient temperature, and solar radiation). By reflecting actual rather than worst-case conditions, DLR typically increases line capacity by 10–30% on average, with larger gains during periods of high wind and cool temperatures that coincide with high wind generation output. This makes DLR particularly valuable for integrating wind resources, as the lines most likely to be carrying wind power are also the lines most likely to have surplus thermal capacity under DLR.

Advanced Power Flow Control (APFC): Power flows on the transmission grid do not follow operator instructions. It instead follows the path of least electrical resistance as governed by Kirchhoff's laws. This means that some lines frequently carry power close to their limits while parallel lines on the same corridor remain underutilized. The result is artificial congestion such that the grid appears constrained not because there is insufficient total capacity, but because power is not distributed efficiently. APFC devices address this problem by actively redirecting power flows away from congested lines and onto underutilized parallel paths. By balancing loading across the network, APFC reduces congestion, lowers curtailment of low-cost generation, and increases the effective transfer capacity of existing corridors.

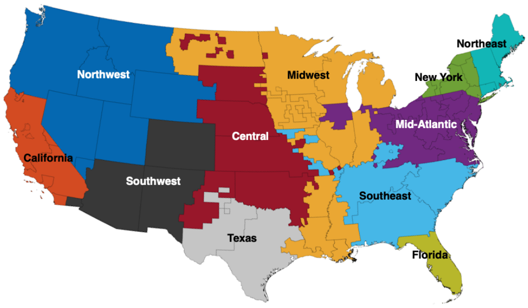
Topology Optimization: The transmission network can be reconfigured in real time by opening and closing switches at substations. This is a process known as transmission switching or topology optimization. Different network configurations produce different power flow patterns, and some configurations are more efficient than others given the current generation dispatch and load conditions. Topology optimization software uses advanced algorithms to identify network configurations that minimize congestion, reduce system costs, and improve reliability in real time. Unlike DLR and APFC which require hardware installation, topology optimization can be implemented primarily through software upgrades to existing energy management systems. Studies have found that topology optimization can reduce system operating costs by 1–5% annually, with larger benefits in heavily meshed networks with significant renewable generation.

B GenX Regional Map

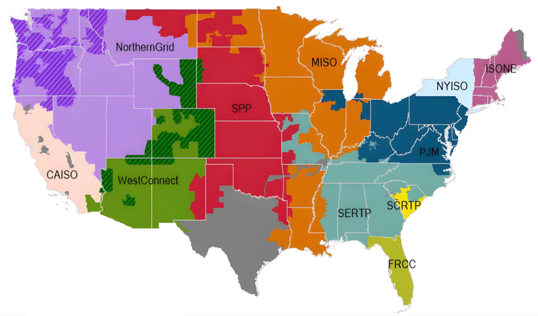
Fig. 1 shows the zones and regional groupings used in the GenX model. The 64 zone map in Fig. 1a is obtained from [8] and [1]. Fig. 1b groups the zones into transmission regions in such a way that it most closely aligns with 1c.



(a) 64 Zone Map



(b) 11 Model Region Map created by aggregating the 64 zones



(c) FERC Order No 1000 Transmission Planning Regions

Figure 1: **a – c, Zonal and Regional Maps.** The 64 zones in **(a)** are based on the EPA's IPM Regions and the regional grouping in **(b)** is done to mimic the FERC Order No. 1000 transmission planning regions in **(c)** as close as possible.

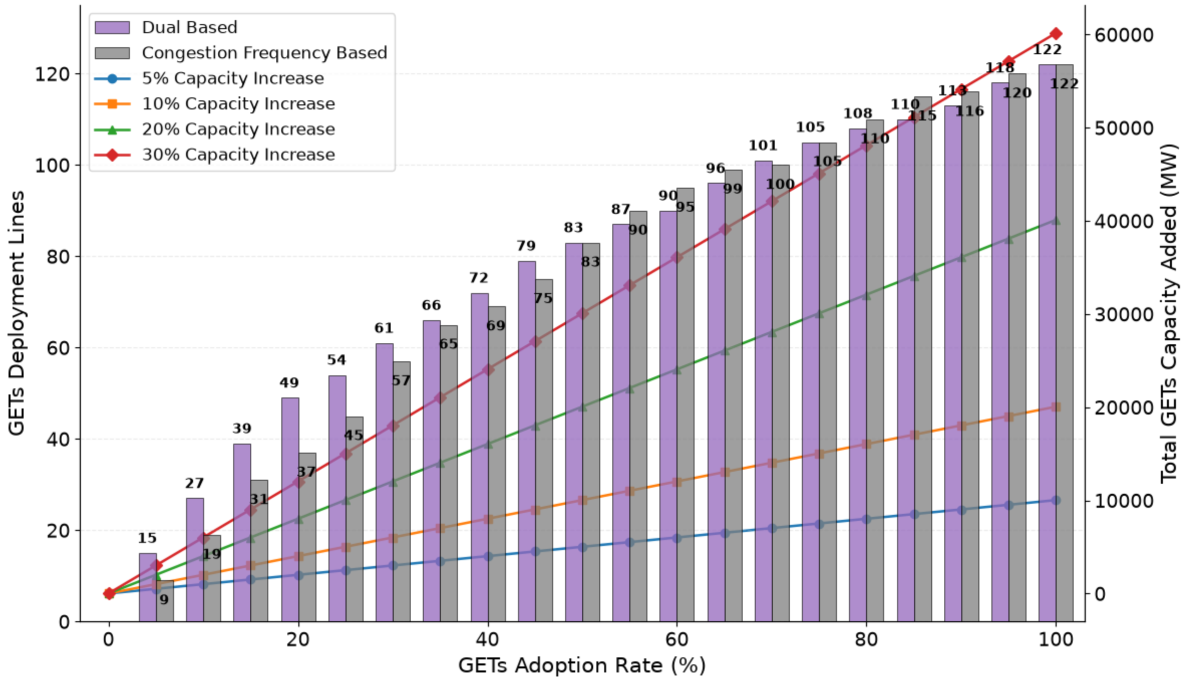


Figure 2: **GETs Deployment Lines vs GETs Adoption Rate.**

Contact.

The MIT CEEPR Research Commentary Series
is published by the MIT Center for Energy and Environmental Policy Research from submissions by affiliated researchers.

For inquiries and/or for permission to reproduce material in this commentary, please contact:

General inquiries: ceepr@mit.edu

Media inquiries: ceepr-media@mit.edu

MIT CEEPR
Center for Energy and Environmental Policy Research

MIT Center for Energy and Environmental Policy Research
Massachusetts Institute of Technology
77 Massachusetts Avenue, E19-411
Cambridge, MA 02139-4307
USA

ceepr.mit.edu

MASSACHUSETTS INSTITUTE OF TECHNOLOGY