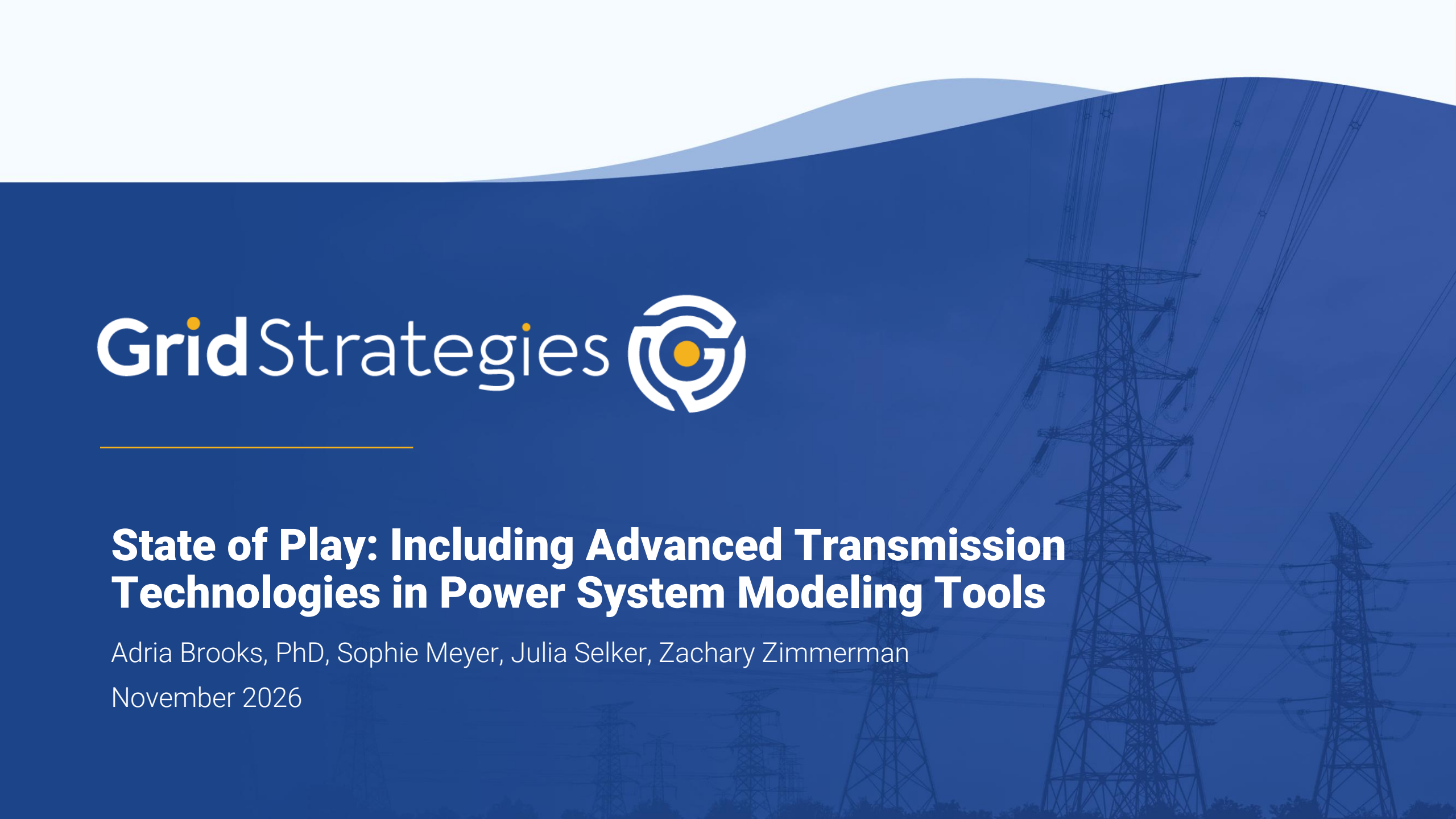


State of Play: Including Advanced Transmission Technologies in Power System Modeling Tools

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November 2026

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Orientation to the report

Section 1 provides relevant introduction and background on ATTs and their role in transmission planning.

Section 2 seeks to answer the question posed by FERC: whether commercial grid modeling software represents ATTs.

Section 3 explains the application of commercial grid modeling software to core grid modeling activities:

- Capacity Expansion Modeling, which explores how resources and grid capacity will serve load;
- Production Cost Modeling, which studies how energy costs change with different resources or grid assets;
- and Power Flow Modeling, which represents the physics of the grid at a snapshot in time.

Section 4 describes the ATTs categories in more detail and collects case studies of deployments.

Appendix provides excerpts from FERC Commissioners' concurrences and other communications related to the June 2026 Show Cause Orders, providing more context for the need for ATT representation in power system modeling software tools.

Executive summary

This report responds to the question implied in FERC's June 2026 show cause orders on large load interconnection: Is commercial grid modeling software capable of accurately accounting for Advanced Transmission Technologies?

We reviewed the modeling capabilities of sixteen commercially-available grid modeling software products to understand how they consider Advanced Transmission Technologies (ATTs). The software tools generally fall into three steady-state grid power system modeling applications: capacity expansion modeling, production cost modeling, and power flow modeling (see descriptions in Section 3). Based on our review of the modeling software documentation and interviews with the software owners, we summarize the ability of each tool to represent four ATTs: High-Performance Conductors, Dynamic Line Ratings, Advanced Power Flow Control, and Transmission Topology Optimization (see descriptions of each technology in Section 4).

The report finds that, as of fall 2026, most commercial grid modeling software can represent ATTs, but few fully represent or optimize for the technologies by default. Studying ATTs for large load interconnection and other purposes is impractical when technologies are only partially included in modeling software. Partial representation requires Regional Transmission Organizations (RTOs), Independent System Operators (ISOs), and utilities to invest time and resources to develop its own manual process or tool to model the technology. While traditional grid modeling tools allow engineers to manually test solutions to grid constraints, newer software programs proactively propose optimized solutions and quantify the benefits and costs of each intervention. Automation and built-in optimization saves time, reduces reliance on engineer experience, and makes new technologies easier to adopt.

Acronyms

ATT – Advanced Transmission Technology
AC – Alternating Current
ACSR – Aluminum Conductor Steel Reinforced
ACSS – Aluminum Conductor Steel Supported
AMP – Accelerating Modern Powerlines Coalition
APFC – Advanced Power Flow Control
B2B – Back-to-Back
CEM – Capacity Expansion Modeling
DC – Direct Current
DFC – Dynamic Flow Controller
DLR – Dynamic Line Ratings
FACTS – Flexible AC Transmission System
HPC – High Performance Conductor
HTS – High Temperature Superconductor
HVDC – High Voltage Direct Current
IEEE – Institute of Electrical and Electronics Engineers
INL – Idaho National Laboratory
IPFC – Interline Power Flow Controller
ISO – Independent System Operator
m-SSSC – Modular Static Synchronous Series Compensator
MVAR – Megavolt-Ampere Reactive
NLR – National Lab of the Rockies
PAR – Phase Angle Regulator
PCM – Production Cost Modeling
PF – Power Flow
PFM – Power Flow Modeling
PST – Phase Shifting Transformer
RA – Resource Adequacy
ROW – Right of Way
RTO – Regional Transmission Organization
SSR – Subsynchronous Resonance
STATCOM – Static Synchronous Compensator
SVC – Static VAR Compensator
TCSC – Thyristor Controlled Series Compensator
TTO – Transmission Topology Optimization
UPFC – Unified Power Flow Controller
VSC – Voltage Source Converter
WATT – Working for Advanced Transmission Technologies Coalition

Section 1.
Background and Introduction



GridStrategies

Background

Modernizing the transmission grid

The transmission grid is largely made up of steel wires wrapped in aluminum and suspended on tall lattice towers. The network connects at substations, where devices like transformers and switches are used to allow power to change voltage and move between circuits. This system is relatively unchanged since the turn of the 20th century and the creation of utilities.

The simplicity of the material and devices on the grid belies its complexity. Unless stored in batteries, electricity is used at nearly the same moment that it is generated, meaning demand for electricity and sources of power are in relationship on a millisecond basis. Large rotating turbines that generate power have been the key to supporting the grid's stability, with their physical mass acting as a kind of shock absorber as consumers flip switches.

The 21st century has expanded access to new generation technology to the grid: inverter-based resources, which can use power electronics to mimic the inertia of large turbines while delivering lower-cost power. New uses of electricity are also changing the demands on the grid: large data center computing loads which can demand as much power as small cities, capable of shifting demand so significantly and quickly that they introduce new balancing risks for the regional grid. The transition to new generation and load technologies is increasing the burden on an aging, inflexible transmission system. Much of the existing transmission system was built in the late 20th century and is approaching the end of its useful life, requiring investment to renew the infrastructure.

Introduction

Modernizing the transmission grid

Advanced Transmission Technologies (defined briefly in this section and in depth in Section 4) are tools that make the most of transmission corridors and infrastructure. New conductors are one category of ATT—using materials stronger than steel for conductor cores, the wires can be hung lower or with fewer towers while carrying much more power, usually doubling capacity for the same price or less than traditional wires. Another subset of ATTs, Grid Enhancing Technologies (GETs), find additional capacity by using infrastructure flexibly, including using more capacity in favorable conditions or controlling power flows.

Though commercialized for many years, ATT adoption has been slow for three primary reasons. First, there is an incentive problem: Utilities are allowed to earn a profit proportional to their capital investments, which are often smaller with ATTs. With little earning opportunity in ATTs, utilities are unlikely to dedicate a business unit to pursuing applications. Second, grid planning executives and engineers see their mandate as ensuring maximum reliability with reasonable infrastructure costs on ten-year timelines, and do not optimize for accelerated timelines, greater efficiency, or lower energy costs in the near term. Finally, there is a technical barrier: since the creation of the electric utility, the transmission system has been viewed as a static asset and utilities may not have the tools to represent a more dynamic grid and value ATTs in their planning models. This report focuses on the third challenge.

The sources and uses of power have changed significantly since the 1900s, but the infrastructure connecting them has not. The way that infrastructure is planned and designed is unrecognizable, from pencils and slide rules to solid-state hard drives, but what we build is still mostly the same. **This paper explores that contradiction: Grid planners use a subset of sixteen different commercial software tools to plan the grid, but it remains very difficult to represent innovative and dynamic transmission technologies within those tools.** If the tools used to model and design the grid cannot test the applicability and cost-effectiveness of ATTs, engineers will not select them.

Why grid modeling software matters

Applications of grid modeling software are explained in detail in Section 3

Engineers analyze transmission needs in grid modeling software for transmission planning and generator and load interconnection studies. These studies determine how the billions of dollars to expand and reinforce the transmission system are spent every year.

FERC has required ATTs in grid planning through Order Nos. 1920 and 2023 (see slide 17), but load growth is putting new pressure on these methods. Large load interconnection requests can require significant grid upgrades and are seeking service faster than new, large-scale transmission lines have traditionally been built. **ATTs are some of the few solutions that can deliver new transmission capacity on the rapid timelines of the emerging needs, but not all grid modeling software represent ATTs fully or properly.**

Grid modeling software tools are where transmission solutions are compared, so a technology missing from the model or not fully represented fails to make a true alternatives comparison. A tool that cannot represent a High-Performance Conductor (HPC), for example, cannot weigh reconductoring against a building a new line or building a new line using an HPC, and the new line with a traditional conductor wins by default. Planning models also output key elements of what a utility files with its regulator to justify its spending: Where the software generates no benefit or cost comparison for an ATT, there is no record supporting that alternative, and regulators lack evidence to evaluate the decision.

A tool that can represent an ATT does not necessarily optimize its settings, nor automatically identify that technology as a solution to a transmission constraint. In some cases, an ATT can be represented only if a planner sets out to model that technology for a specific need with predefined settings. Partial representation shifts the work from the software to the user, so ATT consideration is limited by the planning staff's available hours and analytical capacity. Additionally, the benefits a model cannot capture may go uncounted, which risks undervaluing ATTs.

Advanced Transmission Technologies: Grid Enhancing Technologies and High Performance Conductors

More details and case studies included in Section 4

Grid Enhancing Technologies (GETs)

Dynamic Line Ratings

Hardware and software used to calculate and project the true capacity of transmission lines using real-time and forecasted weather conditions

Advanced Power Flow Control

Hardware used to reroute electricity from overloaded transmission lines to underutilized lines by adjusting circuit impedance

Topology Optimization

Software that identifies reconfigurations of the transmission grid (usually through switching operations) to deliver power most efficiently

High Performance Conductors (HPCs)

Carbon Fiber and Composite Core Conductors and Superconductors

Modern conductor technologies with greater capacity, higher efficiency, and less thermal sag

These technologies are collectively known as **Advanced Transmission Technologies (ATTs)**, which can cost-effectively increase the capacity, efficiency, reliability, and/or safety of power lines, faster than traditional grid infrastructure and at lower cost or with higher net benefits. New innovations may be added to each of these categories as they are developed in the future.

Advanced Transmission Technologies:

Benefits of GETs and HPCs

GETs can decrease congestion costs by up to 50%, at relatively low cost.

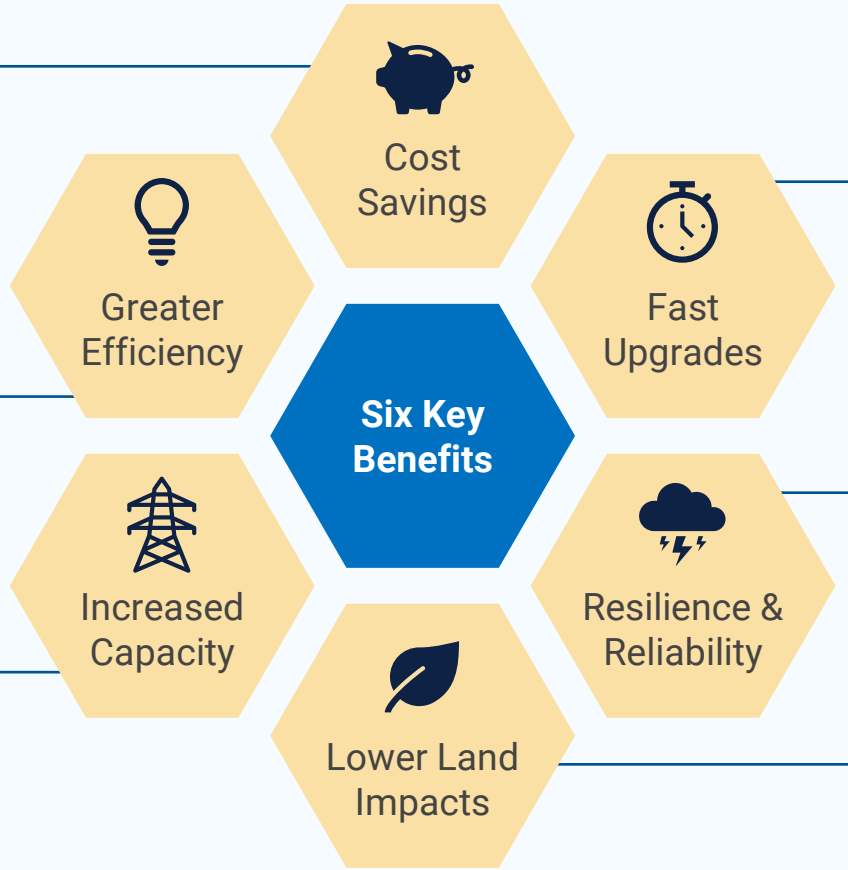
HPCs can double transmission capacity at approximately half the cost of building a new line.

GETs can increase the utilization of high-voltage 345 kV lines by 15-22%.

HPCs reduce energy losses by at least 20-40% for Composite / Carbon Core Conductors, and up to 80% for superconductors

GETs can increase the power transfer capacity of existing transmission lines by 20%+ on average.

HPCs such as Composite / Carbon Core Conductors double transmission capacity, while superconductors can quintuple capacity.



GETs can double the capacity of new generation integrated into the existing transmission grid in months.

HPCs can use existing rights-of-ways and towers, reducing permitting and construction times.

GETs can give operators new tools to manage reliability by unlocking the grid's dynamic capabilities.

HPCs can decrease wildfire risk by reducing line sagging compared to traditional conductors.

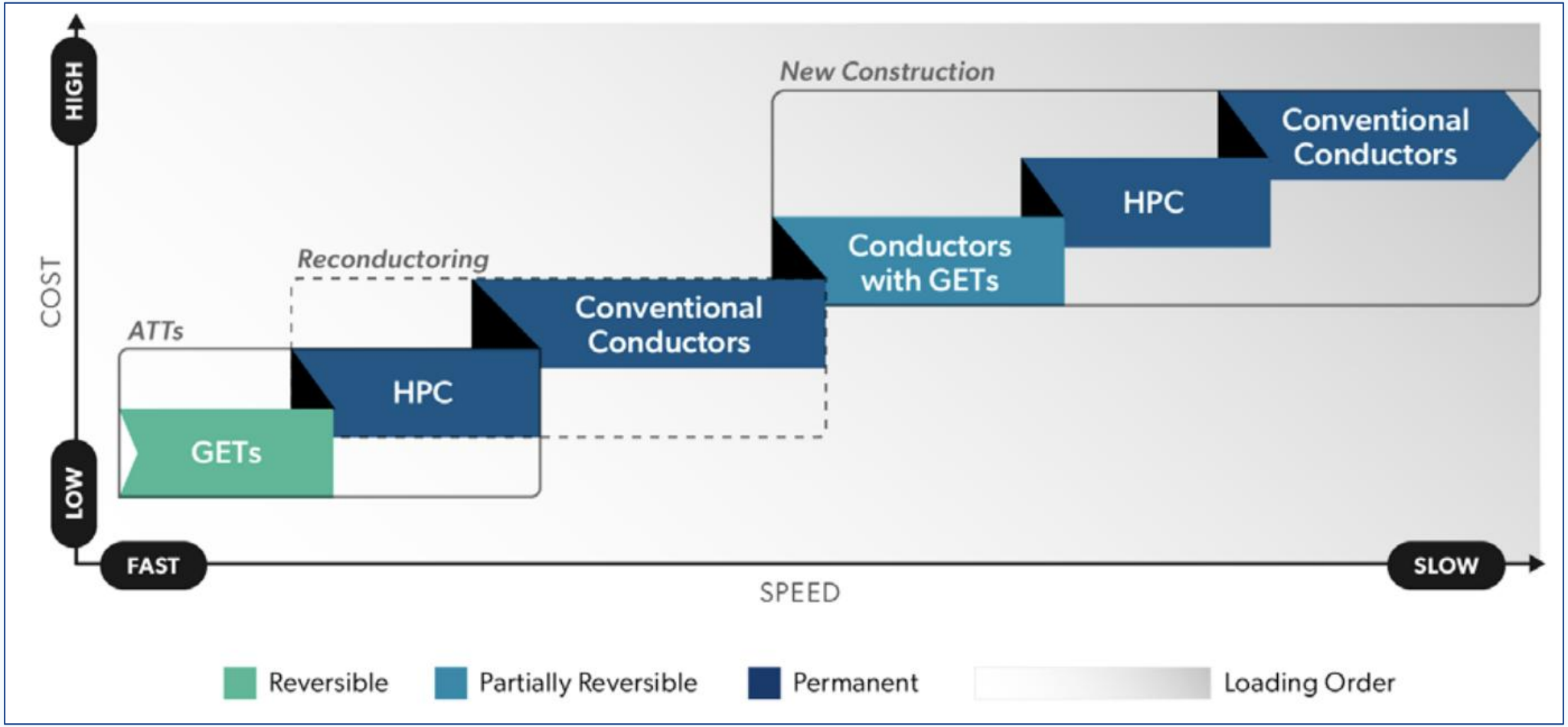
GETs can defer the need for construction of new transmission infrastructure.

HPCs can expand transmission capacity using existing rights-of-way.

See more in Section 4

Transmission Loading Order – Test ATTs Solutions First

The Brattle Group and Grid Strategies proposed a framework for transmission planning for efficiently increasing grid capacity, oriented towards minimizing costs, maximizing benefits, and accelerating capacity additions.



GridStrategies

Source | Tsuchida, B., Bai, L., Tang, S.Z., and Caspary, J., Incorporating GETs and HPCs into Transmission Planning Under FERC Order 1920, April 2025

Barriers to ATTs adoption

1. Utility Business Models

Grid users benefit from ATTs through the savings associated with more efficient operations, but the utility is not often exposed to grid congestion costs or fuel costs, for instance. Rate-regulated U.S. utilities earn a return on the capital they invest in the grid, recovered through rates. Because ATTs lower total capital expenses by making better use of the existing grid, utilities do not have a direct incentive to seek applications of ATTs or to use them to resolve grid constraints. While the savings that ATTs can unlock are real, those savings accrue to parties other than the one deciding whether to pursue them.

Alternative incentive models exist internationally. Regulators in Great Britain and Australia, for example, set utilities' allowed spending for future multi-year periods, then let the utility keep a share of whatever it does not spend. Great Britain sets aside separate, additional funding for network innovation, which enables utilities to test new transmission technologies without having to justify them as capital projects.

2. Engineering Mandates

While RTOs/ISOs and utilities are moving towards multi-value transmission planning, the majority of grid investment is still based on reliability needs. Reliability projects are straightforward to justify based on mandatory North American Electric Reliability Corporation standards, as well as an understanding from regulators and the public that keeping the lights on is critical.

Because failure to meet reliability standards carries severe consequences, engineers often default to familiar upgrades rather than newer solutions. Unless regulators or executives explicitly require consideration of alternatives and enhancements, engineers treat new technologies as discretionary risk and are rarely empowered to investigate the potential benefits of innovation without a clear business case (see Barrier 1).

3. Utility Planning Tools

To unlock all the benefits of ATTs, the technologies must be represented in planning models, operational tools, and market software. These legacy tools are a particular obstacle for GETs, because they assume the grid's capabilities are static, and were not built to represent the flexibility that GETs provide.

Further, valuing the benefit of a flexible grid requires planning based on a comprehensive analysis of future needs, including consideration of all hours of the year, contingency conditions, and an investigation of specific stress events. Current grid planning is based on only a few snapshots of the study year–often focused on peak demand hour–missing much of the value GETs provide.

GETs in the grid modeling paradigm:

Why we should fit a square peg in a round hole for long-term planning, and looking beyond

Industry planners are frequently skeptical of the role GETs can play in planning, assuming the only value comes in operational flexibility and not planning. This is due in large part to the omission of flexibility in planning models and the evaluation tools used in planning processes. Power system planning processes still privilege large, inflexible infrastructure investments, leaving planners stuck applying 20th century solutions to 21st century grid needs.

Long-term reliability planning in the previous era was comparatively simple, driven by large, centralized, thermal generators and shorter span transmission lines. Now, with a robust transmission network built over 150 years and more distributed and inverter-based generation, planning is more difficult. New software and hardware strategies which introduce operational flexibility (e.g. GETs, but also virtual power plants, storage as transmission, etc.) have huge value. However, if these tools are omitted from planning, then they will not be deployed.

GETs have value in long-term planning, but their benefits are often lost in the built-in uncertainty of long-term planning. Planning models that look out twenty years are making such large investment decisions that the 10-20% capacity additions of many GETs may seem insignificant. Long-term planning tools also often fail to represent real-time operating conditions, and the value of flexible solutions that GETs provide are lost in the noise.

The heuristics for modeling ATTs presented in Section 4 fit the square peg of GETs into the round hole of today's long-term planning paradigm. It is important that planning engineers look for where ATTs can resolve constraints that show up in planning models faster and at a lower cost than traditional, greenfield solutions. However, even full integration of GETs into long-term planning may leave their operational value on the table. Near-term planning and intervention is where GETs will shine brightest.

The most obvious application for flexible GETs is in mitigating constraints that emerge in near-term horizons. For this application, utilities will need to create new processes for congestion management, outage mitigation, and optimizing operational headroom or utilization. While all ATTs have applications in long-term planning, the speed-to-capacity value offered by GETs cannot be adequately valued in long-term planning alone.

Recent innovations in planning processes

SPP has initiated a process to increase capacity in the one-to-three-year timeframe, initially based on upgrades that will be funded and proposed by grid customers and users, and is standing up a grid reconfiguration request process.

In 2026, the Southwest Power Pool (SPP) proposed a process to study grid upgrades for generator and load deployment on a faster timeline than their regulated regional transmission planning process allows. Grid users would be able to request studies for upgrades and pay a flat fee for the study to be completed by SPP. The grid user could then "sponsor" the upgrade, paying its full cost. SPP could also initiate their own intermediate planning studies, and those projects could be regionally cost-allocated.

SPP has already followed MISO's lead on economic grid reconfiguration, or transmission topology optimization (TTO). Switching operations identified with TTO can often save millions of dollars of energy costs in the market. MISO's process to allow customers to request grid reconfigurations saved more than $100 million in 2026. SPP's tariff revision to enable this process was approved by FERC in August 2026.

These processes are steps towards full near-term grid planning, which will have significant benefits for electricity costs and grid reliability.

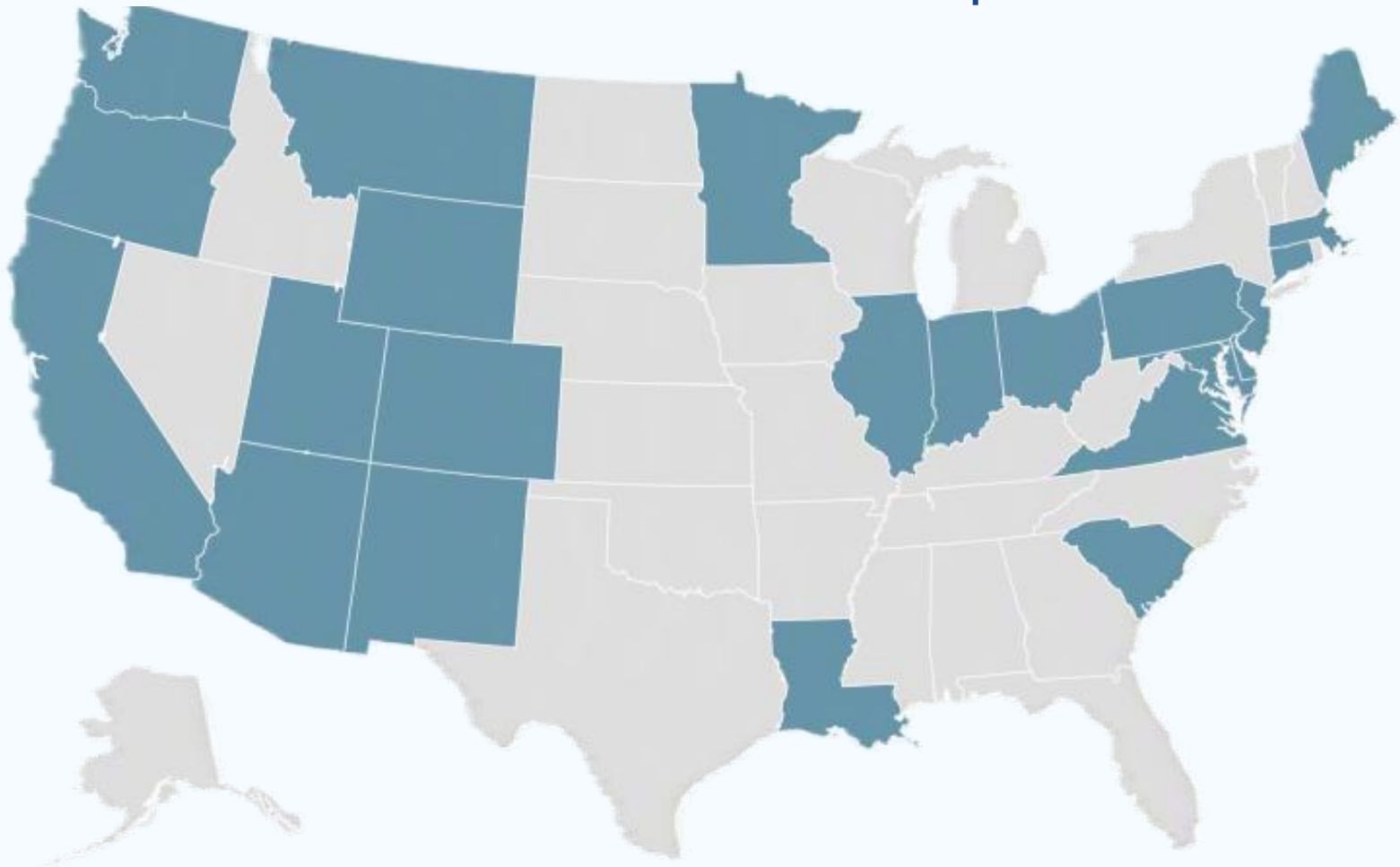
Sources | Southwest Power Pool Revision Request 798, Intermediate Planning, July 22, 2026, and Letter order accepting Southwest Power Pool, Inc.'s 05/21/2026 filing of revisions to Attachment AE of its Open Access Transmission Tariff etc. under ER26-2592, FERC Notational Order August 19, 2026

State and federal policy focuses on long-term grid planning

23 states have passed laws pertaining to ATTs

State laws often require ATT analysis in integrated resource plans, rate cases, or transmission plans. Some require alternatives or enhancement analysis in applications for transmission siting. Others have tasked the utility or state agencies with standalone studies of available GETs and applications as remedies to grid congestion. California, Minnesota, Maine, and Ohio have published such studies.

States with ATT laws as of September 2026



Further Reading | World Resources Institute, US State Legislation on Advanced Transmission Technologies, August 2026

Regulatory landscape

Federal rules increasingly require planners to evaluate ATTs and model them credibly.

Order No. 2023 (2023)

- Found that "alternative transmission technologies" can provide substantial benefits due to their quick deployment and lower costs compared to other types of network upgrades
- Requires transmission providers to consider technologies including advanced power flow control (APFC) devices and advanced conductors, while transmission switching and dynamic line ratings (DLR) are optional.

Order No. 1920 (2024)

- Found that existing planning processes don't adequately weigh the full benefits of transmission options, so cost-effective solutions get passed over.
- Requires transmission providers to consider DLR, APFC devices, advanced conductors, and transmission switching in long-term regional planning, though no adoption is mandated.
- The first long-term planning cycles begin in 2025–2026.

Large Load Show Cause Orders (2026)

- FERC directs each RTO to evaluate alternative transmission technologies as potential solutions before defaulting to network upgrades, and to explain in the study report why they are not used. *See slide 18.*
- RTO responses are due November 16 or 20, 2026, and public comment is due December 16 or 20, 2026.

Sources | FERC Order No. 1920-A, 89 FR 97174 (2024), ¶¶ 47, 51; FERC Order No. 1920, Docket RM21-17 (2024), ¶ 26; FERC large-load show cause orders, June 18, 2026: PJM Interconnection, L.L.C., 195 FERC ¶ 61,211 (2026), Dockets EL26-67 through EL26-72.

FERC orders to show cause seek clarity on use of ATT modeling in transmission planning processes

In June 2026, FERC issued an Order to Show Cause to each RTO/ISO requiring an explanation on whether their regulated Tariffs remain just and reasonable without provisions that:

1) *require the evaluation of alternative transmission technologies in transmission service request studies, **using models capable of evaluating the transmission system to accurately account for alternative transmission technologies**, in all instances, without the need for a request from the Eligible Customer seeking transmission service on behalf of a large load; and*
2) *if traditional network upgrades are selected instead of alternative transmission technologies, inclusion in the study report to the Eligible Customer seeking transmission service on behalf of a large load of a **sufficiently clear demonstration of why alternative transmission technologies are not feasible** (i.e., would not resolve reliability violations identified or meet the relevant planning criteria) or would not result in lower costs or a faster timeline for accommodating the transmission service request; or propose Tariff revisions establishing such provisions.*

   *This transparency and informational requirement is warranted for the regulatory scheme we are establishing for transmission service requests by Eligible Customers on behalf of large loads given demand from and the expedited development timelines for large load customers.**

See the Appendix for concurrences from Commissioners seeking accountability on ATTs modeling and a letter from Commissioner Rosner seeking examples of models that can accurately represent ATTs.

Sources | FERC large-load show cause orders, June 18, 2026: Dockets EL26-67 through EL26-72.
*Line breaks added for emphasis

Section 2.
Power Systems Modeling Software Capabilities



Section 2. Table of Contents

a. Industry power system modeling software considered
b. Interpreting ATTs modeling capabilities
c. Modeling representations and capabilities
    i. High Performance Conductors
    ii. Transmission Topology Optimization
    iii. Advanced Power Flow Control
    iv. Dynamic Line Ratings

Disclaimer

Findings in this section are based on a review of public resources about the capabilities of commercially available software, as well as meetings and exchanges with representatives of the software owners. Where software owners could not be reached to confirm our findings, we made our best judgement based on publicly available information.

Software updates are made frequently, and recent updates may not be captured. This represents our best understanding of software capabilities as of Fall 2026.

These findings are not necessarily endorsed by any referenced software owner or vendor.

More information on each modeling tool and its capabilities can be found here:
ATT Modeling Capability Matrix

Industry power system modeling software considered

Graphical summary of the modeling capabilities of different software tools. A partially filled circle indicates that similar capabilities exist, even if the software tool is not designed to fully perform the modeling function.

	Software Tool	Owner	CEM	PCM	PF
Integrated Modeling	**EnCompass**	Anchor Power Solutions/Yes Energy	●	●	◑
	PlanOS (MAPS, MARS, etc.)	GE Vernova	●	●	●
	PLEXOS	Energy Exemplar	●	●	◑
	PSO	Polaris Systems Optimization	●	●	◑
	SAInt	encoord	●	●	●
Production Cost	**GridView**	Hitachi Energy	○	●	○
	PROBE	PowerGEM	○	●	○
	PROMOD	Hitachi Energy	○	●	○
Power Flow	**FAST**	Electric Power Engineers	○	●	⊛
	FUSION-T	GridAstra	◑	○	●
	Gridscale X PSS/E	Siemens	○	○	●
	Piq	Piq Energy	○	○	⊛
	PowerWorld Simulator	PowerWorld Corp.	○	◑	●
	PSLF (standalone from PlanOS)	GE Vernova	○	○	●
	SUGAR	Pearl Street Technologies/Enverus	○	○	⊛
	TARA	PowerGEM	○	○	●

Note | ⊛ Indicates an automated platform that is integrated with power flow modeling

Interpreting ATTs modeling capabilities

ATT Representation. We use three classifications to designate if a software tool can adequately model the various technologies in the underlying power flow equations:

- **Full** means the technology is represented explicitly in the tool.
- **Partial** means some of the ATT's capability is present in the tool but not all of it.
- **Limited** means the technology is either mostly or fully absent from the tool.

ATT Optimization. We use two classifications to capture if a software tool can optimize use of the technology:

- **Settings Optimized** means the software tool can select the appropriate technological setting to overcome the presented violation (for example, choosing the correct phase angle to correct over-voltage at a bus).
- **Cost Optimized** means the software tool will select the use of that technology against another competing technology that is more expensive. "Cost Optimized" is most relevant for capacity expansion tools that select the least expensive suite of generation and transmission solutions, but there are some production cost and power flow applications where one technology could be compared against a suite of others to recommend the cost-optimal way to resolve a violation.

HIGH PERFORMANCE CONDUCTORS

Modeling representation and capabilities

Limited

Representation in Model: Full, explicit Partial

Technology Included

EnCompass | GridView | PlanOS | PowerWorld | PROBE | PROMOD | PSLF | PSS/E | SAInt | SUGAR | TARA

FULL, EXPLICIT

Several software tools include HPCs in native conductor libraries. Others can calculate needed electrical parameters from basic user-provided information.

PARTIAL

Only consider thermal limits and percentage losses of conductors.

Settings Optimized

CAPABILTY PROVIDED

Software tool will determine which type of conductor is needed to resolve the violation.

LIMITATION

Out-of-model scripts can be used to find the optimal conductor parameters, but they are not optimized natively.

Cost Optimized

FAST | FUSION-T | Piq Energy | PLEXOS | PSO

CAPABILITY PROVIDED

Reconductoring with HPCs is compared against other alternative solutions to resolve violations at least cost.

LIMITATION

Modeling tricks may be required to compare reconductoring against a new line build, but this can be done natively.

TRANSMISSION TOPOLOGY OPTIMIZATION

Modeling representation and capabilities

Limited: EnCompass, FAST, Piq Energy, PROBE

Representation in Model: Full, explicit | Partial | Full, with TTO software*

Technology Included

FUSION-T, GridView, SAInt, SUGAR

FULL, EXPLICIT

Model can select different topologies during a single model run by switching transmission branches on or off at different times.

PARTIAL

Workarounds exist within the tool to test a subset of possible topologies within a model run, but an out-of-model script is still needed to implement.

Settings Optimized

TARA

CAPABILTY PROVIDED

Optimal transmission settings can be determined in a chronological time-series to determine if TTO is an applicable semi-permanent solution to the violation.

LIMITATION

Out-of-model looping scripts can be used to find the optimal transmission settings for some models, but they are not optimized natively.

Cost Optimized

PSO

CAPABILITY PROVIDED

Transmission topology optimization is compared against other alternative solutions to resolve violations at least cost.

LIMITATION

Some tools only consider production cost savings as a result of TTO, rather than least cost capacity expansion mixes.

Enabled only with additional TTO Software*

PowerWorld, PSLF, PSS/E, PlanOS, PLEXOS, PROMOD

Notes All tools can model a transmission line as being in or out of service, but only a few explicitly search for the optimal combination of transmission on/off settings that would resolve a given violation. *Some tools can be paired with additional TTO software (e.g., NewGrid Router) to model topology optimization.

ADVANCED POWER FLOW CONTROL

Modeling representation and capabilities

Representation in Model: Full, explicit Partial

Limited

SAInt

Technology Included

PlanOS | PSLF | PSS/E | SUGAR | TARA

FULL, EXPLICIT

Tool represents the characteristics of at least one APFC device. If explicit device classes are missing, the tool must be able to vary both phase angles and impedances.

PARTIAL

Tool can only model either phase angles or impedances. As a proxy, APFCs can be represented as either a phase shifting transformer or a phase angle regulator.

Settings Optimized

EnCompass | GridView | PowerWorld | PROBE | PSO

CAPABILTY PROVIDED

The device settings can be directly optimized by the tool to resolve the given violation. This can occur as an hourly dispatch or load-flow control loop.

LIMITATION

Out-of-model scripts can be used to find the optimal device settings. Free movement of settings without explicit representation may overstate flexibility.

Cost Optimized

FAST | FUSION-T | Piq Energy | PLEXOS | PROMOD

CAPABILITY PROVIDED

Use of APFCs are compared against other alternative solutions to resolve violations at least cost.

LIMITATION

Some tools only consider production cost savings as a result of APFC, rather than least cost capacity expansion mixes.

DYNAMIC LINE RATINGS

Modeling representation and capabilities

Representation in Model: Full, explicit Partial

Limited

FAST Piq Energy PlanOS

Technology Included

EnCompass GridView

PLEXOS PowerWorld PROBE

PROMOD PSLF PSO

PSS/E* SUGAR TARA

FULL, EXPLICIT

Tool accepts hourly or sub-hourly weather data and weather-to-rating relationships and computes the resulting electrical ratings for conductors directly.

PARTIAL

Tool can accept hourly or sub-hourly user-defined conductor ratings that differ from the default, but they must be calculated out-of-model using weather data.

Settings Optimized

SAInt

CAPABILTY PROVIDED

Tool will identify if dynamic line rating causes violations on neighboring components and notify user.

LIMITATION

Decision to use dynamic line ratings or other rating is not provided, only if violations result from DLR use.

Cost Optimized

FUSION-T

CAPABILITY PROVIDED

Use of dynamic line ratings are compared against other alternative solutions to resolve violations at least cost.

LIMITATION

No tool considers both production cost and capacity expansion savings from DLR.

Notes *Gridscale X PSS/E can be integrated with separate Gridscale X DLR software to fully represent dynamic line ratings.

Section 3.
Power System Modeling



GridStrategies

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Different modeling techniques and tools are used for different purposes in grid planning. This section explains these differences and the tradeoffs of different approaches.

a. Types of power system modeling – what, how and why
   i. Capacity Expansion Modeling (CEM)
   ii. Resource Adequacy Modeling (RAM)
   iii. Production Cost Modeling (PCM)
   iv. Power Flow Modeling (PF)

b. Simplifying assumptions to accelerate computing
   i. Power flow equations
   ii. Compromise: trading resolution for computational efficiency

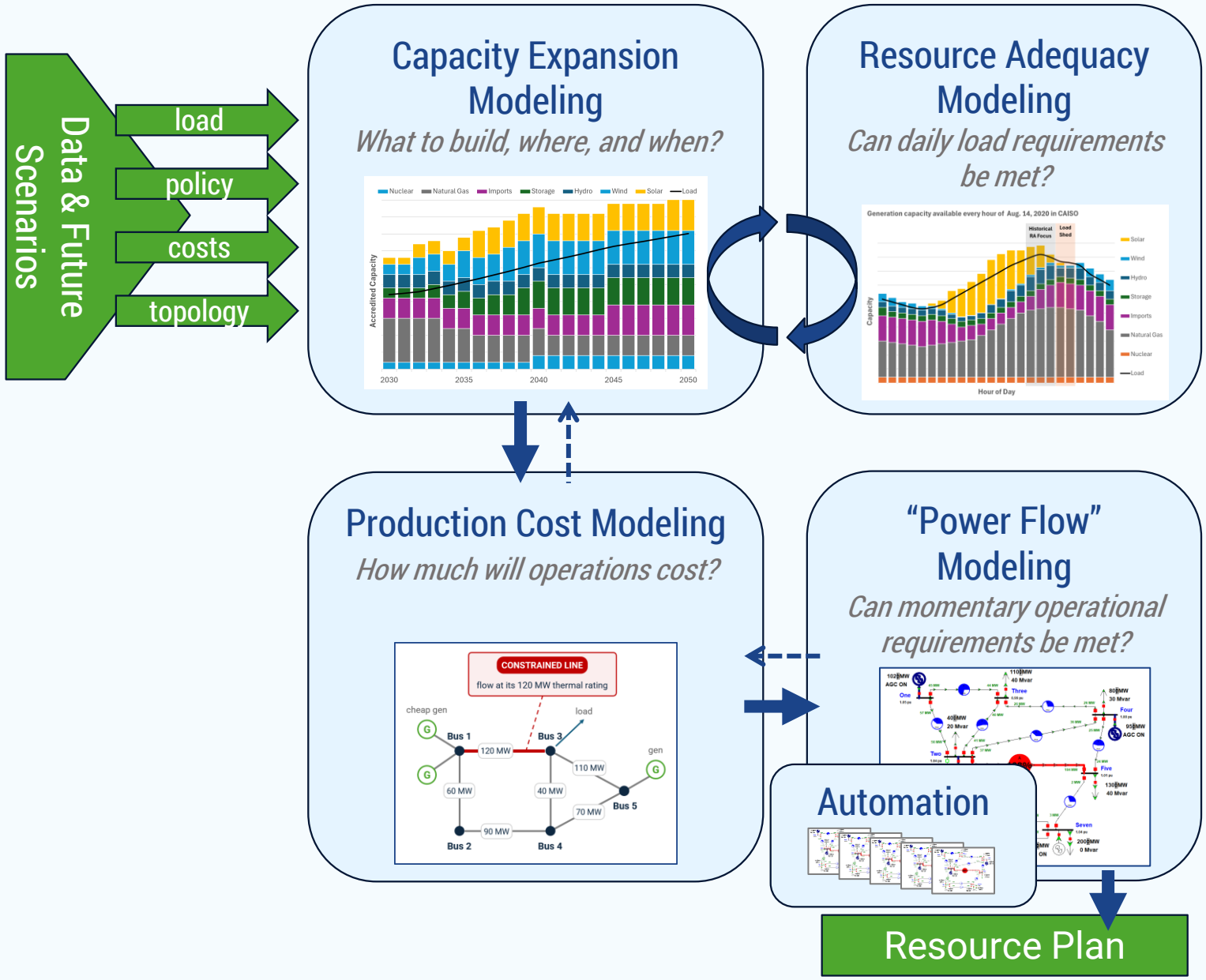
Types of power system modeling

Several steps must be taken to produce a strong integrated resource (generation and transmission) plan.

Each step requires a different *power system model*.

No single model can answer every question: They differ by time horizon, geographic resolution, and how they represent power system physics.

Software tools can be dedicated to a single power system model or integrate multiple into one tool.



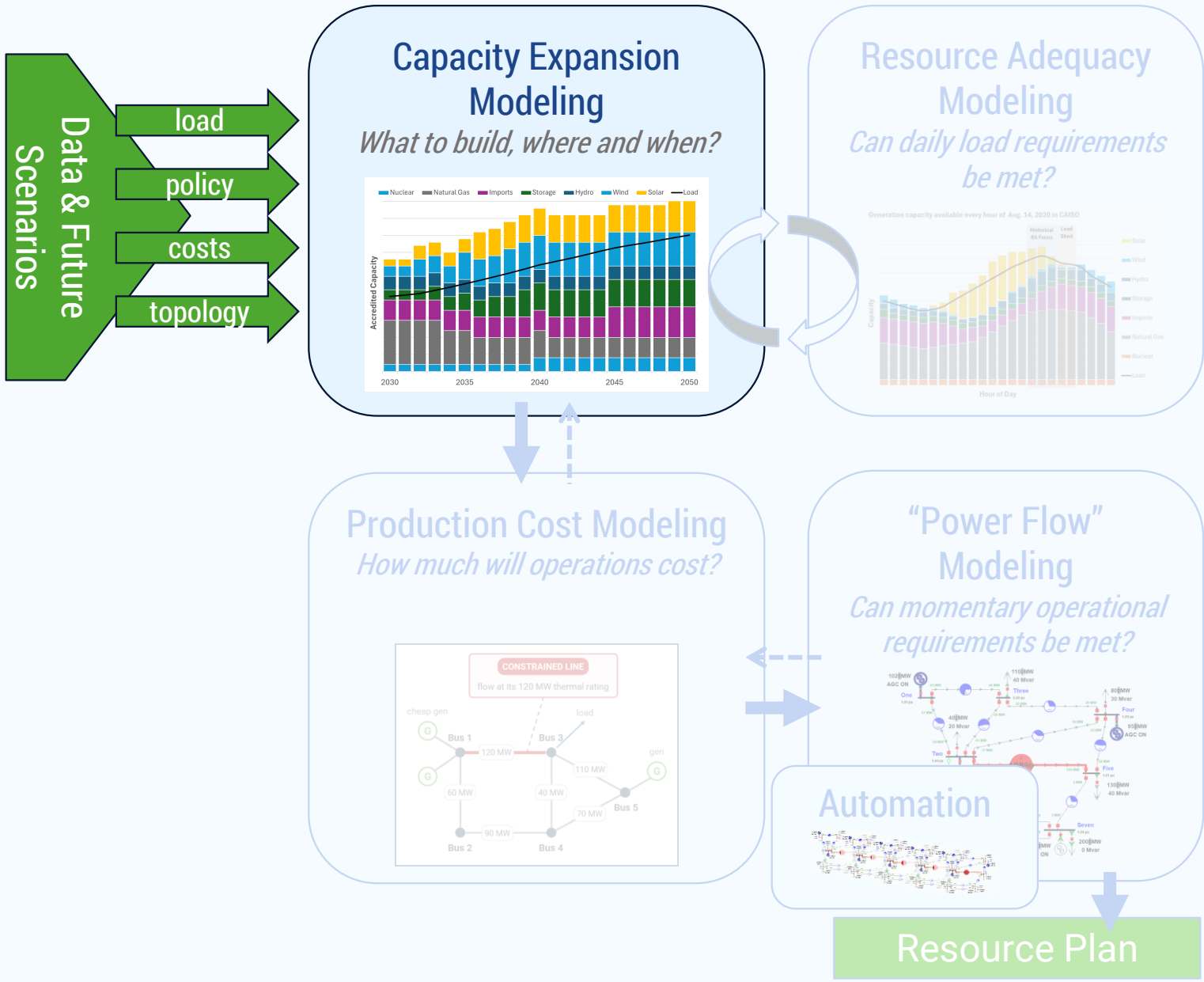
Capacity Expansion Modeling (CEM)

What to build, where, and when?

CEM chooses which resources to build to meet future annual load requirements.

CEM considers a multi-decade horizon given relevant data and assumptions about the future.

Co-optimization between all resource options (generation, storage, transmission) captures important trade-offs to find the lowest-cost combination of resources that sequential, siloed planning can miss.



Capacity Expansion Modeling (CEM)

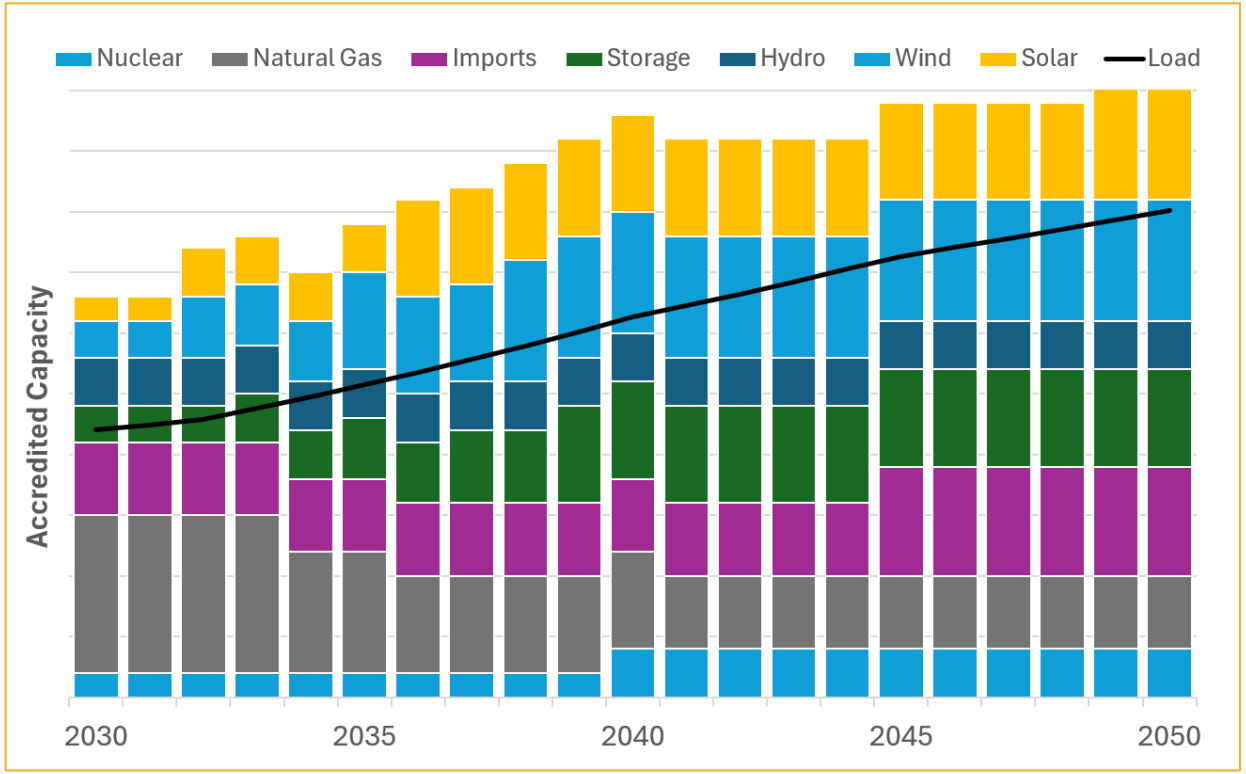
What to build, where, and when: determining the least-cost resource portfolio over numerous years.

Determines the least-cost mix and location of future generation and storage over 20+ years.

- Transmission may be co-optimized, fixed as zonal transfer limits, or omitted, depending on the model.
- Uses: IRPs, policy scenarios, long-range transmission screening.

Simplifications for computational tractability:

- Temporal: use representative time periods rather than every hour or 5-mins a full year.
- Geographic: reduce network detail to zonal or copper-plate (not recommended).
- Limitation: Temporal and/or geographic simplifications mean hourly and/or line-level impacts are checked in PCM and PF, not CEM, which necessitate more modeling iterations.

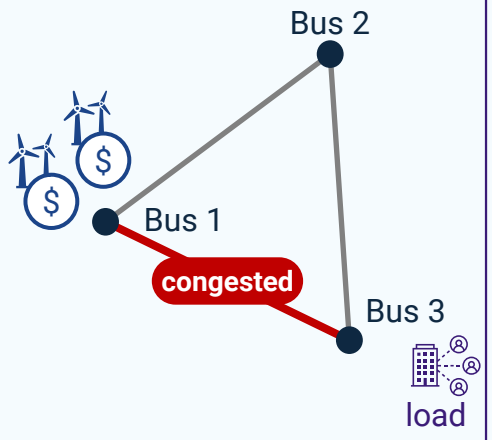


Co-optimized Capacity Expansion Modeling (CEM)

Co-optimization yields the least-cost combination of generation and transmission solutions.

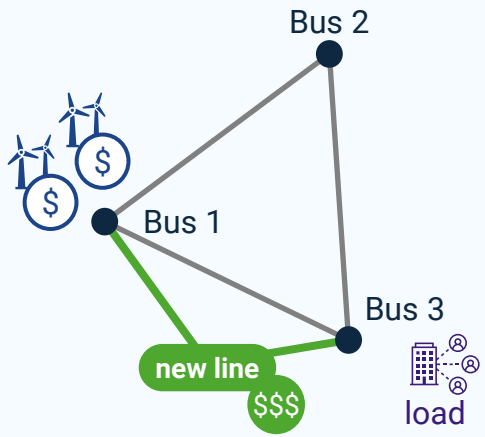
- Co-optimization considers the trade-offs of both generation and transmission to find least-cost solution.
- This differs from traditional planning which solves for generation and transmission in siloed processes, often yielding more expensive solutions.

PROBLEM TO RESOLVE



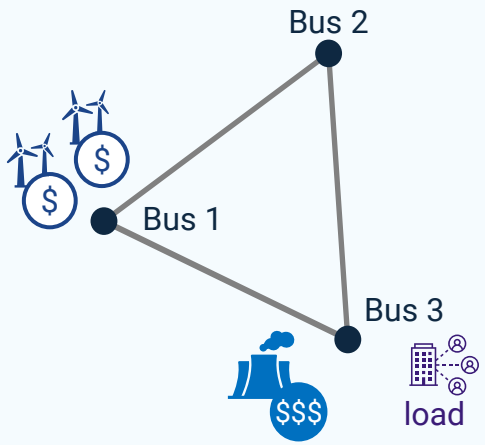
Load growth causes transmission **congestion** and cannot be served.

TRANSMISSION SOLUTION



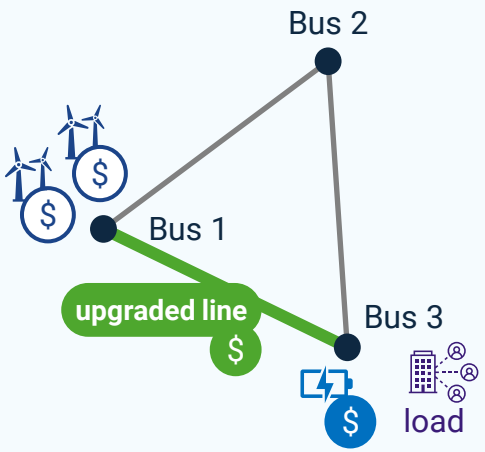
Build a **new line** so inexpensive generation can reach load.

GENERATION SOLUTION



Build a **new plant** near load to alleviate the congested line.

CO-OPTIMIZED SOLUTION



Least-cost mix: **upgrade the line** *and* build a **new, less expensive plant**.

Benefits of ATTs that can be quantified in CEM

Real power transfer increases

- Transfer limits between zones can increase
- Transfer increases calculated using temporal average. Long timespans (e.g., year) will show smaller benefits than shorter timespans

Reduce investment costs + deployment timelines

- CEM is the only tool that considers investment costs and deployment timelines of different solutions
- ATTs are lowest-cost solutions to increase transfers
- ATTs are quicker to deploy than greenfield solutions
- Benefit-to-cost analyses could show ATTs as optimal solution *if* all benefits are monetized and appropriate time horizons are considered

Compatibility with specific generation sources

- Some ATTs complement generation production of specific resources (e.g., DLR and wind)
- This compatibility can only be demonstrated in co-optimized CEM with hourly temporal resolution

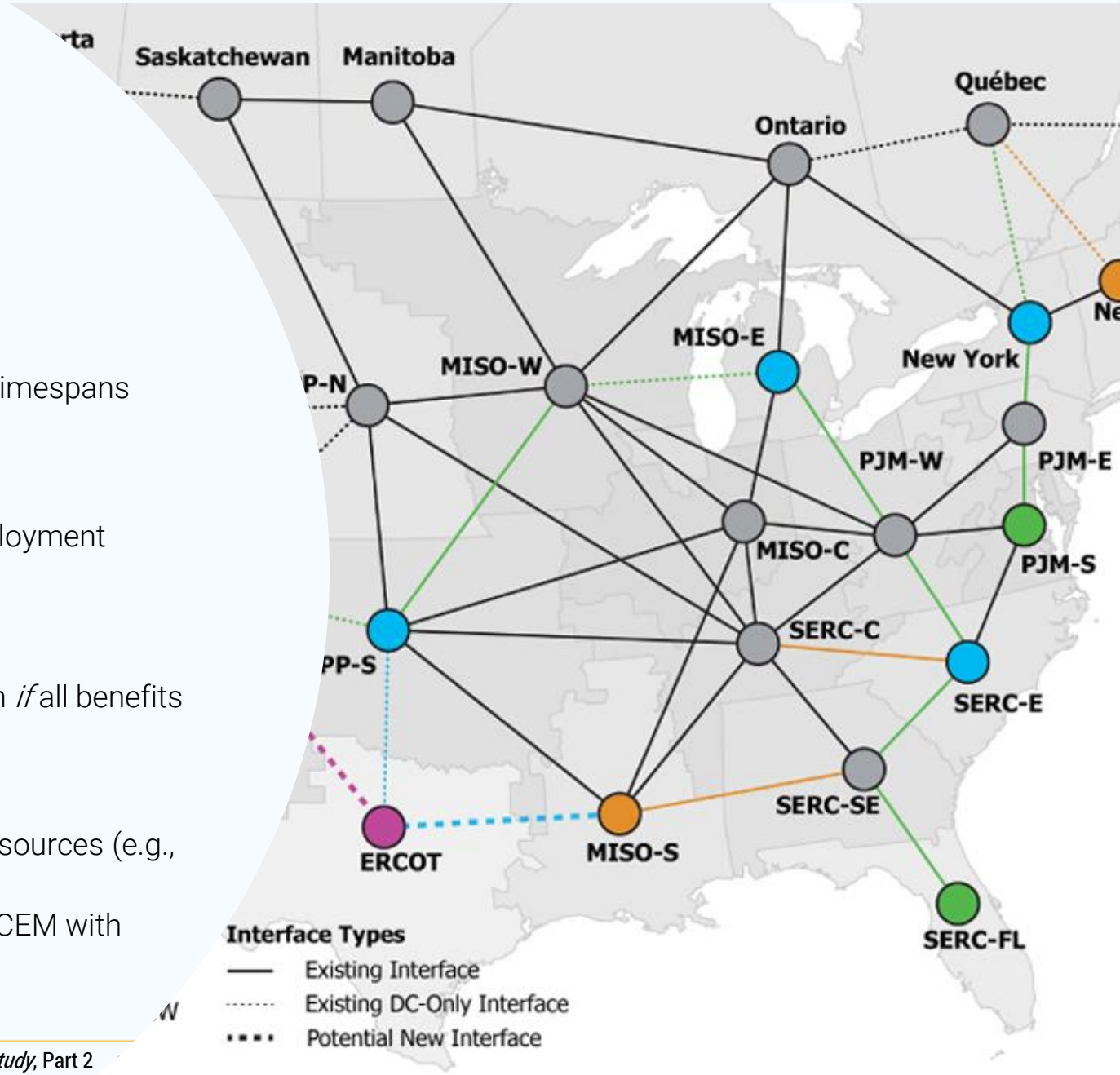


Image source | NERC, *Interregional Transfer Capability Study*, Part 2 (2024)

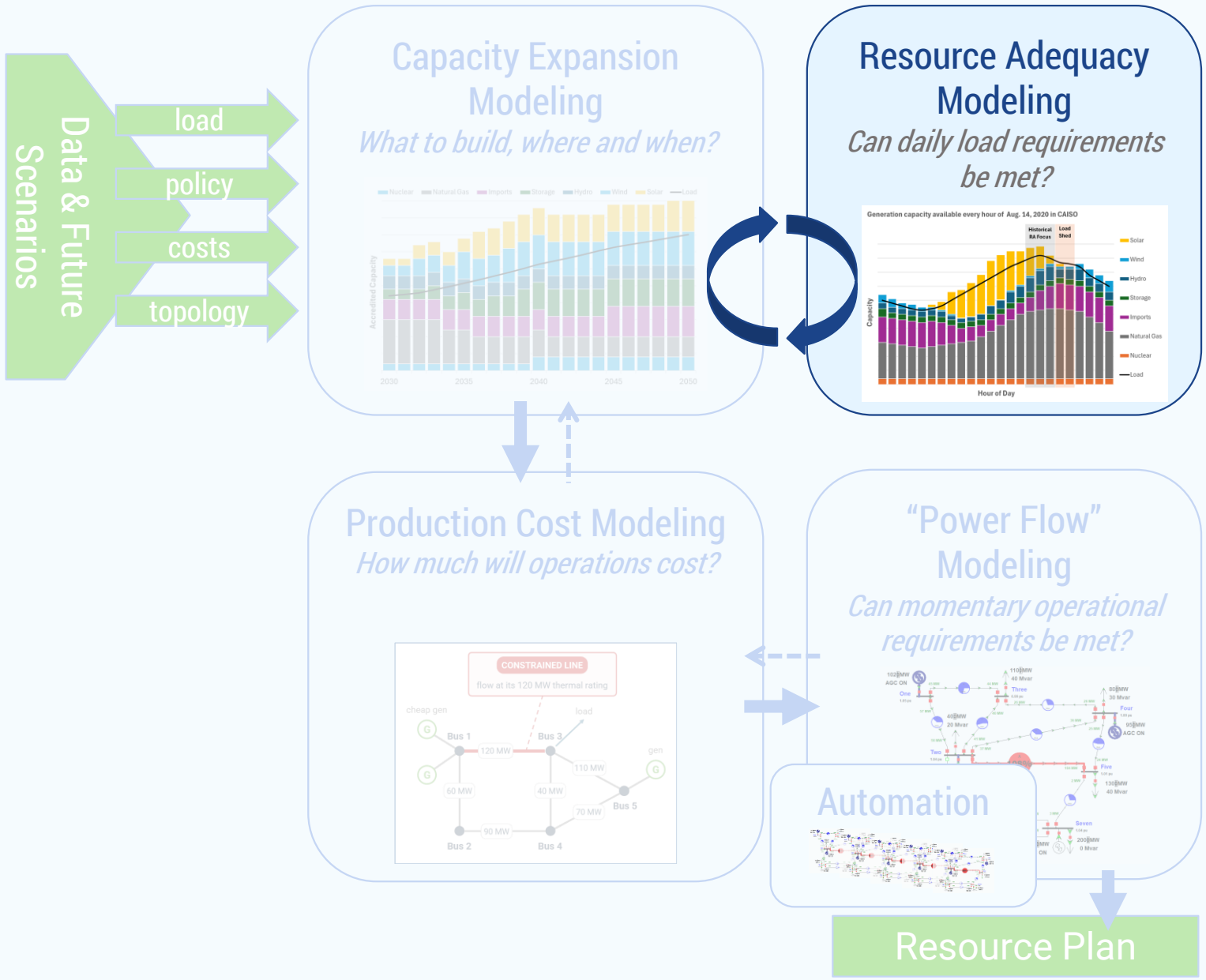
Resource Adequacy (RA) Modeling

Can daily load requirements be met?

RA modeling ensures that enough resources are available to meet hourly load requirements on the most stressful days.

This is an iterative process with CEM to ensure the enough capacity is built in each year.

"Stress" can mean peak load days, or days when resources have historically struggled to meet load, such as during winter storms.



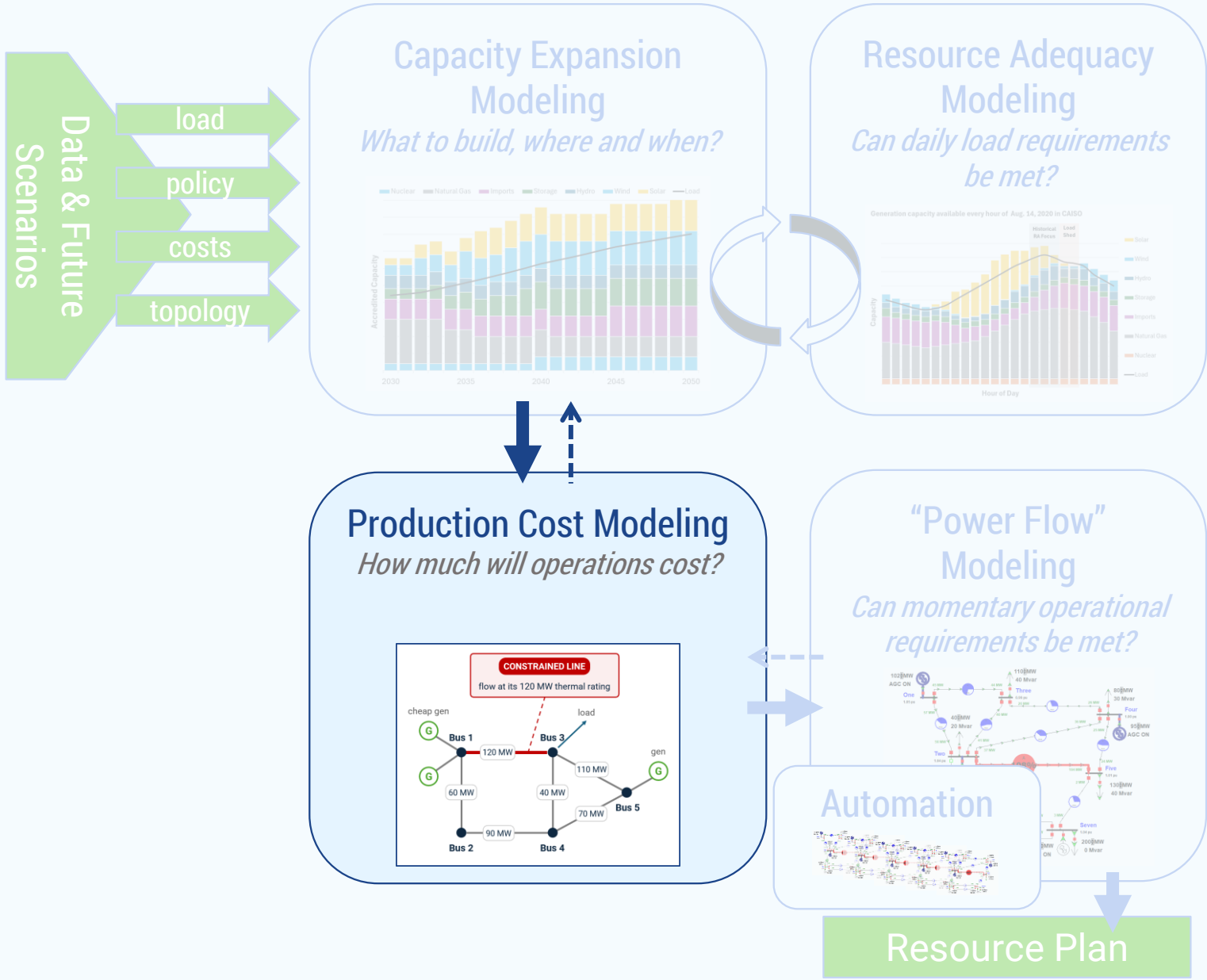
Production Cost Modeling (PCM)

How much will operations cost?

PCM will select from the capacity builds produced in CEM to find the least cost production available.

PCM simulates hourly resource operations to calculate generator dispatch, generator emissions, fuel use, and transmission congestion for a future year.

These outputs are measured in dollars to get total production costs for the modeled year.



Production Cost Modeling (PCM)

How the system is operated in every hour of a year, and at what cost.

Simulates hourly operations for a year by solving unit commitment plus economic dispatch

- Captures ramping, start-up costs, and minimum up/down times that capacity expansion omits

Models the system as AC (full power flow) or DC (linearized) depending on the model and need for speed

Outputs: hourly generation dispatch, generation emissions, generation production cost, transmission congestion, LMPs

Uses: valuing transmission upgrades and quantifying congestion, where ATT congestion-relief benefits are measured

Limitation: takes the resource mix and network as given, so it evaluates a fleet rather than choosing one

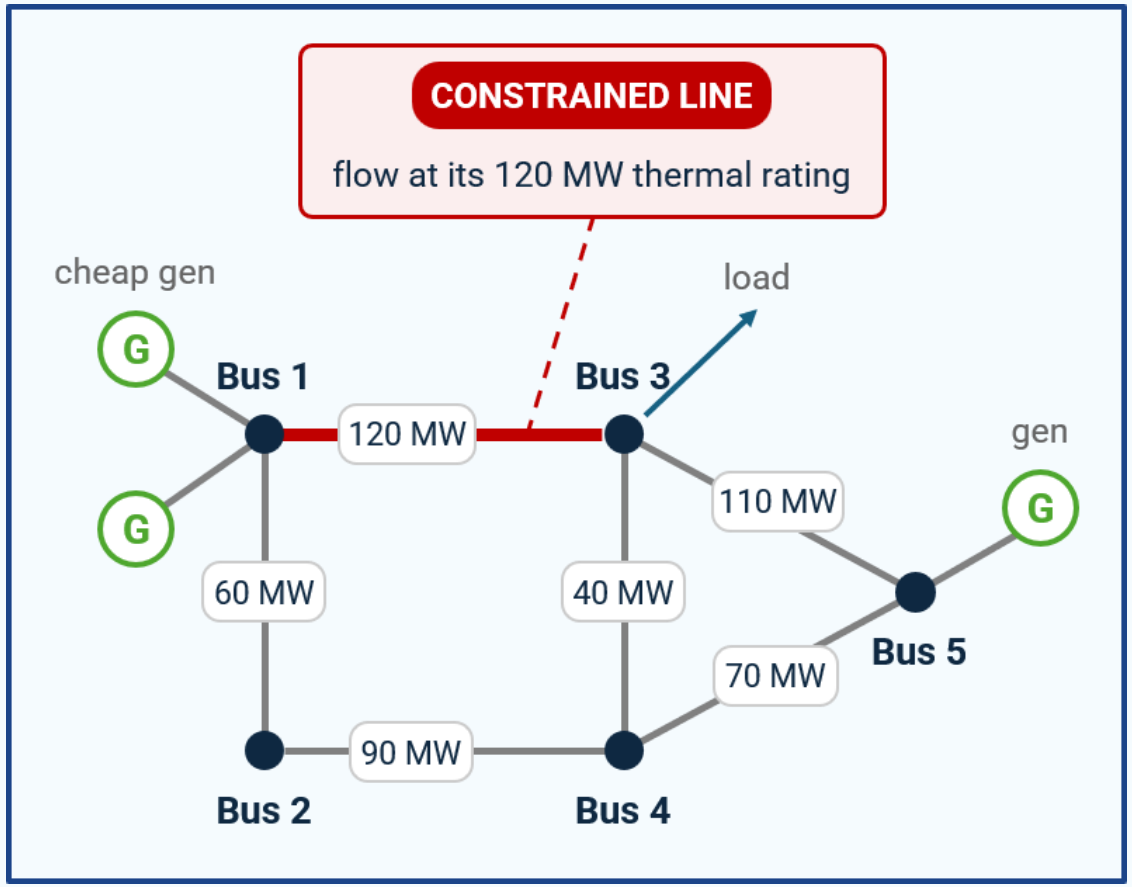


Image source | Stott, Proc. IEEE 62(7):916–929 (1974); Stott, Jardim & Alsaç, IEEE Trans. Power Syst. 24(3):1290–1300 (2009)

Benefits of ATTs that can be quantified in PCM

Real power increases

- Reduced congestion on any individual line results from additional throughput
- Sub-hourly impacts must be averaged to hourly

Line losses

- Explicit modeling of line losses can show reductions with use of advanced conductor materials
- Note that increased losses on other lines of older materials may result from increased utilization of those lines enabled by ATTs elsewhere in the system

Reduced generator production costs

- Additional capacity of lines will lead to less curtailment of lower cost generators, reducing overall system production costs

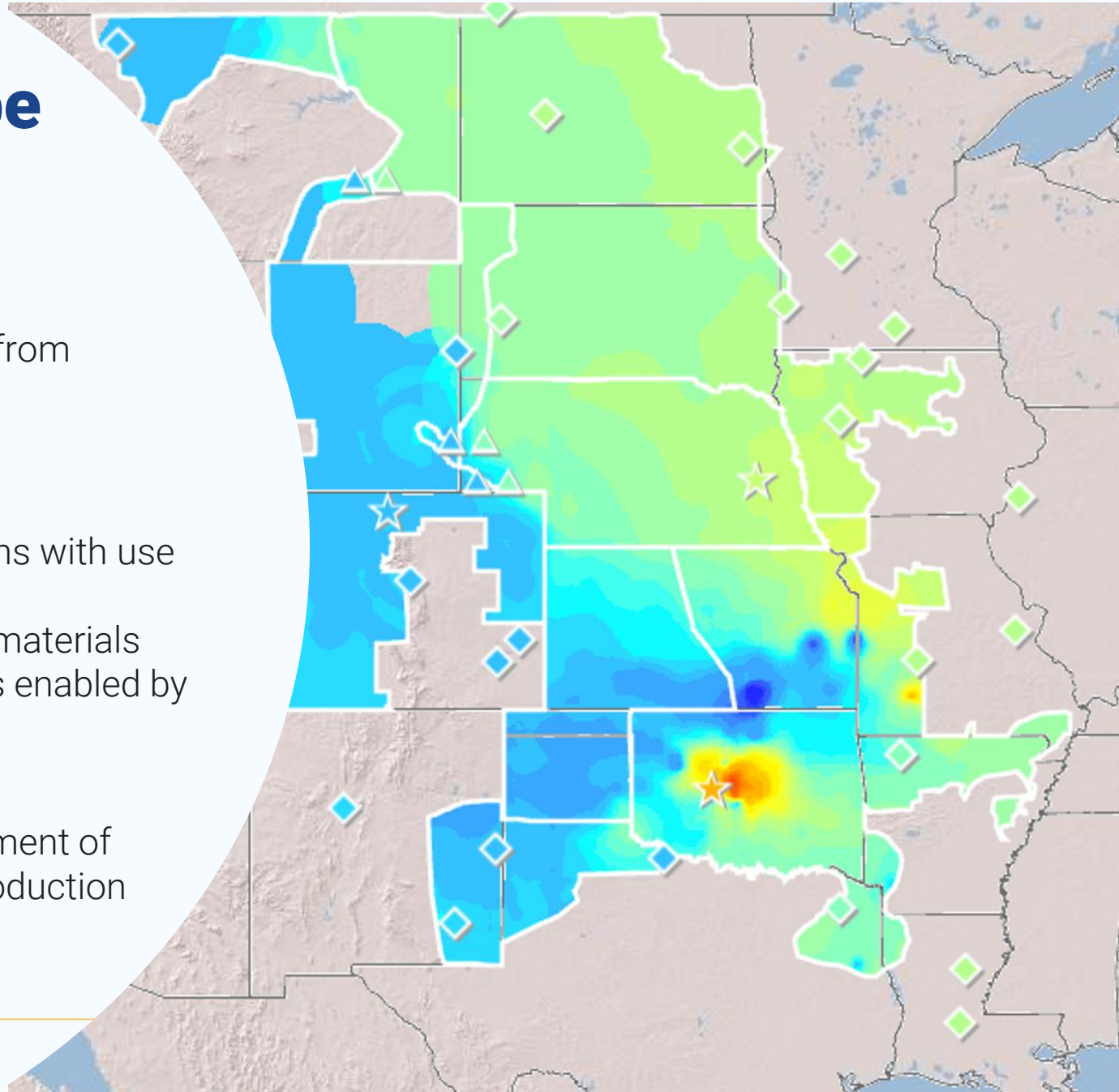


Image source | SPP *Pricing Map* August 16, 2026

Power Flow (PF) Modeling

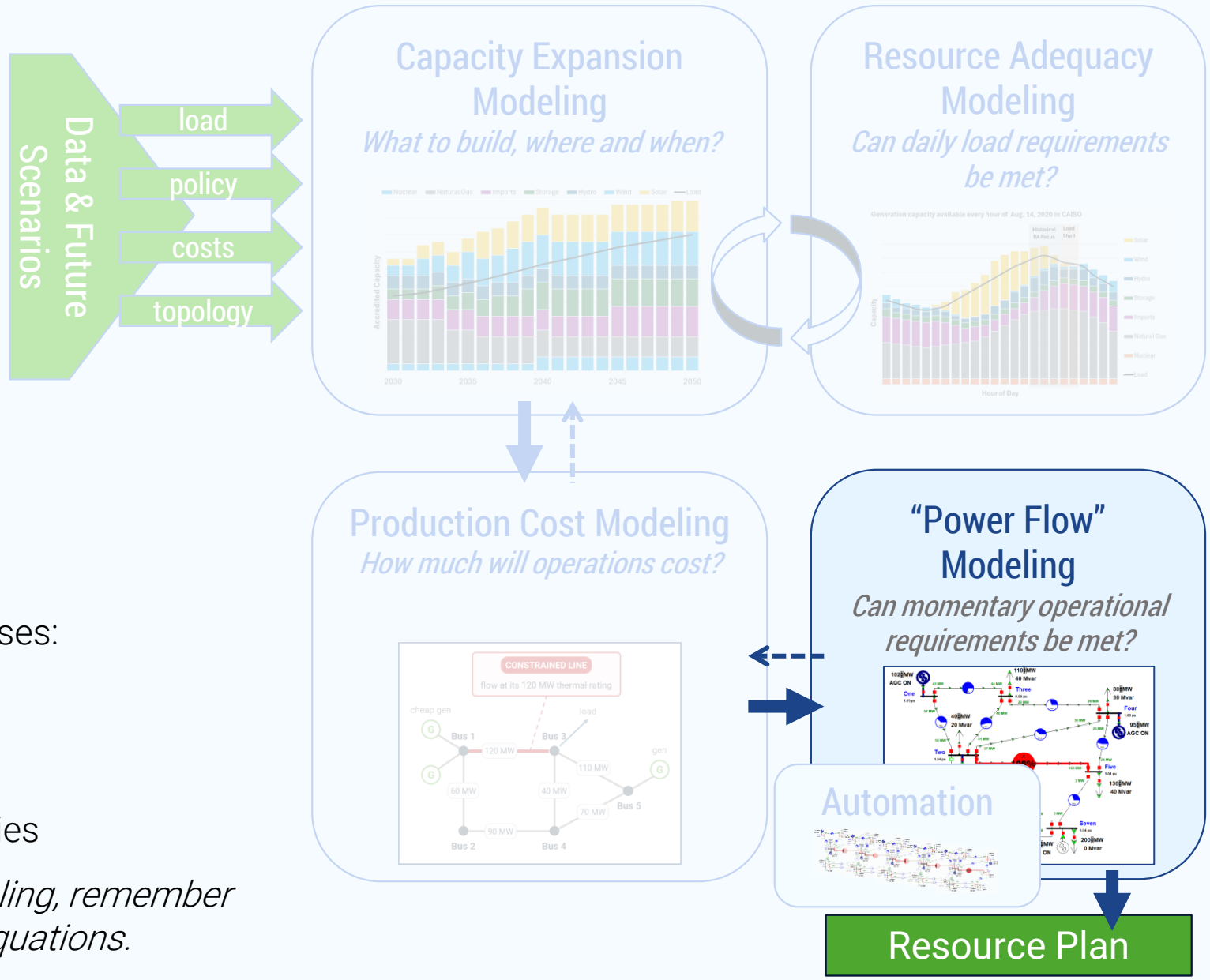
Can momentary operational requirements be met?

PF modeling solves the physical state of the network at a single snapshot, to ensure system thermal loading, voltages, and power flow angles are all within tolerable levels.

PF modeling is the basis for numerous analyses:

- Stability studies
- Reliability studies
- Contingency analysis
- Generation and load interconnection studies

While often referred to as "power flow" modeling, remember that all modeling steps use the power flow equations.

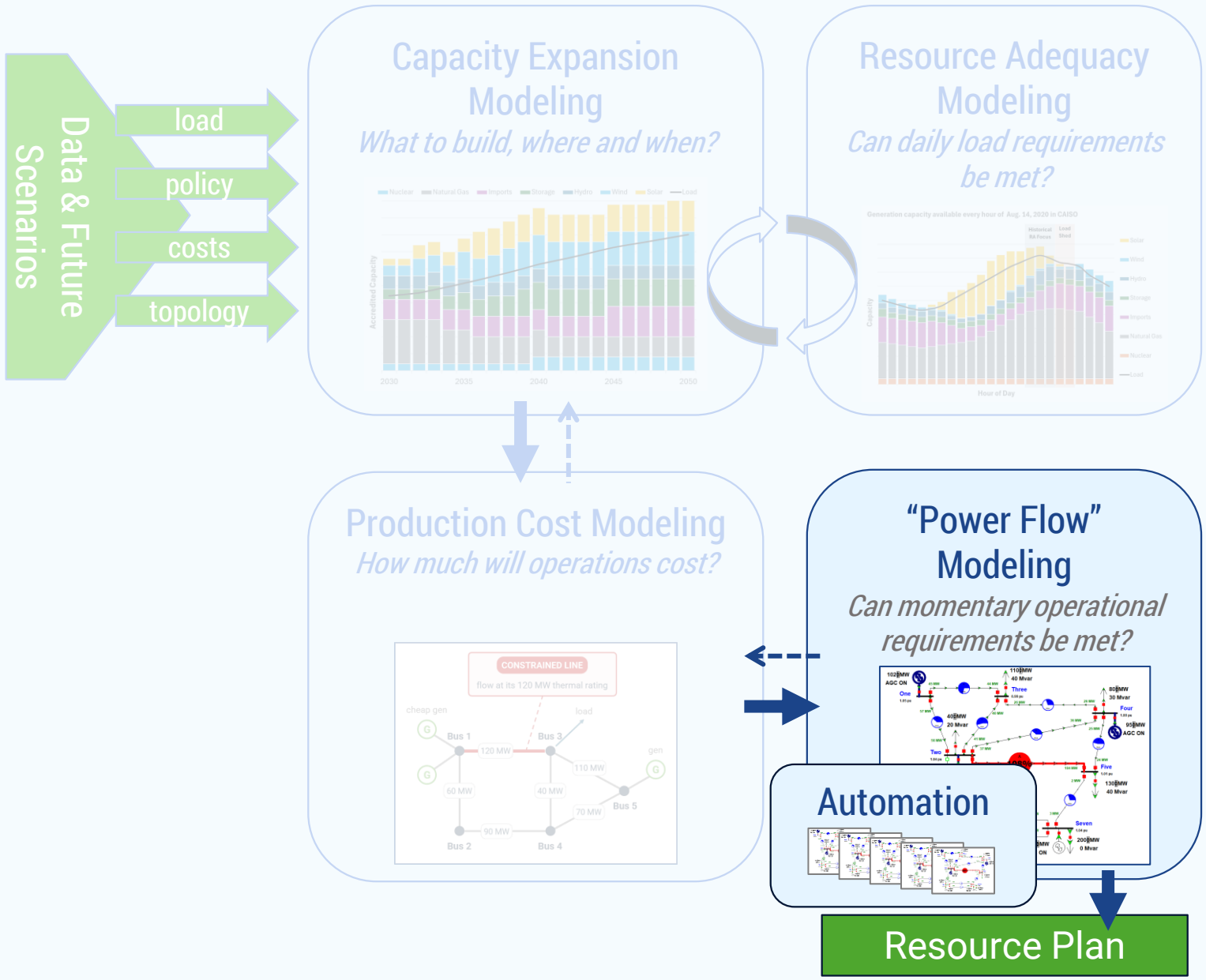


Power Flow (PF) Modeling + Automation

Automation tools are used to run several power flow models more efficiently.

These are increasingly used to perform batch generator or load interconnection studies more quickly than can be traditionally done.

These tools may or may not have a native power flow model application built-into the tool. Those that do not will instead run other power flow tools in an efficient manner.



Power Flow (PF) Modeling

Test for violations on the network given a single set of system conditions.

Solves the steady-state condition for the network at a single moment in time to look for violations at individual facilities. Requires nodal modeling.

Models the system as AC using full power flow equations to capture impedance, voltage, phase angles.

Inputs: system topology, facility electrical parameters (resistance and reactance), load location and amount

Outputs: line loading, bus voltages, bus injections (generation and load), phase angles

Limitation: PF modeling offers a snapshot with no time dimension or cost. It checks whether flows are physically feasible, not which resources to build or how to price them.

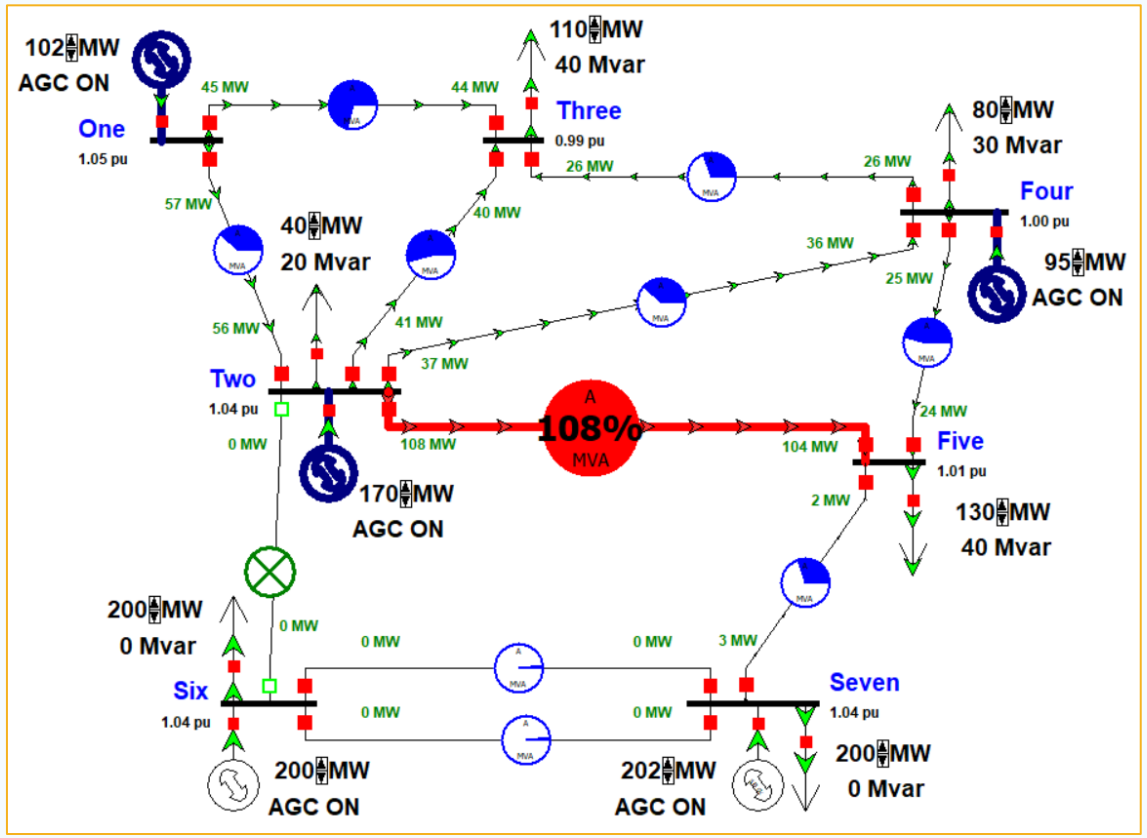


Image source | PowerWorld, Manual: Contingency Sensitivity Analysis (2026)

Benefits of ATTs that can be quantified in PF

Increase throughput of line

- Increase efficiency of facilities by increasing power factor given control over reactive power

Thermal overload relief

- Relieve congested facilities given changes to resistance, reactance, voltage, and/or voltage angle of either the overloaded facility or a neighboring facility

Reduced line losses

- Reduce losses of transferring power by changing bus voltage or line resistance

Over/undervoltage relief

- Relieve either overvoltage or undervoltage violations for a moment in time by changing voltage, voltage angle, or reactive power



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Simplifying assumptions to accelerate computing

Power system models rely on simplifying assumptions to reduce computational requirements and make complex analyses manageable. One such assumption are the use of simplified power flow equations.

These assumptions affect real-world conditions that can be represented and the solutions that emerge from the models, often producing more deterministic results than may be required by actual system conditions.

As computing capabilities continue to improve, modelers and planners should revisit the underlying simplifying assumptions and expand modeling approaches so they can better capture system conditions, uncertainty, operational complexity, and a broader range of potential solutions, including ATTs.

Power flow equations

Each power system model must use a version of the power flow equations to accurately represent system physics.

Actual power flow across an alternating current (AC) transmission line between buses *i* and *j*:

real power $p_{i,j} = \frac{1}{r_{i,j}^2 + x_{i,j}^2}\left[r_{i,j}\left(v_i^2 - v_i v_j \cos(\theta_i - \theta_j)\right) + x_{i,j}\left(v_i v_j \sin(\theta_i - \theta_j)\right)\right]$

reactive power $q_{i,j} = \frac{1}{r_{i,j}^2 + x_{i,j}^2}\left[x_{i,j}\left(v_i^2 - v_i v_j \cos(\theta_i - \theta_j)\right) + r_{i,j}\left(v_i v_j \sin(\theta_i - \theta_j)\right)\right]$

bus *i* voltage

bus *j* phase angle

line reactance

line resistance

- Use of these equations in modeling offers full control of the system. For example, if a user wants to increase real power flow *p*, the model could optimize values for *r, x, v,* or *θ.*
- These are complicated and "intractable" (i.e., computers often fail to find the answer).
- For that reason, only "power flow" models use them.

Sources | Mones, L., "A Gentle Introduction to Power Flow" (2020); McCalley, J., "The DC Power Flow Equations," Iowa State University; Kirtley, J.L., "AC Power Flow in Linear Networks," Massachusetts Institute of Technology.

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Simplified, linearized—sometimes referred to as "direct current (DC) approximation"—power flow equation:

$$p_{i,j} = \frac{1}{x_{i,j}}(\theta_j - \theta_i)$$

- This is a simple, more tractable equation that all modeling programs can use.
- However, it provides fewer modeling levers (control over only x (reactance) and θ (phase angle) available).

Sources | Mones, L., "A Gentle Introduction to Power Flow" (2020); McCalley, J., "The DC Power Flow Equations," Iowa State University; Kirtley, J.L., "AC Power Flow in Linear Networks," Massachusetts Institute of Technology.

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Simplified, linearized — sometimes referred to as "direct current (DC) approximation" — power flow equation:

$$p_{i,j} = \frac{1}{x_{i,j}}(\theta_j - \theta_i)$$

An even simpler option is to ignore the physics underlying power flow and only enforce a maximum flow constraint:

$$p_{i,j} \leq p_{max}$$

- Now only one modeling lever: maximum transfer limit p_{max}

Sources | Mones, L., "A Gentle Introduction to Power Flow" (2020); McCalley, J., "The DC Power Flow Equations," Iowa State University; Kirtley, J.L., "AC Power Flow in Linear Networks," Massachusetts Institute of Technology.

Summary: power flow equations

Each power system model must use a version of the power flow equations to accurately represent system physics.

Actual power flow across an alternating current (AC) transmission line between buses *i* and *j*:

$$p_{i,j} = \frac{1}{r_{i,j}^2 + x_{i,j}^2}\left[r_{i,j}\left(v_i^2 - v_i v_j \cos\left(\theta_i - \theta_j\right)\right) + x_{i,j}\left(v_i v_j \sin\left(\theta_i - \theta_j\right)\right)\right]$$

$$q_{i,j} = \frac{1}{r_{i,j}^2 + x_{i,j}^2}\left[x_{i,j}\left(v_i^2 - v_i v_j \cos\left(\theta_i - \theta_j\right)\right) + r_{i,j}\left(v_i v_j \sin\left(\theta_i - \theta_j\right)\right)\right]$$

Simplified, linearized—sometimes referred to as "direct current (DC) approximation"—power flow equation:

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Sources | Mones, L., "A Gentle Introduction to Power Flow" (2020); McCalley, J., "The DC Power Flow Equations," Iowa State University; Kirtley, J.L., "AC Power Flow in Linear Networks," Massachusetts Institute of Technology.

Compromise: trading resolution for computational efficiency

Models make several simplifications in order to quickly solve. These simplifications can negatively impact ATTs.

Model	Power Flow Equations	Temporal Resolution	Geographic Resolution	Transmission parameters	Impact on ATTs
Capacity Expansion (+ Resource Adequacy)	• Maximum transfer limits • Linearized "DC" at best	• Annual • Seasonal at best • Hourly if integrated with RA modeling	• Commonly zonal, can be flowgate (more granular) or nodal (most granular)	• Capital costs • Time to deploy	• Average annual real power transfer increases • No inclusion of reactive power, voltage, or ancillary service benefits • No inclusion of sub-hourly or weather specific benefits
Production Cost	• Maximum transfer limits • Linearized "DC" • Real AC at best	• Hourly • 5-min at best	• Commonly zonal • Nodal at best	• Line reactance • Line losses	• Average hourly real power capacity increases • Sub-hourly benefits averaged to hourly • Weather impacts tested as sensitivities rather than fully incorporated
Power flow	• Maximum transfer limits • Real + reactive AC	• Single snapshot in time	• Nodal	• Reactance • Resistance • Voltage • Phase angle	• Full benefits, but only for a moment in time • No measurement of time-series benefits (e.g., congestion management over several hours)

Section 4.
Advanced Transmission Technologies



GridStrategies

Section 4. Table of Contents

This section discusses each ATT in more detail:

a. High-Performance Conductors
b. Transmission Topology Optimization
c. Advanced Power Flow Control
d. Dynamic Line Ratings

Each technology subsection includes:

i. Definition
ii. Key deployment case studies
iii. Likely application opportunities
iv. Modeling heuristics
v. Additional modeling considerations

High-Performance Conductors (HPC)

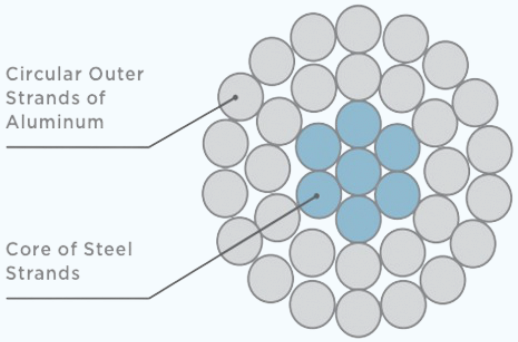
Modern conductor technologies that have greater performance characteristics when compared to traditional conductors.

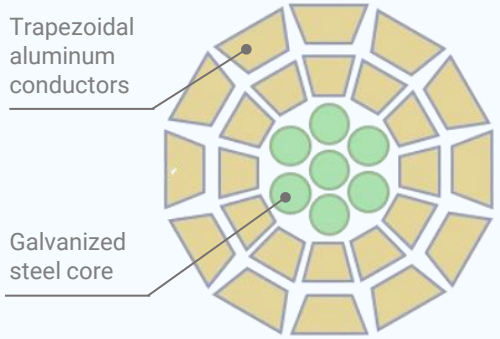
Evolution of conductors

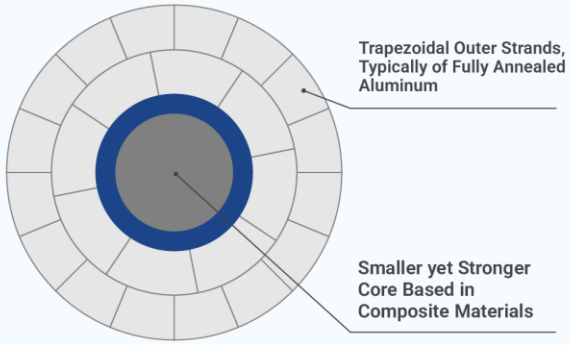
ACSR
Aluminum conductor steel reinforced

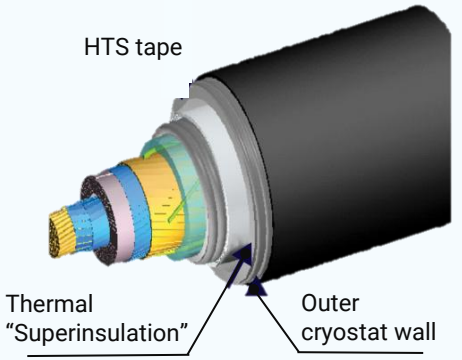
ACSS
Aluminum conductor steel supported

HPC
Carbon / composite core & Superconductors









Carbon / composite core conductors

Also known as "high-temperature, low sag" conductors, these are overhead, bare conductors that use a trapezoid shaped wire of annealed aluminum to carry electrical current and use a carbon fiber or composite core for support, reducing line losses by up to 40%, significantly reducing thermal sag, while materially increasing power-flow capacity at the same voltage and weight as traditional steel-core conductors, allowing for the use of existing towers or shorter or fewer new towers.

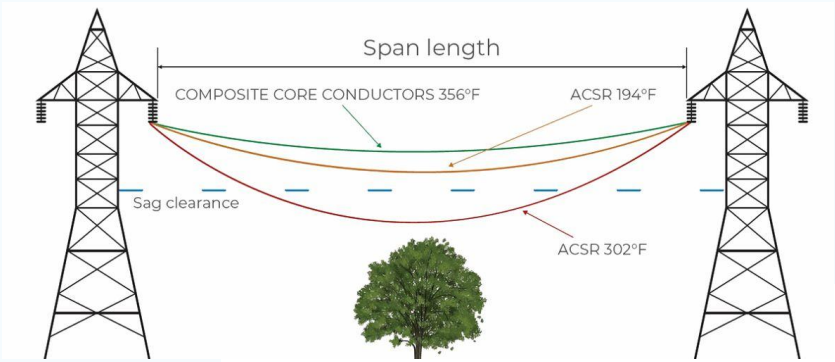
Superconductors

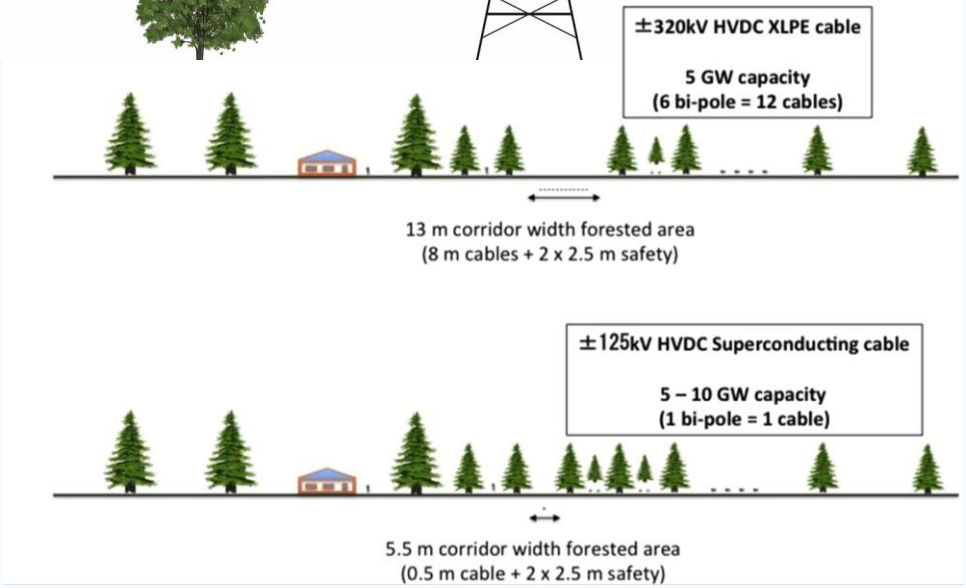
These use a class of metallic compounds that exhibit negligible resistive losses when cooled using liquid nitrogen, enabling very low power losses and very high power-flow capacities.

GridStrategies

Sources | GridLab, Reconductoring Technical Report (April 2024); ACORE, High Performance Conductor Playbook (October 2024).

High-Performance Conductors: case study examples





2020 Southern California Edison

Enabled reconductoring of a 230 kV line without structural retrofits, increasing capacity 60%, reducing construction time by 30 months and avoiding $85 million compared to a rebuild, and the reduced sag helped avoid damage from a 2020 wildfire.

2023 Basin Electric

Basin Electric constructed a 27-mile, 230 kV transmission project that reduced tower height and cut structure count by 15% (from 183 to 155 structures), lowering up front costs by 10-20%.

Munich SuperLink Superconductor

The planned 110 kV line will connect Munich's grid to the transmission system and can deliver 500 MW, a roughly 67% capacity increase over conventional conductors, partially using existing conduits, some less than half a foot in diameter, to minimize construction disruptions or additional corridor acquisitions.

Likely HPC opportunities

There are many scenarios where HPCs are particularly suitable. Focusing attention here will limit the number of possible scenarios that a planner must consider HPCs as a viable alternative.

Power Flow / System Need

- Relieve thermal congestion and unlock additional network capacity
- Address time-sensitive or uncertain demand growth
- Reinforce constrained transmission corridors

Increase Resilience & Environmental Constraints

- Reduce overhead-line sag and wildfire exposure
- Minimize land use, visual impacts, and environmental disturbance
- Enable underground solutions in environmentally sensitive or congested locations

Carbon Core Conductor: Enhance Overhead Lines

- Increase capacity within existing rights-of-way (ROW)
- Improve efficiency and reduce transmission losses up to 20%
- Improve line loading
- For new lines, reduce number of structures or structure height and reduce impact/disturbance within ROW
- Reconductoring can reduce conductor sag and potentially avoid tower modifications
- Reconductoring can add needed capacity in 18-36 months

Superconductor: High-Density Power Transfer

- Transfer very high power through compact underground corridors
- Reinforce urban networks where space and ROW are limited
- Deliver high capacity at lower voltages, potentially avoiding additional voltage transformation infrastructure

Modeling heuristics: HPCs

Note: Best practice would be to model any ATT facility under consideration in a power flow study to find the specific electrical changes, which would then be carried over to PCM or CEM. The table provides heuristics that can be applied at the system planning stage.

Variable	Capacity Expansion	Production Cost	Power Flow
Capital cost	**Carbon/composite core**: Costs decrease by ~50% given a doubling of capacity compared against in-kind ACSR replacement. Costs decrease by 60-75% for HPC reconductoring against traditional ACSR greenfield at same capacity. **Superconductors**: Installed costs decrease by 20–30% given a 2-5x in capacity compared with traditional XLPE cable solutions for new capacity in constrained urban areas.	N/A	
Time to install	**Carbon/composite core**: Time unchanged if in-kind replacement. Decreases by 3-7 years if replacing traditional new build with HPC reconductoring. **Superconductors:** Installation will decrease due to fewer and smaller cable circuits, reduced civil works and avoided substation voltage upgrades.	N/A	
Capacity	**Carbon/composite core**: Thermal limits increase by 75-100%. **Superconductors:** Thermal limits increased by 400-900%. If **zonal modeling**, then apply these capacity changes only to the proportion of inter-zonal lines which will use HPC.		**Carbon/composite core**: Line ampacity increases by 75-100% **Superconductors:** Line ampacity increases by 400-900%
Line losses	**Carbon/composite core**: Line losses decrease by 20-40% **Superconductors:** Line losses decrease by 95%		**Carbon/composite core**: Line resistance decreases by 20-40% **Superconductors:** Line resistance decreases by 95%
Reactance	N/A	**Carbon/composite core**: Line reactance does not change **Superconductors**: Reactance decreases by 75-95%	

Sources | AMP Coalition, Grid Strategies, ACORE Macro Grid Initiative, *UNLOCKING THE GRID: A Playbook on High Performance Conductors for State and Regional Regulators and Policymakers* (October 2024)

Additional considerations for HPC modeling

Data Availability

Product specification sheets provide important electrical parameters needed for proper modeling. For example:

- CTC Global technical specifications: https://ctcglobal.com/datasheets/
- TS Conductor technical specifications: https://tsconductor.com/technical-resources/

Project Design & Benefits

Power system modeling tools do not capture benefits like shorter and fewer towers, narrower rights-of-way, ability to use existing towers for increased capacity, etc. These benefits only arise in project design and siting feasibility studies.

As a base assumption, HPCs compared to ACSR decrease thermal sag by 90% and:

- Decrease the number of towers by 15-30%; and
- Increase ruling span (distance between towers) by 15-30%

OR

- Decrease height of towers by 5-15%; and
- Decrease right-of-way width by 10%

HPC manufacturer tools can help compare suitability of conductors for project design:

- CTC's Conductor Comparison Program
- TS Conductor's Conductor Comparison Tool

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Note: Besides existing vendors' tools, we are not aware of any software that accurately models the vendors' HPC parameters to optimize the sags of the HPC and then determine the economic value.

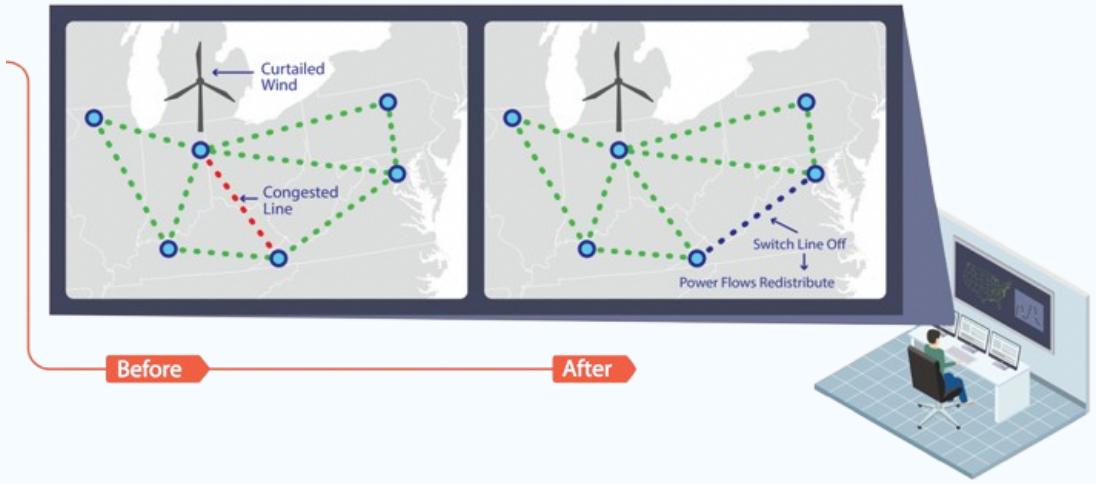
Transmission Topology Optimization (TTO)

Software that finds ideal grid configurations to avoid constraints and unlock more capacity

Changes in network topology redistribute flow or power through the transmission system. TTO software evaluates possible grid reconfigurations (generally through switching operations) for their reliability and production cost benefits.

In planning, topology optimization identifies changes that mitigate congestion and reduce production costs in unit commitment and dispatch, and substation designs that preserve reconfiguration optionality for operations.

TTO also supports transmission operations and operations planning when responding to outages or congestion.



Transmission switching

The act of reconfiguring the grid, by opening or closing specific transmission elements to safely route power and direct flows around congestion.

Topology optimization

Software quickly identifies reliable, beneficial, and practical reconfigurations, from a set of approved switching actions or across the whole network and can re-evaluate as conditions change through the day.

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Source | FERC Order No. 1920, n. 2554; WATT Coalition, What are GETs?

Transmission Topology Optimization: case study examples



2019 PJM

Topology optimization found to reduce congestion costs by 50% in PJM, in ex-post study.

2021 MISO

Alliant customers saved 49% in congestion costs ($24 million) over 2 years.

2025 ISO-NE

TTO reduced the most heavily loaded constraint flows in the region by 31%.

2022 SPP

TTO eliminated a constraint that reduced congestion costs for Evergy customers by 85%.

Likely TTO opportunities

TTO analysis is done quickly and at negligible incremental cost. The opportunities listed below are highlighted for their significant value and comfortable distance from the operational time frame, so that engineers can develop confidence in TTO analysis before applying it in near-real-time scenarios.

Outage scheduling and mitigation

- Outage will cause significant economic or reliability constraints
- Scheduling an outage is challenging

Planning: Power Flow / System Need

- Constraint driven by uneven flow distribution
- Unused capacity on parallel paths
- Need is moderate, uncertain, or time-sensitive

Improving economic dispatch

- Congestion patterns are persistent or recurring

Substation design

- Analyze value of future flexibility/optionality in bus configurations

Modeling heuristics: TTO

Note: Best practice would be to model any ATT facility under consideration in a power flow study to find the specific electrical changes, which would then be carried over to PCM or CEM. The table provides heuristics that can be applied at the system planning stage.

Variable	Capacity Expansion Modeling	Production Cost Modeling	Power Flow Modeling
Capital cost	Costs are $0 per facility, after initial integration of TTO system ($500k - $5M)	N/A	
Time to install	Time to install is 0 months, after initial integration of TTO system (~4 months)	N/A	
Capacity	Transfers through congested branches are reduced by 5-25%. Generation curtailment is reduced by 25-75% in areas with high transmission congestion. If reduced branch congestion or generation curtailment cannot be modeled, directly, instead model this as an equivalent increase in the thermal limits of the relevant branches.		Thermal violations of some branches are reduced by 5-25%.

Additional considerations for TTO modeling

Benefits of TTO

TTO can provide many planning and operational benefits. Some of these benefits may be omitted in specific analyses as they cannot all be easily included in each power system model.

- Reduced generation curtailment
- Reduced or deferred transmission investments
- Increased production cost savings
- Mitigate transmission congestion
- Provide operational flexibility
- Improve benefit-to-cost analysis for transmission expansion portfolios

How to model

TTO software is a decision support software tool that searches for topology changes—such as opening or closing lines, splitting buses, or reconfiguring substation arrangements—to mitigate congestion and improve reliability on target constraints while ensuring no new constraints are created or existing constraints are worsen.

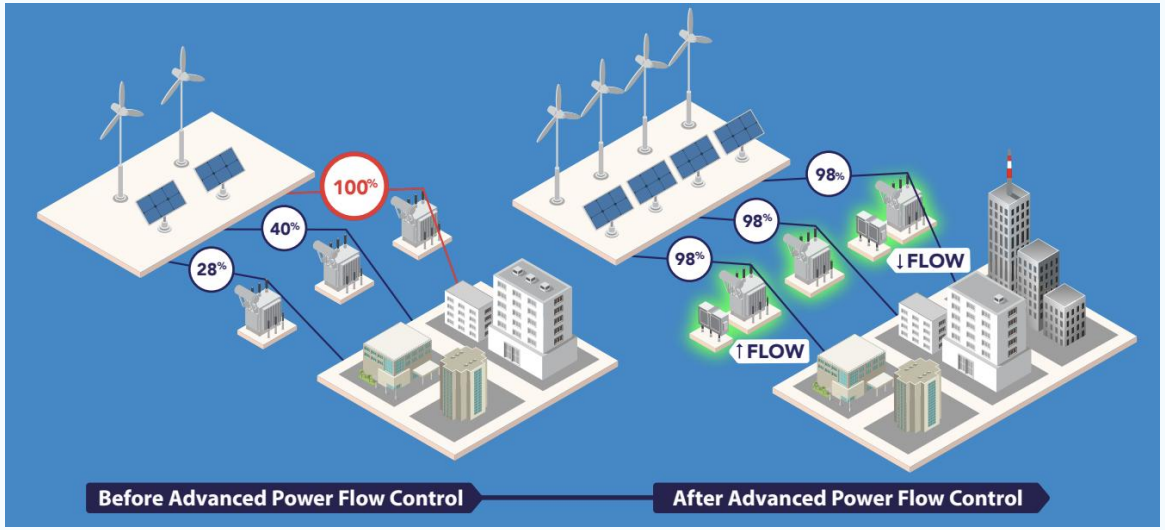
TTO is modeled once a few candidate optimized topologies are identified with TTO software as open or closed transmission lines, with the corresponding bus either split or merged, depending on the confirmation. Open actions are equivalent to removing the associated elements from the model.

TTO software should first be used to identify a small number of candidate optimized topologies to resolve or mitigate the identified transmission need. Then, these candidate topologies can be modeled using standard modeling software, using the same steps for any planning studies. Scenarios with and without topology changes can be run to evaluate whether proposed switching actions relieve the identified issue without violating security criteria.

Advanced Power Flow Control (APFC)

Hardware that redirects power from overloaded to underutilized transmission corridors by adjusting impedance.

Power divides across a transmission network in inverse proportion to the *impedance*, or effective resistance, of each path, so one circuit can reach its thermal limit while parallel circuits sit lightly loaded. APFC alters the impedance by changing the phase angle of a path to push or pull power across the network, controlling how much flows on a given path and balancing overloaded lines against underutilized corridors. The devices can be set to adjust automatically or manually.



APFC technology highlight: modular static synchronous series compensators

Devices at substations inject a voltage in series with the circuit, changing its effective impedance and redistributing flow toward underused circuits. Unlike older static synchronous series compensators, newer *modular* technologies have many additional benefits and can be redeployed to other locations when needed.

Sources | FERC Order No. 1920, n. 2552; INL, Case Studies of Grid Enhancing Technologies, at 3; WATT Coalition, What are GETs?

Types of Power Flow Control technologies

Several power flow control devices are already widely used. Newer advanced power flow control technologies can be modeled by emulating older devices.

	Conventional Switched Devices	Flexible AC Transmission System (FACTS) Devices	
Shunt Devices	Switched Shunt Compensation	Static Var Compensator (SVC)	Static Synchronous Compensator (STATCOM)
Series Devices	Switched Series Compensation	Thyristor Controlled Series Compensator (TCSC)	Modular Static Synchronous Series Compensator (m-SSSC)
Shunt & Series Devices	Phase Shifting Transformer / Phase Angle Regulator (PST/PAR)	Dynamic Flow Controller (DFC)	Unified / Interline Power Flow Controller (UPFC/IPFC)
		HVDC Back-to-Back (B2B) Tie	HVDC Voltage Source Converter (VSC) B2B Tie

Advanced Power Flow Control Devices

While several benefits may be missed, it is possible to model APFC devices as older power flow control devices (like PSTs) that are already included in modeling tools.

Application	PST	TCSC	UPFC	m-SSSC
Power flow control	✓	✓	✓	✓
Transient stability	✓	✓	✓	✓
Power oscillation damping	–	✓	✓	✓
Controllability	–	?	✓	✓
Delivery (years)	5-7	2-3	unknown	<1

Advanced Power Flow Control: U.S. case studies



2026 Northeast

12 modules saved 16% on a traditional solution while providing 50% more power flow control.

2024 California

Utilities identified reliability applications in CAISO's 2024 transmission plan. PG&E deployed APFC to unlock 100MW+ of capacity in 2026.

2024 New York

APFC unlocked 185 MW of capacity to accommodate new generation, at lower cost and smaller footprint than legacy solutions.

2023 Texas

APFC deployed to resolve stability issues and increase grid capacity by 300MW.

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Further Reading | EPRI GET SET White Paper on Advanced Power Flow Control, January 2025
Image source | SmartWires

Advanced Power Flow Control: International case studies





2025 Central Europe

In one of Europe's most congested corridors, APFC was deployed to remove 3,300 hrs/year of congestion across Slovenia, Austria and Croatia's borders.



2024 Northern England

APFC unlocked over 2GW of capacity across seams and saves $400 million in curtailment costs.



2023 Colombia

Enabled the connection of over 400 megawatts of hydro and solar power across three transmission lines.



2021 United Kingdom

APFC deployed to unlock 500MW of capacity, powering 300,000 homes.

Likely APFC opportunities

There are many scenarios where APFC are particularly suitable. Focusing attention here will limit the number of possible scenarios that a planner must consider APFC as a viable alternative.

Power Flow / System Need

- Constraint driven by uneven flow distribution
- Unused capacity on parallel paths
- Need is moderate, uncertain, or time-sensitive

Reconductor / Rebuild Alternative

- 10–40% capacity increase needed
- 10–50 mile line, or costly ROW
- Capacity needed in <24 months

Phase Shifting Transformer Alternative

- New PST lead time >2–3 years
- Reduce loading/duty on existing PSTs

Series Compensation / Reactor Alternative

- Series caps create SSR concerns
- Series reactors add losses & MVAR drop
- Variable flow control preferred over fixed impedance

Modeling heuristics: APFC

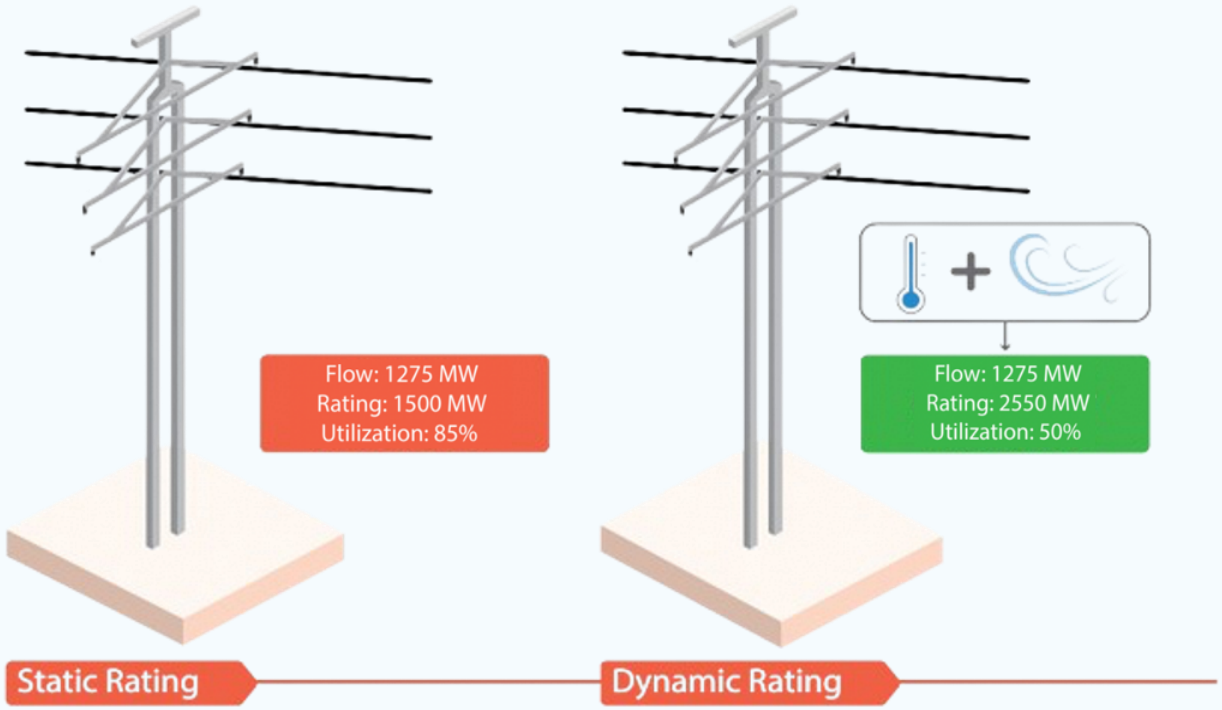
Note: Best practice would be to model any ATT facility under consideration in a power flow study to find the specific electrical changes, which would then be carried over to PCM or CEM. The table provides heuristics that can be applied at the system planning stage.

Variable	Capacity Expansion Modeling	Production Cost Modeling	Power Flow Modeling
Capital cost	Costs decrease by 50% or more compared to traditional upgrades. Actual applicability will need to be confirmed in power flow modeling.	N/A	
Time to install	Time to install 1–2 years, compared 2–5 years for rebuild and compared to 5–10 years for traditional new build.	N/A	
Capacity	Power flow limits between zones (zonal CEM) or nodes (nodal CEM) can be estimated to increase by up to 40% as an initial screening test.	Line power flow limits increase by up to 40% as an initial screening test.	The power flow model finds the true capacity increase.
	Note: Accurate capacity increases should be derived from an offline PF study, then used as fixed variables in the CEM and PCM models.		
Impedance	N/A	Line reactance can increase or decrease by between -70% and +300%. Identify whichever setpoint maximizes power transfer across target facility.	Modify electrical parameters to cause an increase or decrease to line impedance to maximize power transfer: • line series reactance (between -70% and +300%) • bus phase angle (±20-30 degrees)
		Note: Changing impedance via electrical parameters is an alternative to changing capacity limits directly.	

Dynamic Line Ratings (DLR)

Hardware and software used to calculate the true capacity of transmission lines based on weather conditions.

Wires carrying electricity generate heat–if they get too hot, they start to soften and sag. Utilities determine static thermal ratings, which assume hot, sunny, windless conditions to prevent lines from overheating. On cold or windy days, however, power lines can easily deliver 50% or more energy than their labeled limits.



DLR Technologies

DLR measures the true conditions to calculate the true operating capacity of transmission lines while staying within temperature limits. These technologies use measured or modeled real time ambient conditions, including wind, to maximize the existing grid's capacity without adding or modifying grid infrastructure. This means more capacity is available immediately at a low cost.

DLR serves as a cost-effective tool to increase system capacity of existing transmission and optimize planning and construction of new transmission.

Source | WATT Coalition, What are GETs?

Dynamic Line Ratings: Case study examples





2021 Deployments across 3 states

DLR exceeded static reference ratings by 9-33% in winter, and 26-36% in summer

DLR exceeded static ratings >85% of the time



2022 Pennsylvania

Increased line capacity by 25% on average.



2022 Massachussetts & New York

Increased capacity by 30% and reduced 350MW of curtailments, equivalent to powering 80,000-100,000 homes.



2012 Belgium

Increased capacity by >20%, 90% of the time.

Likely DLR opportunities

DLR is most useful for managing thermally limited circuits and grid monitoring.

Power Flow / System Need

- Constraint driven by thermal line limits
- Conductor is less wind-shielded

Reconductor / Rebuild Alternative

- 10–20% capacity increase needed
- 10–50 mile line
- Capacity needed ASAP

Asset Condition and Safety Monitoring

- Line is reaching end-of-life, and may need replacement

Improving Economic Dispatch

- Persistent congestion, especially in cooler, windier scenarios
- Medium or long-term outage expected to curtail low-cost generation

Modeling heuristics: DLRs

Note: Best practice would be to model any ATT facility under consideration in a power flow study to find the specific electrical changes, which would then be carried over to PCM or CEM. In addition, accurate estimates of DLR value must be based on local weather data.

Variable	Capacity Expansion Modeling	Production Cost Modeling	Power Flow Modeling
Capital cost	Decrease by 95% or more compared to traditional new build OR Estimate $20,000 per mile in absolute terms If an organization has selected a DLR vendor/technology, more accurate cost estimates may be available internally	N/A	
Time to install	3 - 6 months in absolute terms	N/A	
Capacity	When weather data cannot be used, thermal limits between nodes increase by 10-30% as an initial screening test. When locational weather data is available, thermal limits between nodes increase by • 20% for every 1 m/s above static wind speed rating (usually 0.6 m/s), and • 1% for every 1°C below static ambient temperature rating (usually 40°C). Note: The values can also be applied in the opposite direction for low wind and high temperature conditions.		Line ampacity increases by • 20% for every 1 m/s above static wind speed rating (usually 0.6 m/s), and • 1% for every 1°C below static ambient temperature rating (usually 40°C).
	If **zonal CEM**, then apply these capacity changes only to the proportion of inter-zonal lines which will use DLR.	Note: A time-series of ratings across all hours—based on climate-change informed historical weather data—should be developed and used in place of static or seasonal ratings and should match weather assumptions in the rest of the model.	Note: A reasonable estimate of the weather conditions at time of simulation should be used to define ampacity of the line.

Source: https://www.osti.gov/servlets/purl/2476805/

Additional considerations for DLR modeling

Using national weather data, modelers can establish a conservative time-dependent line rating for any period, whether it's a single snapshot, seasonal average, or 8760 (every hour of the year) analysis.

Modelers usually do not need to consider DLR at every hour of the day. They could instead focus on estimating DLR capacity when the capacity is needed, such as in peak demand scenarios for resource adequacy planning or when generation is not deliverable for interconnection studies.

Data Availability

- National Lab of the Rockies (NLR) report describing DLR database: https://www.osti.gov/servlets/purl/2476805/
- NLR national hourly DLR database: https://data.openei.org/submissions/6231
- NLR scripting package to develop hourly timeseries ratings for any transmission line: https://github.com/NatLabRockies/DynamicLineRatings
- NLR National Solar Radiation Database: https://data.openei.org/submissions/1
- NLR WIND database: https://data.openei.org/submissions/2

Data Use and Help

DLR vendors can study local topography and model wind and weather on a very granular scale, to get the most accurate expectation of the capacity impacts of DLR in all weather conditions.

Additional considerations for DLR modeling

Forecasting and Weather Modeling

A key benefit of DLR is accurate rating forecasting, which enables resource scheduling in the day-ahead markets. These forecast algorithms can be informed by historical data collection, commercial weather forecasting services, computational fluid dynamics, and other strategies.

Resolution of Ratings

Seasonal, daily, hourly ratings may be appropriate for capacity expansion, production cost, and power flow control.

DLR systems can use multiple sensors and validation mechanisms for more accurate ratings

DLR improves on ambient-adjusted and seasonal ratings by increasing the accuracy and precision of input variables in rating calculations. These inputs can be calculated using weather stations, line- or tower-mounted sensors, or distributed acoustic and temperature sensing using fiber optic cables. Sensing options have tradeoffs in cost, accuracy, and longevity.

Ambient-adjusted ratings can introduce additional risks to the system. Accounting for temperature shifts but not changes in wind can obscure true capacity changes. For instance, weaker wind may offset some or all of the cooling benefit of lower nighttime temperatures. The risks and operational value of ambient ratings versus DLR depends on demand and power-flow patterns, but additional information from accurate data can be applied.

Dynamic Line Ratings are based on IEEE Standard 738-2023

The standard calculation for line rating is an equation based on

- environmental conditions (temperature, wind speed and direction, irradiance),
- conductor physical properties (diameter, emissivity, etc.), and
- operating parameters (maximum conductor temp).

Only two environmental variables were presented in the Modeling Heuristics: wind speed and ambient temperature. Modelers could introduce more details if desired.

Appendix.
FERC Commissioner Statements

Excerpts from Commissioner See's Concurrence on June 2026 Show Cause Orders

"7. Moving to areas where the Commission has a more direct role in ensuring cost responsibility, we need to pull all the levers we have to keep rates fair and transparent. Today we reaffirm our responsibility to assign jurisdictional costs to the customers who drive or benefit from grid upgrades, not shift them onto families and small businesses. For instance, today's orders seek to reduce large-load driven network upgrade costs through alternative transmission technologies, or ATTs (also commonly called Grid Enhancing Technologies). In determining how best to meet the needs of this historic large load growth, technologies that can improve system capability faster than traditional upgrades and at lower costs deserve a hard look. ATTs may not be the best tool in every circumstance, but where they are they can support timely interconnections and avoid potentially tens or hundreds of millions of dollars in unnecessary network upgrade costs that would otherwise flow into transmission customers' bills.

"8. So our approach today supports continuing the Commission's policy to roll most network upgrade costs—including those in the large load space—into the embedded-cost rate most transmission customers pay. But it includes an asterisk that this policy works for ratepayers only so long as we remain committed to pursuing technological innovations that keep those costs at a responsible and accountable level. Today's order thus calls for transmission providers to sufficiently evaluate ATTs to assess if and how they can meet large loads' interconnection needs. The answer may be yes or no in a given case. But if the transmission provider opts for traditional network upgrades, they must demonstrate why ATTs are not feasible or would not result in lower costs or a faster timeline for the large load interconnection customer. In short, the goal is to respect transmission providers' engineering judgments while protecting against upgrade costs when ATTs could solve transmission needs faster and with a lower bill."

Source | Commissioner See Concurrence, June 18, 2026

Excerpts from Commissioner Chang's Concurrence on June 2026 Show Cause Orders

"1. I write separately to emphasize the importance of building actionable records in these proceedings, particularly with respect to our consideration of customer protection, transmission service, and alternative transmission technology reforms."

"Lastly, today we preliminarily find that each RTO/ISO's tariff is unjust and unreasonable because the tariff lacks clear and consistent provisions requiring the evaluation of alternative transmission technologies as potential solutions to accommodate an Eligible Customer's request for transmission service on behalf of a large load. Specifically, it is important for RTO/ISOs and transmission owners to evaluate whether alternative transmission technologies are feasible in reducing the cost of transmission system upgrades or allow for a faster timeline for accommodating the transmission service request. As many transmission owners have explored various alternative technologies in pilot projects, it is time to roll out all available technologies to reduce risks and costs for customers, as well as help the industry continue to develop new technologies that can increase the robustness of our transmission system while protecting customers from higher costs."

Source | Commissioner Chang Concurrence, June 18, 2026

Excerpt from Commissioner LaCerte's Concurrence on June 2026 Show Cause Orders

"1. I also support the use of alternative transmission technologies to unlock every megawatt of existing capacity from our current transmission system. We have the technology. We should use it now to enable faster interconnection of large loads, lower costs to customers, and help prevent cost shifting."

Source | Commissioner LaCerte Concurrence, June 18, 2026

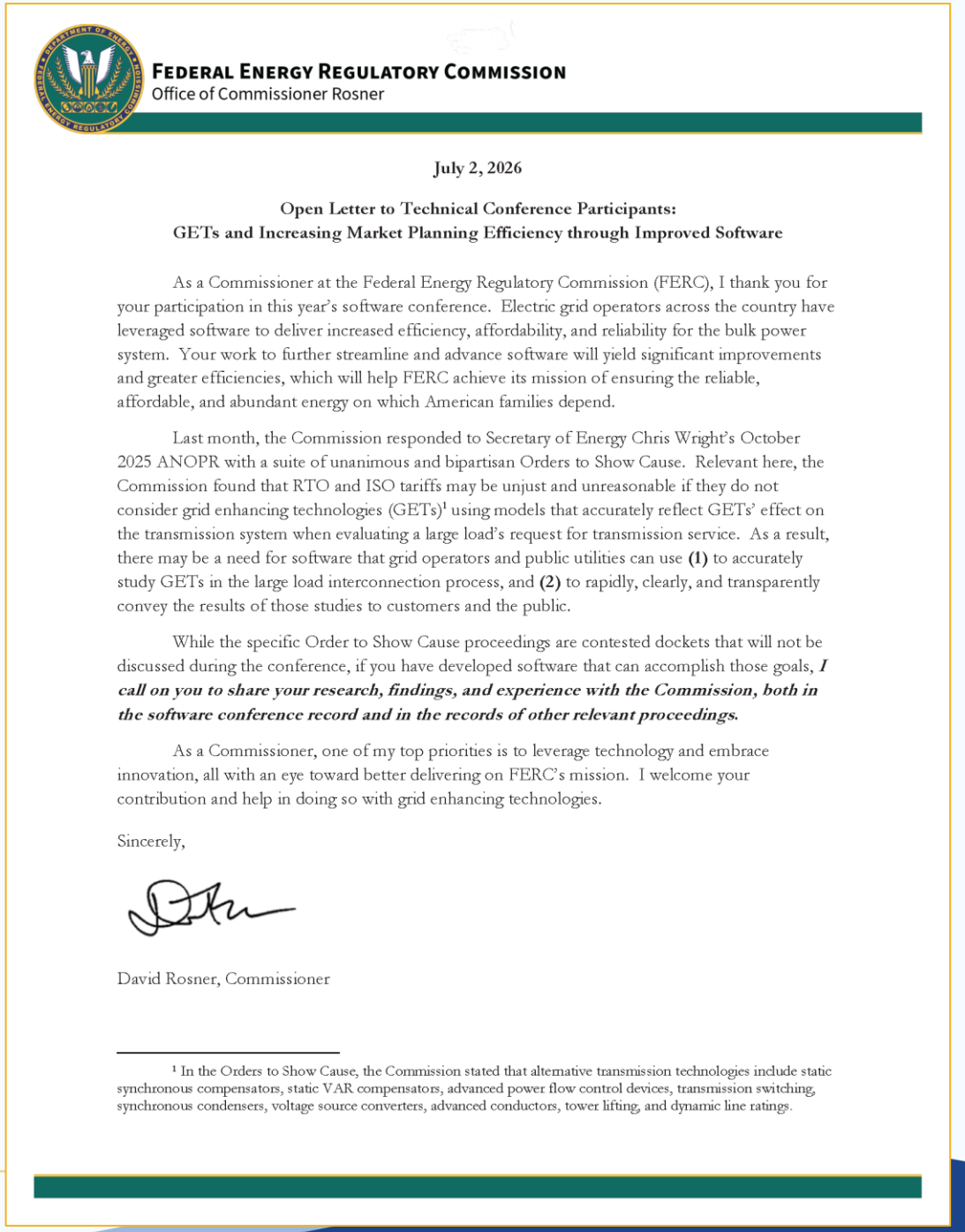
Excerpt from Commissioner Rosner's Concurrence on June 2026 Show Cause Orders

"5. Another win for consumers is requiring RTO/ISOs to consider grid enhancing technologies (GETs), including dynamic line ratings, when adding new large loads to the grid. GETs are technologies that squeeze more juice out of the existing grid, reducing the need for expensive upgrades and speeding up the time connect. Ensuring that RTO/ISOs consider GETs in the planning process—and if GETs are not used, explain why—not only helps new large loads get connected more quickly, but is also a commonsense step towards saving all consumers money. Put differently, today's orders will help us understand if we are leaving efficiencies on the table, an outcome we cannot afford."

Source | Commissioner Rosner's Remarks on the Large Load Show Cause Orders, E-7 to E-12, June 18, 2026

Commissioner Rosner's July 2026 Letter to Technical Conference Participants

"Relevant here, the Commission found that RTO and ISO tariffs may be unjust and unreasonable if they do not consider grid enhancing technologies (GETs)[using models that accurately reflect GETs' effect on the transmission system when evaluating a large load's request for transmission service. As a result, there may be a need for software that grid operators and public utilities can use (1) to accurately study GETs in the large load interconnection process, and (2) to rapidly, clearly, and transparently convey the results of those studies to customers and the public."



FEDERAL ENERGY REGULATORY COMMISSION
Office of Commissioner Rosner

July 2, 2026

Open Letter to Technical Conference Participants:
GETs and Increasing Market Planning Efficiency through Improved Software

As a Commissioner at the Federal Energy Regulatory Commission (FERC), I thank you for your participation in this year's software conference. Electric grid operators across the country have leveraged software to deliver increased efficiency, affordability, and reliability for the bulk power system. Your work to further streamline and advance software will yield significant improvements and greater efficiencies, which will help FERC achieve its mission of ensuring the reliable, affordable, and abundant energy on which American families depend.

Last month, the Commission responded to Secretary of Energy Chris Wright's October 2025 ANOPR with a suite of unanimous and bipartisan Orders to Show Cause. Relevant here, the Commission found that RTO and ISO tariffs may be unjust and unreasonable if they do not consider grid enhancing technologies (GETs)[1] using models that accurately reflect GETs' effect on the transmission system when evaluating a large load's request for transmission service. As a result, there may be a need for software that grid operators and public utilities can use **(1)** to accurately study GETs in the large load interconnection process, and **(2)** to rapidly, clearly, and transparently convey the results of those studies to customers and the public.

While the specific Order to Show Cause proceedings are contested dockets that will not be discussed during the conference, if you have developed software that can accomplish those goals, ***I call on you to share your research, findings, and experience with the Commission, both in the software conference record and in the records of other relevant proceedings.***

As a Commissioner, one of my top priorities is to leverage technology and embrace innovation, all with an eye toward better delivering on FERC's mission. I welcome your contribution and help in doing so with grid enhancing technologies.

Sincerely,

David Rosner, Commissioner

[1] In the Orders to Show Cause, the Commission stated that alternative transmission technologies include static synchronous compensators, static VAR compensators, advanced power flow control devices, transmission switching, synchronous condensers, voltage source converters, advanced conductors, tower lifting, and dynamic line ratings.

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Source | Open Letter to Technical Conference Participants, July 2, 2026