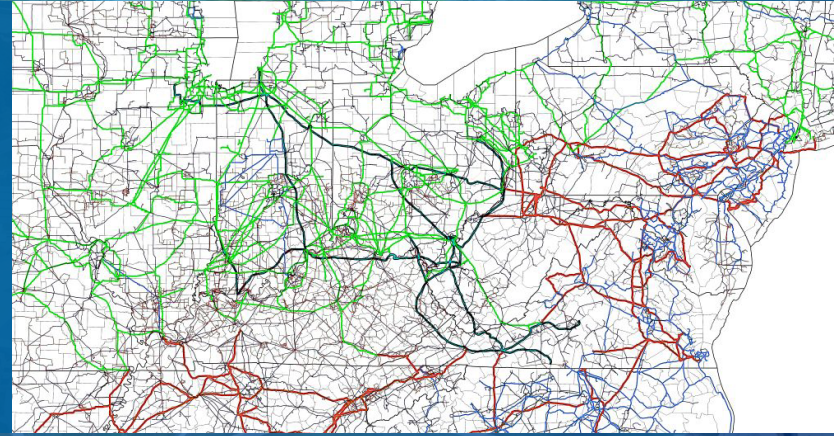


AUGUST 5, 2025

# TRANSMISSION PLANNING MODELS AND TOOLS

NARUC-NASEO COMPREHENSIVE  
ELECTRICITY PLANNING INITIATIVE



Source: ANL

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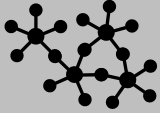
This work has been supported by DOE-Grid Deployment Office.



# OBJECTIVES

- High-level overview of a wide range of modeling practices and tools used in transmission planning.
- A technical background in power system planning is not required or assumed.
- This session is organized into two 15-20 minute parts, with time for Q&A after each.

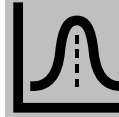
# TRANSMISSION PLANNING IS CHALLENGING



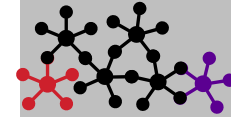
**Highly complex modeling** is required to capture physics and economics.



**Investments are large**, require a long lead time, and have a long lifetime.



**Uncertainty is high** and arises from many distinct sources.



**Strong interdependencies** with generation and distribution: influence flows in both directions.

# TRANSMISSION PLANNING SERVES MULTIPLE PURPOSES

## Reliability

Long history as primary goal of transmission planning, still constitutes the majority of transmission planning analysis. Underpins all transmission planning policy, including FERC Order 1920 (2024).

## Economic

FERC Order 890 (2007) introduced a requirement to consider economic efficiency of the network, identifying “significant and recurring” congestion.

## Public Policy

FERC Order 1000 (2011) introduced a requirement to “consider transmission needs driven by public policy requirements established by state or federal laws or regulations.”

# MODELING STEPS IN TRANSMISSION PLANNING

Construct Representative Futures (Including Policy)

Translate Futures to Specific Models

*Part 1*

**Scenario Development**

Perform Reliability Analyses

Perform Economic Analyses

Determine Needs

Identify and Evaluate Potential Solutions

*Part 2*

**Needs Identification**

**Solution Evaluation**



# PART 1: SCENARIO DEVELOPMENT



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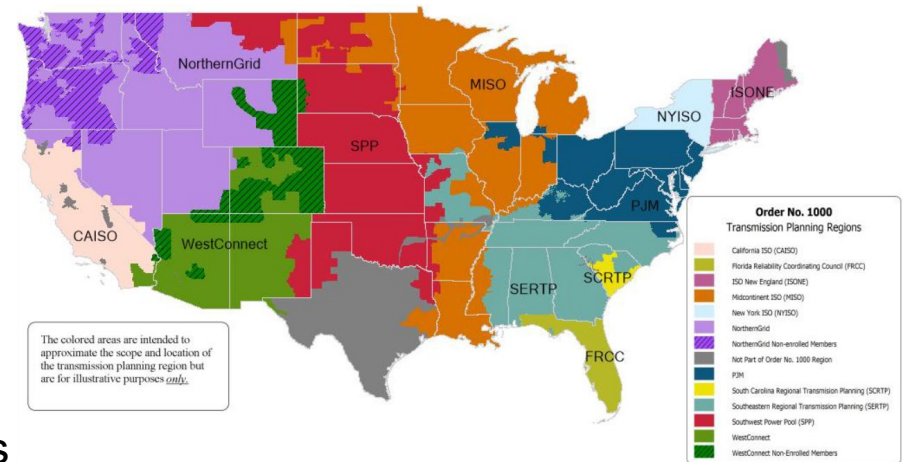
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# LOCAL AND REGIONAL TRANSMISSION PLANNING

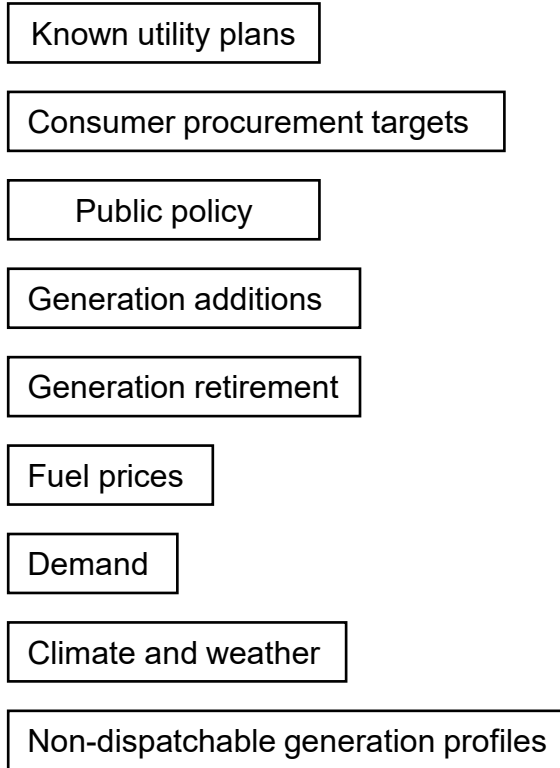
- FERC Order 1000 identifies planning regions; each transmission owner in a region must participate in the regional process and interregional coordination (Led by ISO/RTO or regional planning group)
- Transmission owners (whether in ISO/RTO region or not) conduct local planning apart from Order 1000 regional planning
- Short-term (Regional and local): 1-5 years
- Mid-long-term (Order 1000): 5-15 years
- Long-term (Order 1920): 20 years



Reference map of regions in FERC Order 1000.  
<https://www.ferc.gov/media/regions-map-printable-version-order-no-1000>

# CONSTRUCTING FUTURES

**Estimates and  
Best-Available  
Information  
&  
Uncertain  
Variables**



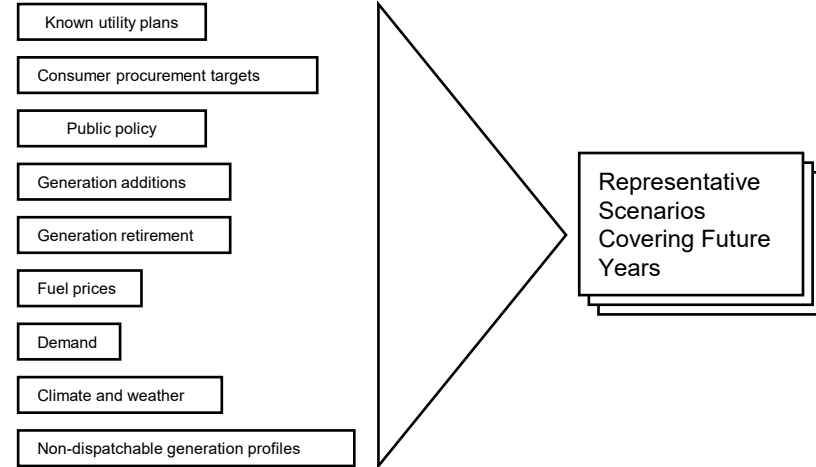
**Representative  
Scenarios  
Covering  
Future Years**

***Regional Planning: 1-3  
Scenarios, 5-15 years  
Order 1920: Three 20-  
year Scenarios***

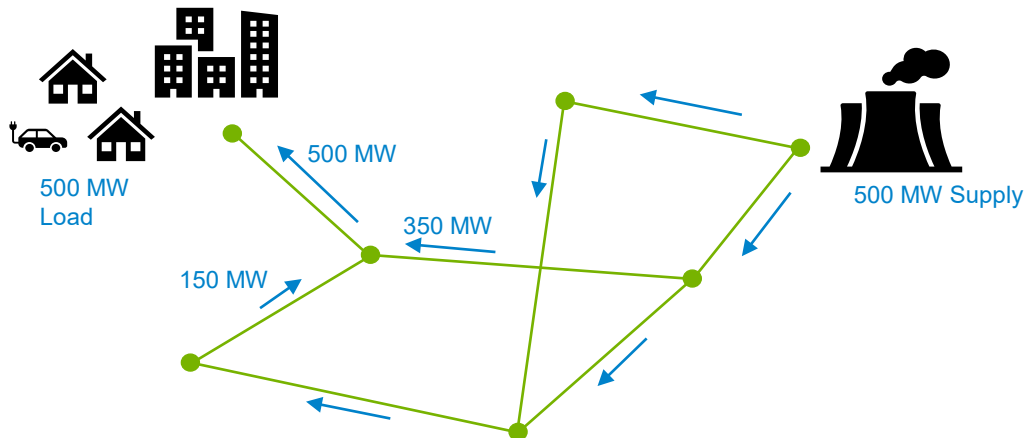
# WHAT'S IN A SCENARIO?

**All the data required to perform reliability and economic assessments, including**

- Power flow data: transmission topology, equipment ratings, engineering parameters, available generation
- Reliability data: contingencies to analyze, weather sensitivities, extreme weather events
- Economic data: generator heat rates, fuel prices



# POWER FLOW MODELS



Given certain generation and demands, how does power flow through every line, transformer, and element of the network from generation to load? (also known as load flow)

## Copper Plate

*Assume lossless and unlimited transmission.*

## Pipe+Bubble/ Transportation/ Network Flow

*Model transmission capacity constraints, ignore physics of circuits, ignore losses (usually).*

## DC Power Flow

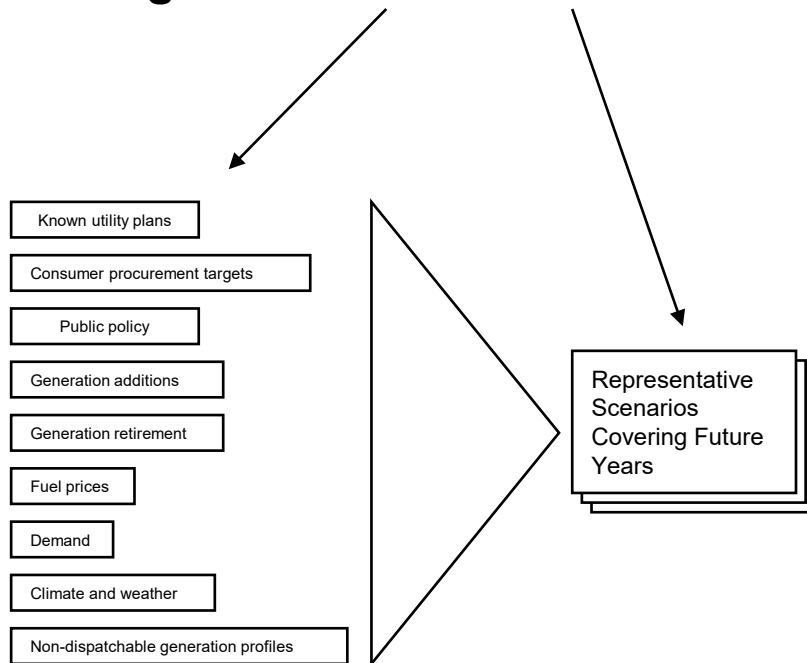
*Model capacity constraints, linear approximation of physics, ignore losses (usually), ignore voltage magnitude.*

## AC Power Flow

*Model capacity constraints and full steady-state physics, including losses. Only model that includes voltage and reactive power.*

Increasing Complexity and Accuracy

# How do we get from here to here?



Step 1: Define Input Values  
Step 2: Capacity Expansion Modeling

**Persistent question:  
How do we reduce the  
many uncertainties  
into concrete inputs?**

# HOW IS DEMAND FORECASTING DONE?

- ISOs/RTOs have in-house teams and software for short-term and long-term forecasting.
- Data-driven approaches (regression models) work well for short-term demand, but long-term demand is influenced by exogenous features which need to be incorporated.
- Long-term forecasts often report monthly or seasonal peak demand, but estimates can be made at higher temporal resolutions (e.g. ERCOT hourly)
- Spatial resolution is typically load zone

# COMPONENTS OF LOAD FORECASTS

## Major changes and uncertainties

- Data centers
- Onshoring of industry
- Electrification of natural gas loads
- EV adoption
- Building stock changes (replacement and growth)
- Population changes
- Efficiency and weatherization progress, adoption, and mandates

## Weather-dependent

- Building heating
- Building cooling
- Behind-the-meter generation
- Agricultural equipment

## Intra-day cycles

- Industrial processes
- EV charging
- Appliances

# REPRESENTING FORECAST UNCERTAINTY

- The uncertainty in a forecast is propagated through the models
- These probabilistic models are translated into a set of scenarios based on realizations of the underlying uncertainty
- For example, if heat and humidity are the modeled uncertainties,
  - 50/50 forecast represents the estimated load under average heat and humidity: 50% chance load will exceed the forecast.
  - 90/10 forecast represents estimated load under 90<sup>th</sup> percentile heat and humidity: 10% chance load will exceed the forecast.

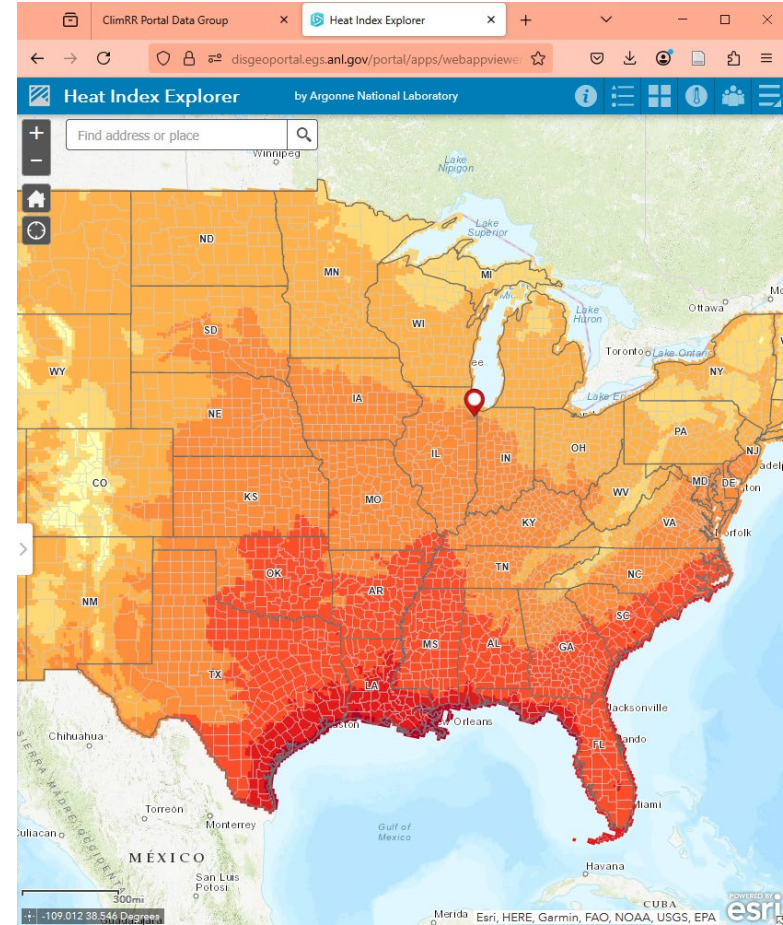
# CLIMATE AND WEATHER DEPENDENCIES

## Key challenges

- Translating weather variables to power system impacts
  - Load: highly dependent on **temperature, humidity; solar insolation** where significant behind the meter PV is present
  - Generation: **wind speed, solar insolation, temperature, humidity, water** availability and temperature
  - Transmission: **temperature, wind speed**, relevant to dynamic line rating and advanced conductors
  - Extreme conditions and natural hazards
- Capturing **weather-driven correlations** across infrastructures
  - Significant opportunity to capture impacts across models

# WEATHER DATA

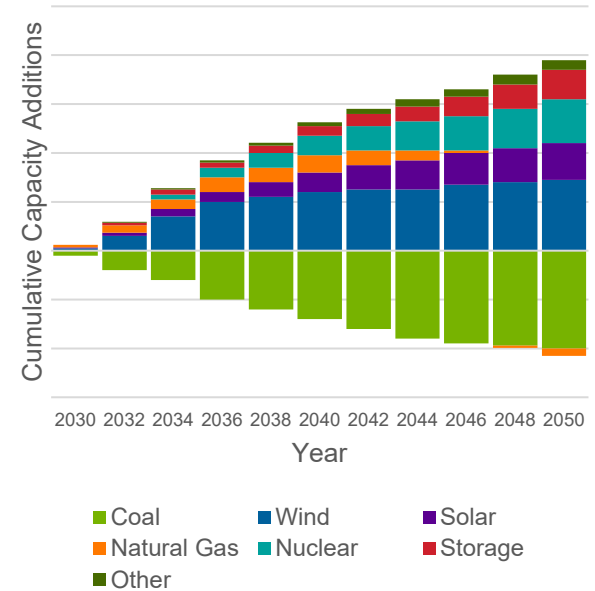
- **Historic observations:** real measurements, but challenges with spatiotemporal interpolation, missing/anomalous data, and availability of variables of interest
- **Reanalysis:** takes historic observations and estimates variable values at a uniform spatial and temporal scale, e.g. ERA5, 1940-present, hourly, 31km grid, but doesn't represent future trends
- **Future climate simulations and downscaling** are also used, e.g. ClimRR (climrr.anl.gov), NCDB (climate.nrel.gov)



climrr.anl.gov

# CAPACITY EXPANSION MODELS

- A capacity expansion model determines optimal generation type, sizing, siting, and installation timing over a future time period given an estimate of future demand.
- Constrained by many factors, including
  - Resource adequacy criteria
  - Policy mandates
  - Siting constraints
  - Transmission topology and capacity
- And driven by one or more objectives
  - Least-cost, including investment and operations costs
  - Policy goals
  - Others, e.g. welfare, equity



**Simple example of generation additions and retirements from a long-term capacity expansion study.**

Source: ANL

# CAPACITY EXPANSION

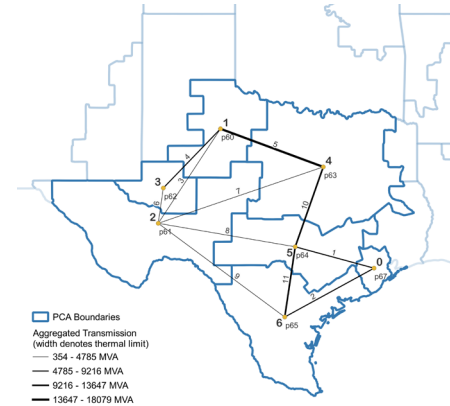
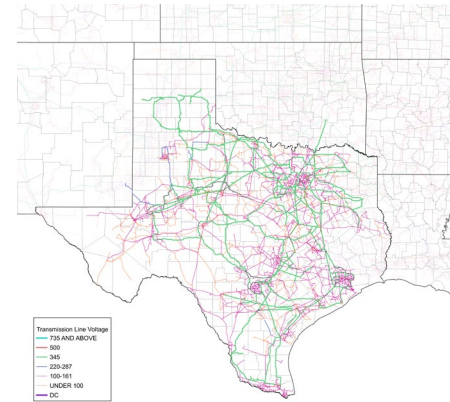
## Key considerations: Spatiotemporal characteristics

### Temporal Aspects

- Time horizon of study: near- vs. long-term
- Representative periods: peak day vs. 8760 and everything in between
- Resolution: daily, hourly, sub-hourly

### Spatial Aspects

- Geographic scope: if regional, include representation of outside areas?
- Resolution: zonal (sizing of zones) vs. nodal
- Transmission model: aggregated vs. individual lines, DC vs. pipe flow vs. copper plate



Examples of a nodal and coarse zonal model of the ERCOT grid. (ANL)

# CAPACITY EXPANSION

## Key considerations: Generator and policy modeling

### Generator and fuel characteristics

- Fidelity: aggregated vs. plant vs. unit
- Energy storage: operational strategy, sequential temporal modeling?
- Variable resources: model of resource availability, accounting for uncertainty, capacity value
- Fuel prices: modeled vs. fixed input, fuel availability modeled?
- Retirements: modeled vs. fixed input

### Policy

- Which policies are included and how are they modeled?

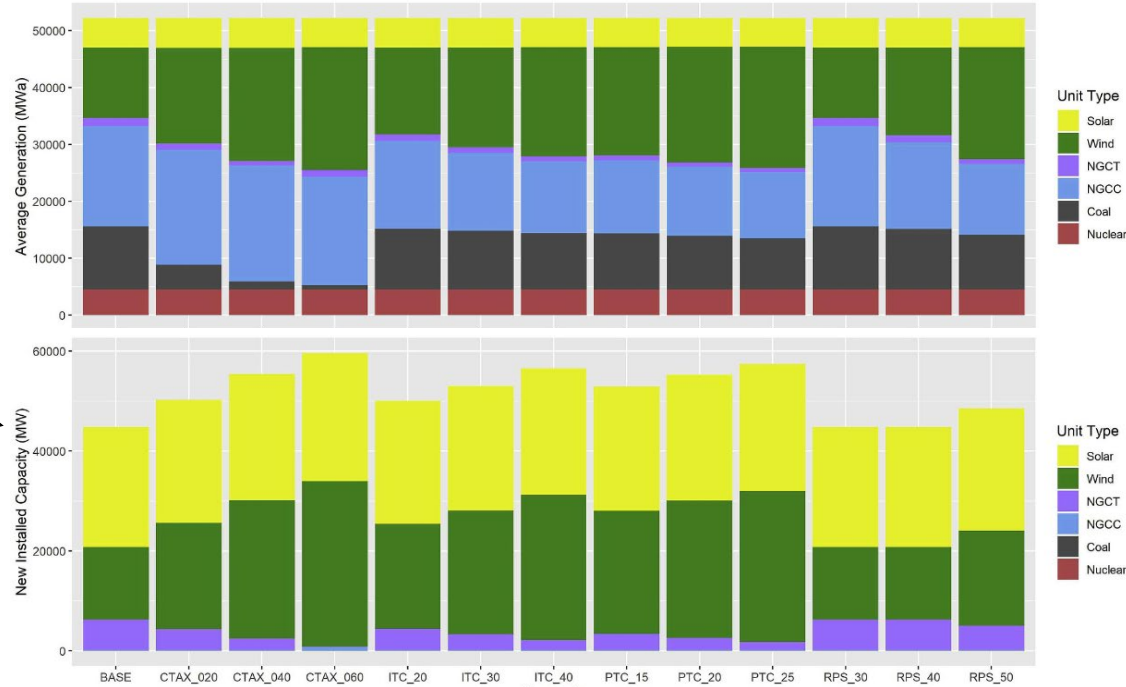
# ANALYZING SCENARIOS

These considerations can be varied across scenarios to assess outcomes to

**operations**

and **new installed capacity**

under various modeling decisions and policies.



Policy Scenario

**Example average generation and total capacity additions from a capacity expansion study.**

T. Levin et al. "The long-term impacts of carbon and variable renewable energy policies on electricity markets", 2019. *Energy Policy*.

# CAPACITY EXPANSION TOOLS

- Commercial: Energy Exemplar *PLEXOS* and *Aurora*, Hitachi *PROMOD*, GE *PlanOS*, EPRI *EGEAS*
- Research: Argonne *A-LEAF*, NREL *ReEDS*, MIT/Princeton *GenX*, Johns Hopkins *JHSMINE*, TU Berlin *PyPSA*

...and others.

# AFTER CAPACITY EXPANSION: TRANSLATION

## A few challenges in translation to reliability and economic models

### Siting Generation

If the capacity expansion model was zonal or copper plate, where should the new generation be located in the full nodal model?

### Disaggregating Demand

How should the zonal demand forecasts be applied to individual nodes in the full nodal model?

### Developing Study Cases

What conditions should be considered in the reliability analysis, and which hours are representative in the economic analysis?

**NERC standards place some requirements on these, and planning entities have developed heuristic approaches to address them within those bounds.**



# Q&A



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# PART 2: NEEDS IDENTIFICATION AND SELECTION



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# RELIABILITY ANALYSIS

- Created after the 1965 northeast blackout, NERC develops mandatory standards for reliability in operations and planning.
- Reliability analyses are the core studies in transmission planning.
- Multiple perspectives make up reliability studies, covering a wide range of grid phenomena and timescales.
- NERC defines reliability standards for transmission planning practice, along with many others relevant to transmission planning, including facility design, ratings, and connections, modeling and data, and critical infrastructure protection.

# NERC TRANSMISSION PLANNING STANDARDS

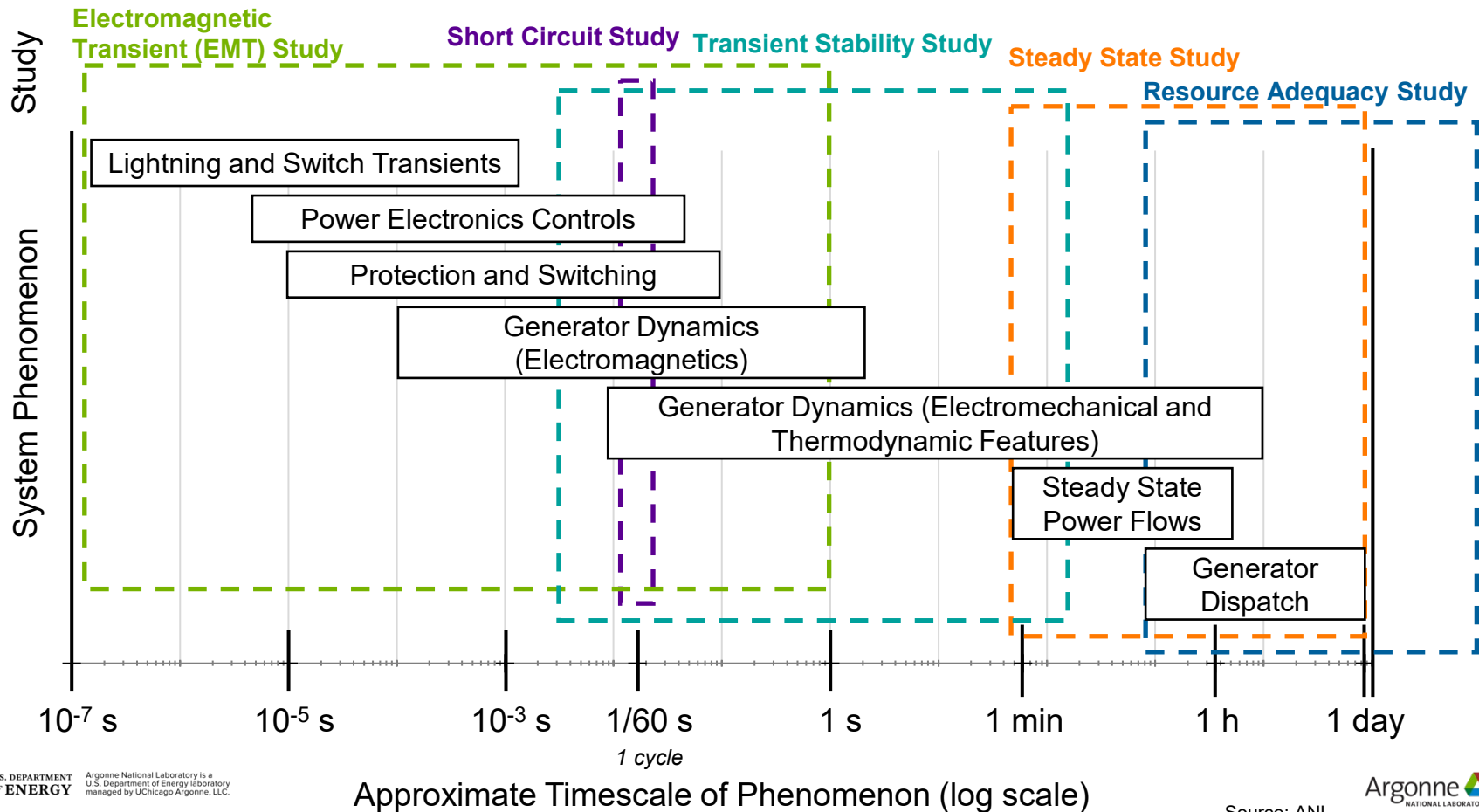
- **TPL-001-5.1:** Transmission System Planning Performance Requirements
  - Requires annual near-term and long-term assessment
  - On- and off-peak load must be included
  - **Contingency studies** must be performed
  - Required analyses:
    - **Steady state**
    - **Transient stability**
    - **Short circuit**
- **TPL-007-4:** Transmission System Planned Performance for Geomagnetic Disturbance Events
- **TPL-008-1:** Transmission System Planning Performance Requirements for Extreme Temperature Events (Filed and Pending Regulatory Approval)

# NERC CONTINGENCY EVENTS

## TPL-001-5.1, Table 1 – Steady State & Stability Performance Planning Events

Category	Event Type (Summary)
P0	Normal system, no contingency (N-0)
P1	Normal system loses one major component: generator, line, transformer, shunt device, one pole of DC line (N-1)
P2	Normal system experiences a line to ground fault (N-1)
P3	System after adjusting to loss of a generator unit loses one more major component (N-1-1)
P4	Normal system experiences a fault plus a stuck breaker, losing multiple components (N-?)
P5	Normal system experiences a fault with delayed clearing (N-1)
P6	System after adjusting to loss of one major components loses one more major component (N-1-1)
P7	Normal system loses two major components which share a common structure: adjacent circuits or bipolar DC line (N-2, also called “tower contingency”)

# RELIABILITY PHENOMENA AND STUDIES



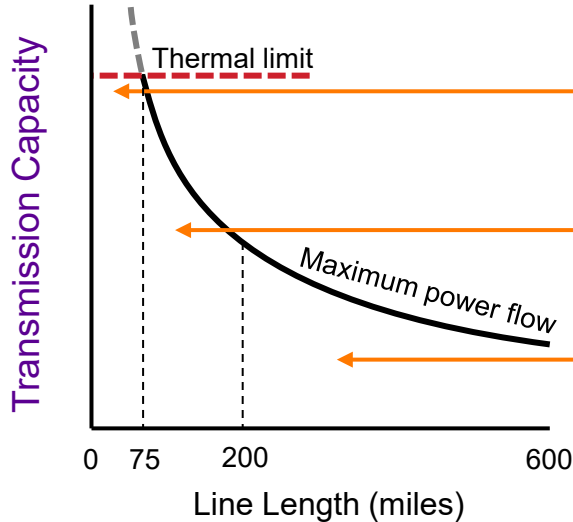
# STEADY STATE ANALYSIS

## Transmission constraints of interest

- Three features account for most transmission constraints:
  - **Thermal Limits:** Arise from the material limitations of the conductor. As current on the conductor increases, it creates more heat and the line sags. The actual physical limit depends on ambient temperature and wind; thermal limits are set very conservatively.
  - **Voltage Drop:** Depends on the line's electrical parameters and surrounding system conditions. The voltage drop across a heavily loaded line can be large, potentially leading to voltage issues in the system.
  - **Steady State Stability:** also depends on the line's electrical parameters and system conditions. The voltage angle difference across heavily loaded lines may also be large, which has implications for generator stability and synchronization.

# STEADY STATE ANALYSIS

## Example: line loadability by length



Source: ANL

**Thermally constrained:**  
*often the only limit at play for short lines; can apply to any line length*

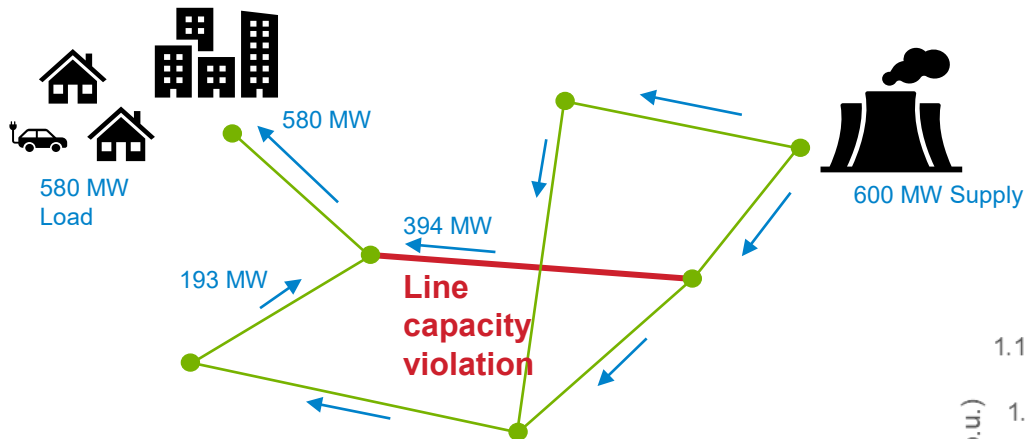
**Voltage constrained:**  
*begins to arise for medium-length lines*

**Stability constrained:**  
*most typical of long, higher voltage lines*

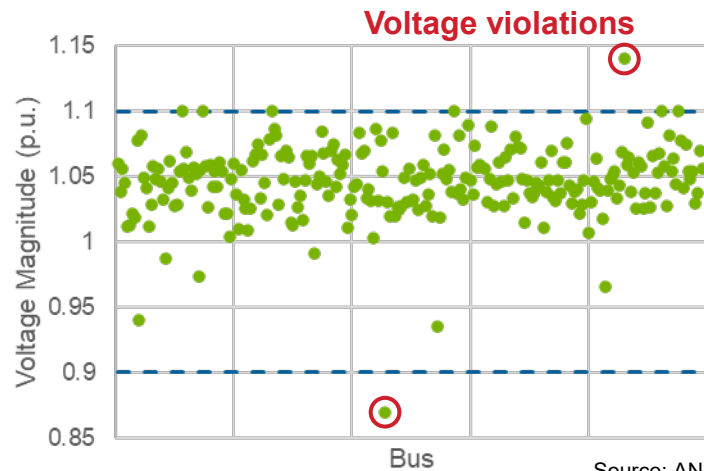
**Thermal constraints** arise entirely from the engineering design of the individual line: conductor material, diameter, bundling, etc.

**Voltage and stability constraints** depend on both the line and the operational state of the rest of the system.

# POWER FLOW VIOLATIONS



AC and DC power flow can identify line capacity violations, but DC can only identify thermal violations and is less accurate (may over- or under-estimate).



Source: ANL

AC power flow must be used for voltage/reactive power studies.

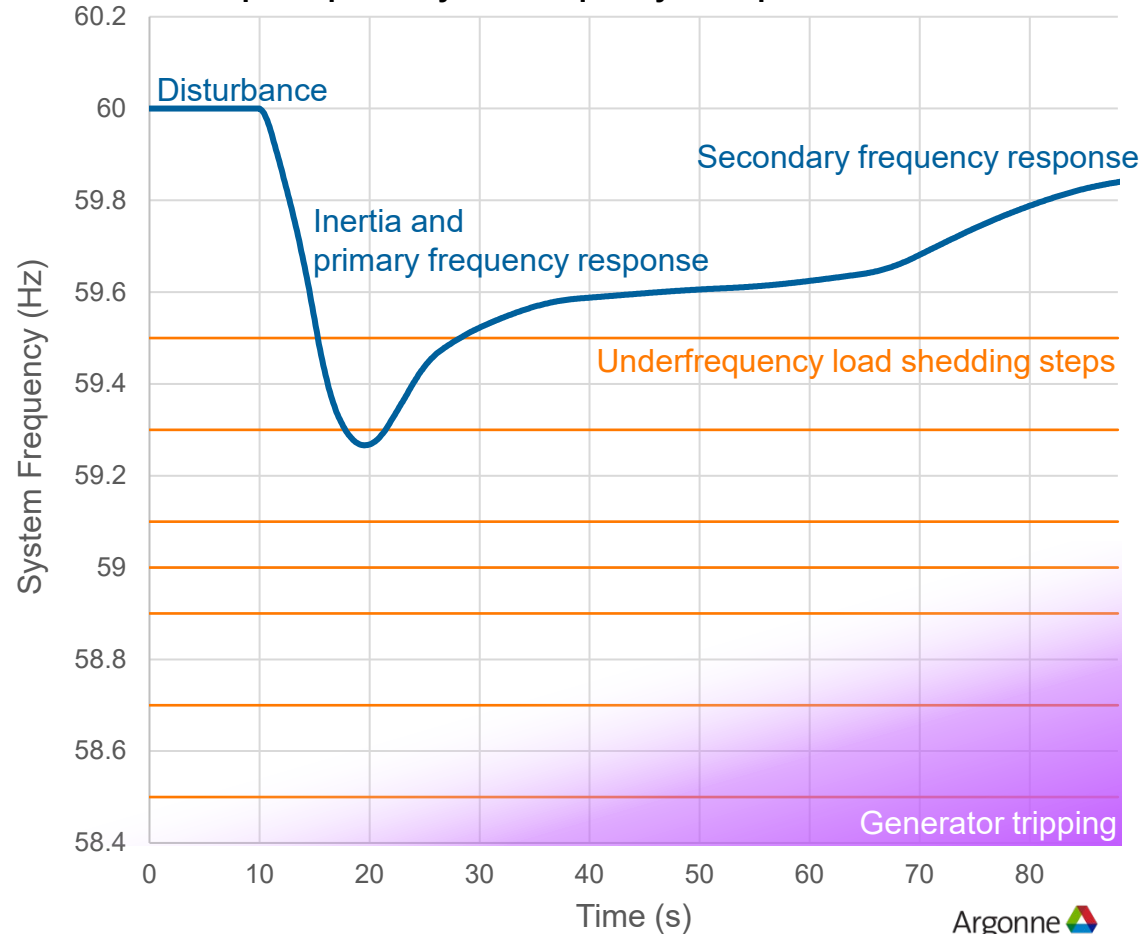
# MODELS FOR STEADY STATE STUDIES

- DC Power Flow: May be used for simplistic studies accounting for only thermal constraints. No ability to assess voltage or steady-state stability.
- AC Power Flow (bus-branch model): Used to analyze thermal, voltage, and steady-state stability constraints.
- Software:
  - Siemens *PSS®E* is used throughout the Eastern Interconnection, GE *PSLF* in the Western Interconnection; others include *PowerWorld*, DigSILENT *PowerFactory*, *MATPOWER* (open source MATLAB), *PandaPower* (open source Python), *PowerModels* and *Sienna/Ops* (open source Julia).
  - PowerGem *TARA* is a more specialized software for contingency studies and transfer limit calculations and is widely used in transmission planning.

# TRANSIENT STABILITY

- Electric power systems are complex electromechanical systems.
- Two important dynamic values are **frequency** and **voltage**.
- Frequency corresponds to the rotation speed of synchronous generators; control responses involve many generators and act at several timescales.
- Voltage stability depends on the relationship between active power, reactive power, and voltage magnitude.

Example of power system frequency in response to a disturbance.

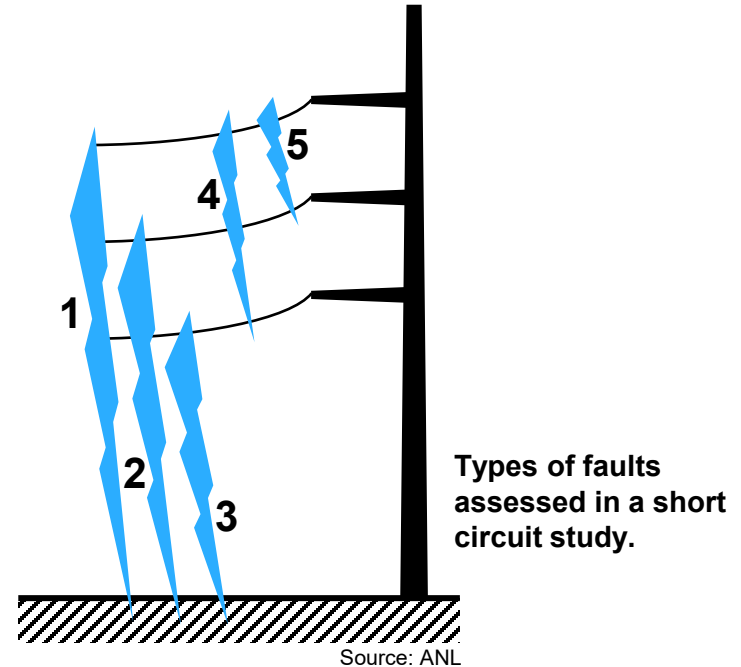


# SOFTWARE FOR TRANSIENT STABILITY

- Siemens *PSS®E*, GE *PSLF*, and *PowerWorld* are widely used for stability studies.
- NREL's *Sienna\Dyn* is an open source simulation tool for transient stability.
- When a system has significant levels of inverter based resources, electromagnetic transient (EMT) simulations may be needed, which simulate greater detail and much higher temporal resolution. *EMTP* and *PSCAD* are typically used for these studies.

# SHORT CIRCUITS AND SYSTEM PROTECTION

- Circuit breakers protect the system and its surroundings from the adverse effects of a faulted component
- Breakers divide the system into zones, ensuring faults affect only the appropriate zones
- Short circuit studies determine the required breakers (fault current interrupting capacity) for any type of fault:
  1. Three phase to ground
  2. Double line to ground
  3. Single line to ground
  4. Three phase
  5. Line to line



# SHORT CIRCUIT STUDIES

## Importance in Transmission Planning

- Changes to generation and transmission impact short circuit characteristics, which may necessitate multiple breaker upgrades
- Protection equipment upgrades are a very common transmission need
- Substations typically have 1 or 1.5 (sometimes 2) circuit breakers per circuit
- Example: Recent RTEP project in PJM consisting of one 345 kV circuit breaker upgrade, \$2.7M estimated total cost

# SHORT CIRCUIT TOOLS

- Many steady state analysis tools include short circuit calculation modules:
  - Siemens *PSS®E*, GE *PSLF*, *PowerWorld*, and DigSILENT *PowerFactory*
- Siemens *Gridscale X* (formerly known as *CAPE*) can provide more detailed analysis of protection operations and settings
- *ETAP* and Eaton *CYME* are also used for short circuit calculations but more often at the distribution level

# ECONOMIC STUDIES

- These studies share many similarities to capacity expansion models, but rather than identifying generation and retirements, they focus on questions like
  - Which available generator units should be committed to generate the next day? (unit commitment)
  - Of the units that are committed, what should each produce to [reliably] serve demand at least cost? ([security constrained] economic dispatch)
  - How does transmission congestion contribute to the cost of meeting demand (shadow prices), and what are the different prices on each side of a congested interface (locational marginal price, LMP)

# FROM STUDIES TO NEEDS

- Reliability violations under the NERC criteria for analyses constitute a reliability need which the planning entity must address.
- Some exceptions are allowed with significant justification and a plan to address the violation.
- Public policy needs can arise from a separate public policy planning process which includes the policies in the scenario development process. These needs may be categorized separately.
- Economic needs are identified as persistent sources of congestion leading to market inefficiency. Per Order 890, planning entities must identify these but are not required to address them.

# POTENTIAL SOLUTIONS

- New transmission line(s)
- Substation upgrades (switchgear, transformers)
- Reconductoring
  - Conventional conductors
  - Advanced conductors
- Voltage upgrades
- Series compensation
- Power flow control
  - Phase shifting transformers
  - Flexible AC Transmission Systems (FACTS)
- Storage as a transmission asset (SATA)
- Operational solutions
  - Dynamic line rating
  - Transmission switching (topology optimization)

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**Alternative transmission technologies required for consideration under Order 1920**

# FROM NEEDS TO SOLUTIONS

- Many ISOs/RTOs have a competitive transmission process in which they issue a request for proposals soliciting competitive solutions to address each identified need. Transmission providers in non-RTO regions manage this individually.
- The process must include clearly defined selection criteria which are used to evaluate projects.
- Benefit calculations are used in cost-benefit selection criteria
- Order 1920 defines seven benefits to consider:

**Avoided replacement**

**Reduced loss of load probability**

**Production cost savings**

**Reduced transmission losses**

**Reduced congestion due to outages**

**Mitigation of extreme weather impacts**

**Capacity cost benefits from reduced losses**

- Calculation of these benefits relies on many of the same concepts and tools already discussed.



# Q&A



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