Appendix to GETting Interconnected in PJM

Grid-Enhancing Technologies (GETs) Can Increase the Speed and Scale of New Entry from PJM's Queue

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Detailed Methodology

Study scope and set-up

Quanta, our analysis partner, created a comprehensive power flow model to set up this analysis, drawing on future year power flow cases. Forty-five individual power flow cases were created using PSSE and TARA, encompassing the following study scope:

- Five states within the PJM footprint: Virginia, Ohio, Pennsylvania, Illinois, and Indiana
- Three future years: 2026, 2028, 2030
- Three load conditions: summer, winter, and light load

The study scope was limited to a portion of the PJM footprint to meet project timeline and budget targets. The five states selected were chosen due to the large amount of queued generation present in their footprint, and the future years were selected with an eye toward nearer-term opportunities for integrating new generation in the region. Quanta then conducted power flow and contingency modeling (steps 1 and 2), testing the application of GETs as network upgrades for queued projects, followed by production cost modeling in PROMOD (step 3).

Step 1: Establishing the power flow cases for this analysis

Quanta added queued projects through PJM's Transition Cycle 1, totaling approximately 126 GW, to each of the power flow cases. For each power flow case, they assessed thermal overloads under both pre- and post- contingency conditions (P0–P7) in TARA, in accordance with NERC Reliability Standards and PJM's rules regarding generator deliverability. Quanta strictly followed PJM deliverability rules and regulations in order to accurately represent how these technologies might be studied by PJM in a future interconnection study process. Due to the large amount of new queued generation being added, running the power flow model resulted in high levels of transmission line overloads.

Quanta also re-ran the contingency analyses while enforcing reliability constraints in order to quantify the magnitude of curtailment that would be experienced in the absence of grid upgrades (note that this contingency analysis does not quantify expected annual curtailment; estimating annual curtailment requires production cost modeling, not typically included in interconnection studies). Curtailment of resources up to 100% was observed. Since most interconnecting generation drops out of the queue when faced with high upgrade costs (which correlate with higher curtailment magnitudes), generators that experienced greater than 90% curtailment levels were eliminated from the analysis in order to focus on the most viable interconnecting projects; this equated to approximately 52 GW of projects being removed from the subsequent analyses. Another 66 GW of projects caused no thermal overloads, so were not considered for GETs applicability. The remaining 8 GW of projects, experiencing moderate levels of thermal overloads, were assessed to determine if GETs could be used to alleviate the grid impacts they triggered (see Appendix Exhibit A-1).

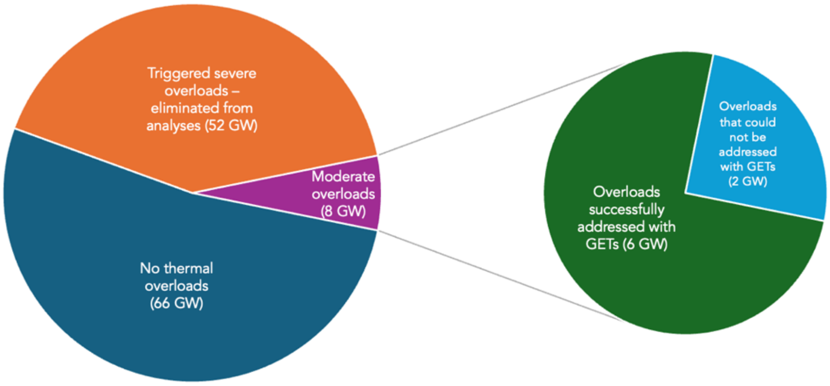


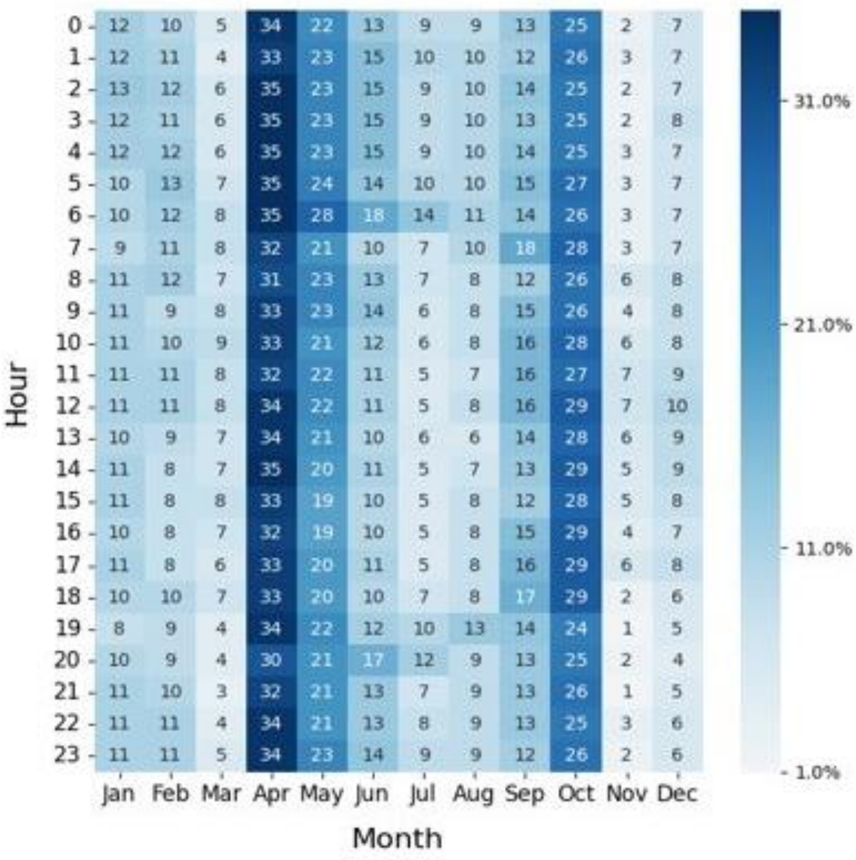
Exhibit A-1. Snapshot of the total queued generation capacity accounted for in this analysis, and the smaller volume for which GETs were assessed.

Step 2: Applying GETs to the power flow models

Before broadly applying GETs to the power flow model, Quanta worked with vendors to conduct a deep-dive analysis of each technology to understand where it could be best applied.

The deep-dive analysis for dynamic line ratings (DLR) was conducted on 11 monitored facilities and revealed an average summer line capacity increase of 17%. LineVision first calculated the static rating of a given overloaded line, assuming a 3 ft/sec wind speed (w/sensitivity analysis that also included 2 and 4 ft/sec speeds). Then, LineVision calculated the dynamic rating given wind speed, temperature, and irradiance data for that geographic location. Compared with the static rating, the average percent capacity increase of the dynamic rating was shown in a heatmap for representative days of each month out of a modeled year for each location. An example of this is shown in Exhibit A-2 below. DLR would be best applied in areas where there are typically windy conditions, although it is viable even in areas with lower levels of wind, such as 2–4 ft/sec wind speeds, particularly if there are conservative pre-existing estimates of static line ratings. In many cases, the dynamic rating was found to exceed the static rating by greater than 30%.

Operationally, DLR hardware will inform the operator of what uprate can safely be realized for a particular line, given ambient conditions at a particular time. However, it was infeasible to produce and apply predictive weather forecast models to every point of interconnection being studied in the limited scope of this work. Quanta modeled the deployment of DLR across the study footprint by applying a conservative 10% uprate (from the static rating) to lines with modest overloads (<110%); this served as a rough estimate of potential rating increases that could be realized by the application of ambient DLR sensors.



Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	12	10	5	34	22	13	9	9	13	25	2	7
1	12	11	4	33	23	15	10	10	12	26	3	7
2	13	12	6	35	23	15	9	10	14	25	2	7
3	12	11	6	35	23	15	9	10	13	25	2	8
4	12	12	6	35	23	15	9	10	14	25	3	7
5	10	13	7	35	24	14	10	10	15	27	3	7
6	10	12	8	35	28	18	14	11	14	26	3	7
7	9	11	8	32	21	10	7	10	18	28	3	7
8	11	12	7	31	23	13	7	8	12	26	6	8
9	11	9	8	33	23	14	6	8	15	26	4	8
10	11	10	9	33	21	12	6	8	16	28	6	8
11	11	11	8	32	22	11	5	7	16	27	7	9
12	11	11	8	34	22	11	5	8	16	29	7	10
13	10	9	7	34	21	10	6	6	14	28	6	9
14	11	8	7	35	20	11	5	7	13	29	5	9
15	11	8	8	33	19	10	5	8	12	28	5	8
16	10	8	7	32	19	10	5	8	15	29	4	7
17	11	8	6	33	20	11	5	8	16	29	6	8
18	10	10	7	33	20	10	7	8	17	29	2	6
19	8	9	4	34	22	12	10	13	14	24	1	5
20	10	9	4	30	21	17	12	9	13	25	2	4
21	11	10	3	32	21	13	7	9	13	26	1	5
22	11	11	4	34	21	13	8	9	13	25	3	6
23	11	11	5	34	23	14	9	9	12	26	2	6

Exhibit A-2. Output of the DLR deep dive analysis for one location, showing hourly line percent capacity increases for a modeled year.

Advanced power flow controls were incorporated directly into the power flow and contingency models via a Python script from Smart Wires. This script automated the analysis and application process to address overloads on meshed grid topologies across the study footprint.

NewGrid, a topology optimization (TO) software provider, conducted the deep-dive analysis for TO, again applicable only to constraints on meshed (not radial) grids. NewGrid found reconfiguration solutions for five of ten constraints initially provided to them. The solutions created no new violations elsewhere on the system and addressed P1, P2, P4, and P7 contingency conditions. In some cases, the reconfiguration (e.g., opening a breaker at a substation) and resulting redistributed power flows did not affect normal operations, but modified the elements such that under the contingency, the utilization of other nearby elements increased but did not overload those elements. In other cases, the reconfiguration solution identified would trip one or more queued projects along with the contingent elements; however, with low probability of contingency occurrence, this outage would likely amount to downtime for the queued resources on the order of minutes per year. These results informed the broader application of topology optimization to address overloads arising from P1, P2, P4, and P7 contingencies.

After the broad application of all three of these GETs to the 8 GW of queued projects that triggered moderate grid impacts, Quanta found that GETs could effectively alleviate the impacts for 6.6 GW of projects, without creating new issues elsewhere on the grid. The number of GETs implemented in each state is shown in Exhibit A-3.

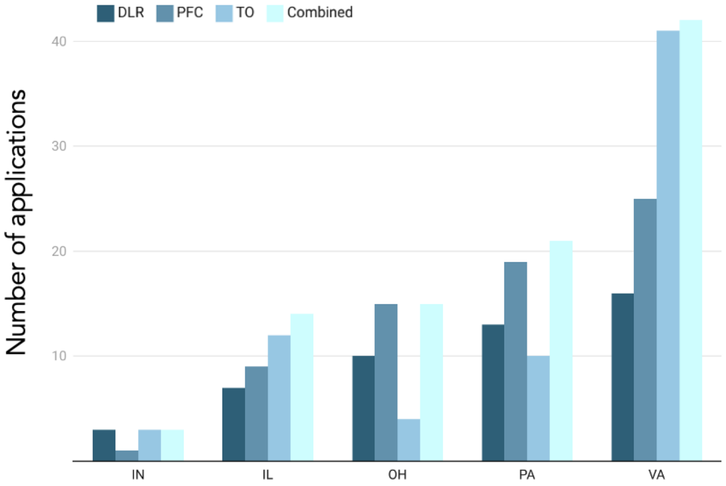


Exhibit A-3. Count of overloads where GETs were successfully applied in each state, individually and in combination.

Step 3: Evaluating the impact of GETs

Quanta ran an 8,760 economic dispatch analysis in PROMOD to assess the impact of GETs and the 6.6 GW of queued resources they enabled to interconnect within the next four years. The PROMOD database is derived from Simulation Ready Data provided by Ventyx/Hitachi Energy. The database was modified to reflect the specifics of the study conditions and queued projects under evaluation. They compared two scenarios: the business-as-usual scenario and the GETs scenario (same business-as-usual case, plus GETs and GETs-enabled generation by 2026. Production cost modeling was run for three future years: 2027, 2030, and 2033; 2026 power flow results informed the 2027 production cost run; 2026 and 2028 power flow results informed the 2030 production cost run, and 2026, 2028, and 2030 power flow results informed the 2033 production cost run.

Quanta calculated and compared production cost savings, emissions reductions, and congestion relief (quantified in constrained hours per facility) for both scenarios. The production cost savings results are primarily detailed in the *Findings* section of the Insight Brief and expanded upon here.

Production cost modeling results are driven by the dispatch changes in the before and after scenarios. The majority of production cost savings come from the displacement of coal- and gas-fired generation by solar and wind generation. The increase in renewable generation stems from both the newly added generators enabled to interconnect with GETs and the existing renewable generators enabled to deliver more power thanks to the congestion relief GETs provide to the system. Exhibit A-6 depicts a comparison of the increase in renewable generation with the reduction in coal- and gas-fired generation.

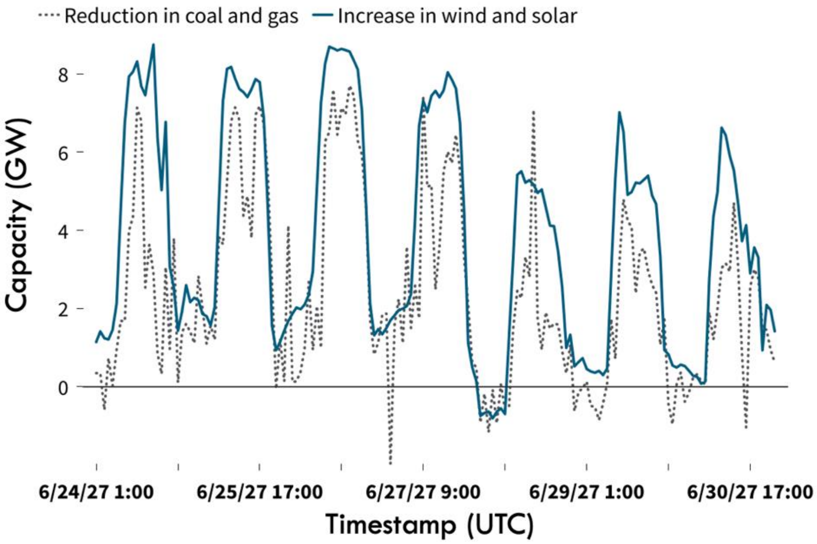


Exhibit A-4. Comparison of PJM-wide hourly reduction in coal- and gas-fired generation and corresponding increase in wind and solar generation for the with-GETs PROMOD scenario.

Another significant change to the dispatch in this analysis is the addition of new battery storage resources enabled by GETs, as there is very little storage currently installed in PJM's system. However, PROMOD's battery storage modeling capabilities are limited, a feature we would hope to see updated in future versions of the software. For example, battery resource charging and discharging is modeled to replicate pumped hydropower storage resources, and is added into the "hydro + storage" generation category. Exhibit A-5 below depicts the hourly "hydro + storage" charging and discharging profile for the BAU and GETs scenarios during the same week in June 2027; based on the generation in the queue, the differences between the scenarios reflect the addition of new storage resources in the GETs scenario.

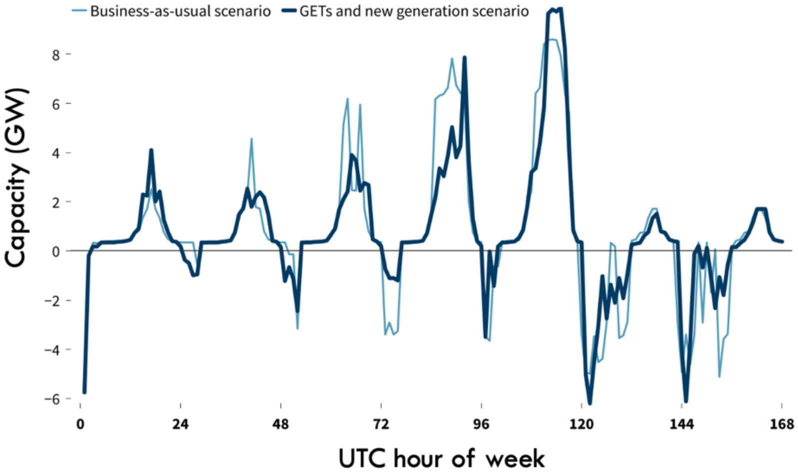


Exhibit A-5. PJM-wide hourly "hydro + storage" charging and discharging profiles for both PROMOD scenarios during the same week in June 2027.

Compared with the business-as-usual scenario, the GETs scenario led to a reduction in PJM's carbon dioxide (CO_2) emissions of 3.5% in 2027. Given that PJM's business-as-usual annual emissions total in the hundreds of millions of tons of

CO_2 per year, this scale of reduction (equivalent to 12 million tons) is significant. Similar levels of reductions were found for sulfur dioxide (SO_2). Exhibit A-4 showcases the emissions reduction results for three future years.

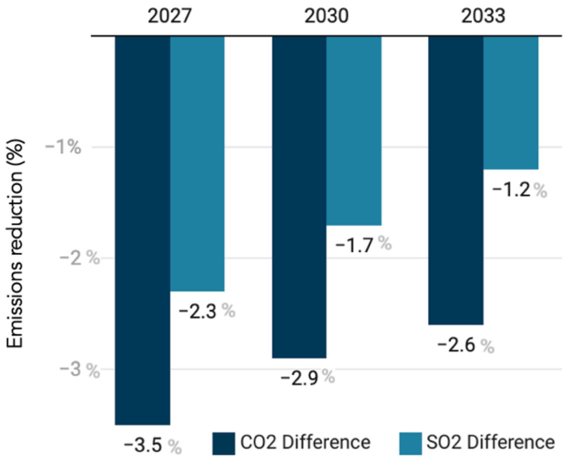


Exhibit A-6. Emissions reduction enabled by GETs deployment for three future years.

Summary

The rigorous analytical methodology described here was chosen to emulate the same interconnection feasibility study analysis in the same software utilized by PJM. In summary, our analysis partner ran forty-five individual power flow cases testing the application of GETs as network upgrade alternatives, which informed the creation of two production cost model scenarios. The comparison between those two scenarios resulted in the economic dispatch improvements presented in the work.