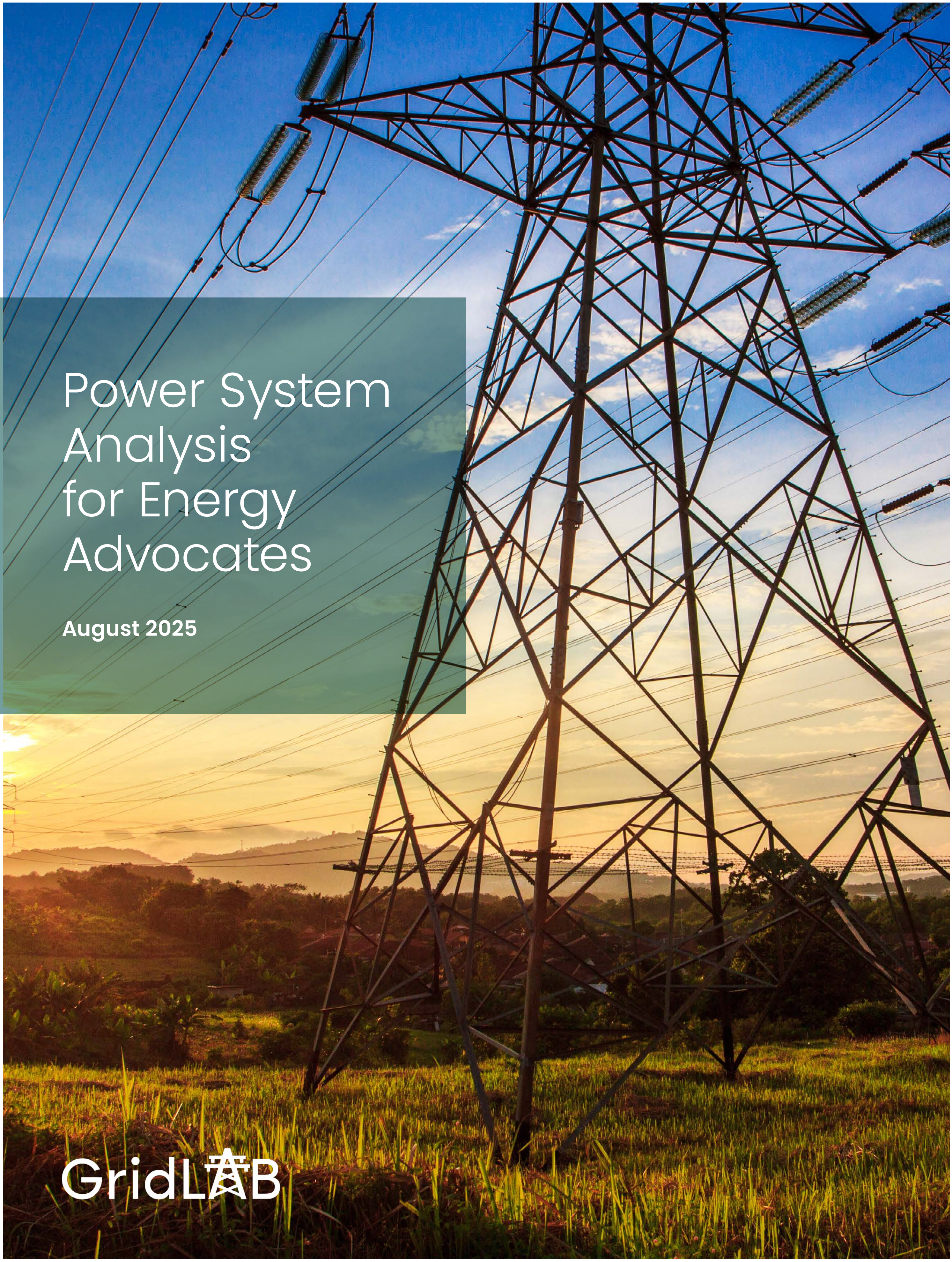

Power System Analysis for Energy Advocates

August 2025

GridLAB

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ACKNOWLEDGEMENTS

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Abbreviations

BA	Balancing Authorities
Branch	a representation of a three-phase transmission line or transformer that connects busses
Bus	a node on the network where real power, reactive power, voltage, and voltage angle are being calculated
DC	Direct Current
DFAX	Distribution Factor
EMT	Electromagnetic Transient Analysis
ERO	Electric Reliability Organization
ERCOT	Electric Reliability Council of Texas
FACTS	Flexible Alternating Current Transmission Systems
Generator	a source of electric power. Real power is injected into the network at "generator busses." These are represented by circles in power system diagrams
GETs	Grid Enhancing Technologies
GFM	Grid Forming Inverters
HPC	High Performance Conductor
HVDC	high voltage-direct current
ISO	Independent System Operator
ITCS	Interregional Transfer Capability Study
kV	kilovolt
LGIA	Large Generator Interconnection Agreement
Load	an end consumer of electric power. Real power is consumed at "load busses." These are represented by triangles in power system diagrams. The distribution system is equivalenced at each bus into single point loads. The topology of the distribution system is often not represented in transmission models.
MW	Megawatt
NERC	North American Electric Reliability Corporation
OASIS	Open Access Same-Time Information System
One-Line	a visual representation of the network model showing busses, branches, generators, and loads.
RAS	Remedial Action Schemes
RE	Regional Entities
RTO	Regional Transmission Organization
SCED	Security Constrained Economic Dispatch
STATCOMs	Static Synchronous Compensator
SVCs	Static VAr Compensators

Introduction

The transmission system is the backbone of the electricity network in the United States. Most electric energy today is generated at large power plants spread out across the country and shipped to the business centers, manufacturing hubs, mining regions, and neighborhoods where it is needed via high-voltage (69kV and above) transmission lines. Historically, utility planning prioritized building the most cost-effective power generation sources to meet forecasted demand. Under this paradigm, transmission planning was treated as a secondary, follow-on effort to build out the network needed to connect specific generation resources to specific loads.

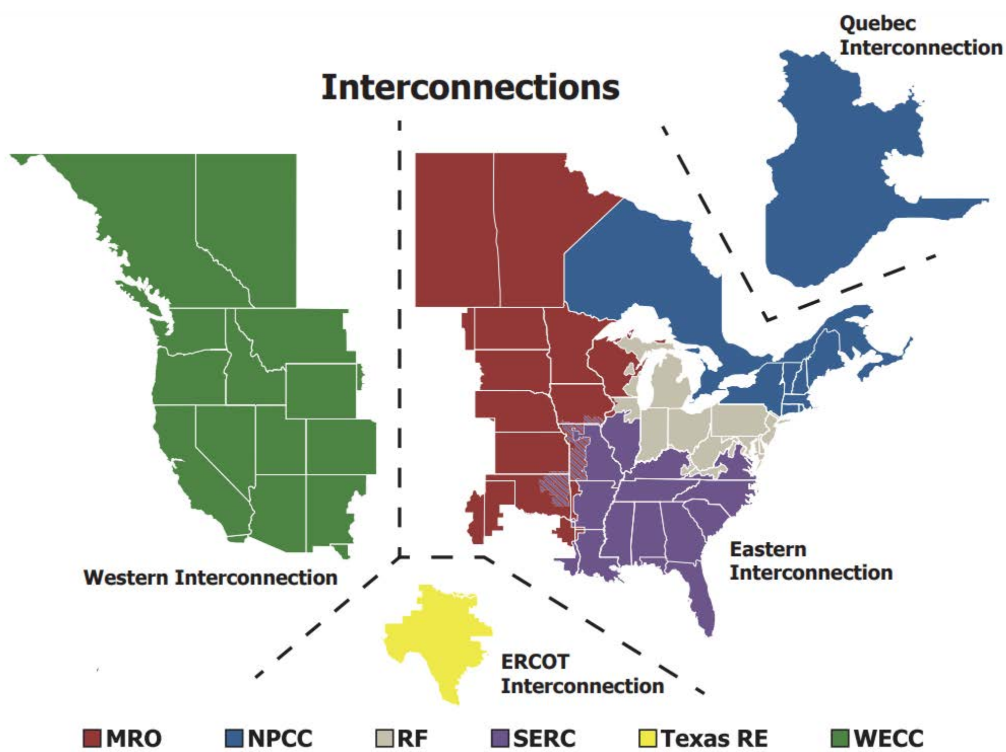
However, the landscape of the energy grid is changing. For the first time in a generation, grid planners are forecasting unprecedented demand growth driven by datacenters, electrification, and manufacturing. At the same time, natural gas, which for decades had been considered the lowest cost, highly reliable means of generating electricity, has suffered price spikes and susceptibility to extreme weather. As a result, diversifying the resource stack is becoming a key priority to increase system reliability, keep prices low, and reduce emissions.

Given this challenge, transmission system expansion has become an essential part of America's energy future and the processes that governed transmission development for the last several decades are insufficient to create the network needed for our future energy needs. **Energy advocates now need to have a basic understanding of how the transmission system is modeled and analyzed to effectively intervene at all levels of energy system regulation**. This guide provides an outline including how transmission planning regions are organized, the mechanics of power system analysis, and the limitations of current processes. Throughout the guide, links to resources are provided so that advocates can dive deeper into the concepts as needed.

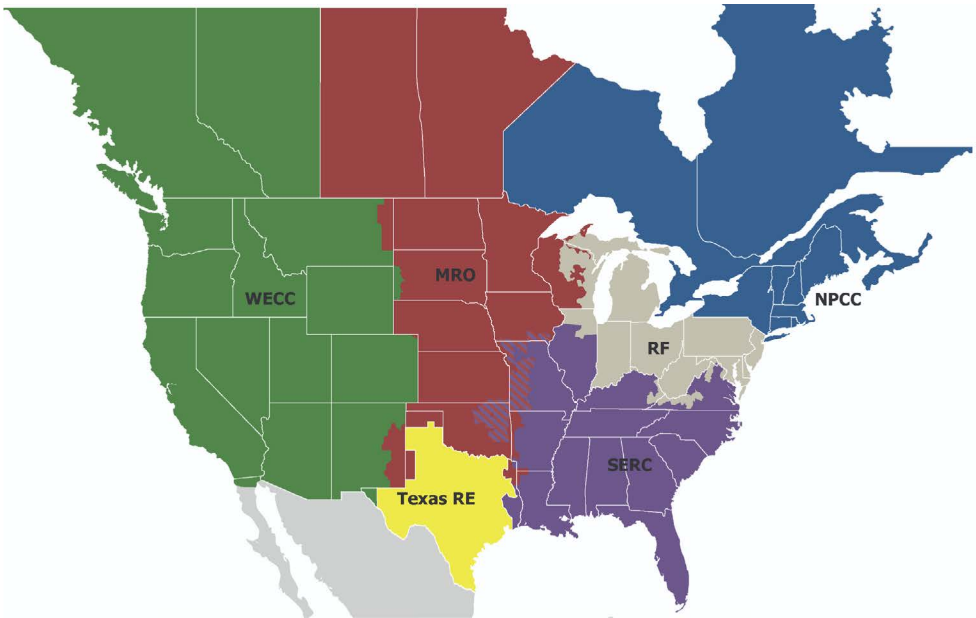
Transmission expansion can unlock new lower cost generation, increase system reliability, and reduce pollution. For this reason, it is important for energy advocates of all types to understand and engage in their region's transmission planning process. Unfortunately, transmission system analysis is a highly technical and time-consuming undertaking, which can be a barrier for advocates. Therefore, the goal of this document is to provide a simplified explanation of concepts to focus on the outcomes important to energy advocates. **For this reason, important electrical engineering concepts, especially around three-phase AC systems, are not presented in their entirety.**

US transmission planning regions

The US is divided into three "interconnections," or electrically distinct transmission regions that operate independently of each other, including the "Western Interconnection," "Eastern Interconnection," and Electric Reliability Council of Texas (or "ERCOT"). As part of the fallout of the Northeast Blackout of 2003, the Energy Policy Act of 2005 authorized the Federal Energy Regulatory Commission (FERC) to designate a national Electric Reliability Organization (ERO). On July 20, 2006, FERC issued an order certifying the **North American Electric Reliability Corporation (NERC)** as the ERO for the United States. All of these regions are subject to NERC reliability standards including the Canadian provinces. Very little energy is exchanged between these interconnections, other than relatively small HVDC (high voltage-direct current) ties.



The interconnections are further divided into **Regional Entities (RE)** that comprise the **Electric Reliability Organization (ERO)**. These entities are responsible for regional coordination and adherence to NERC standards.



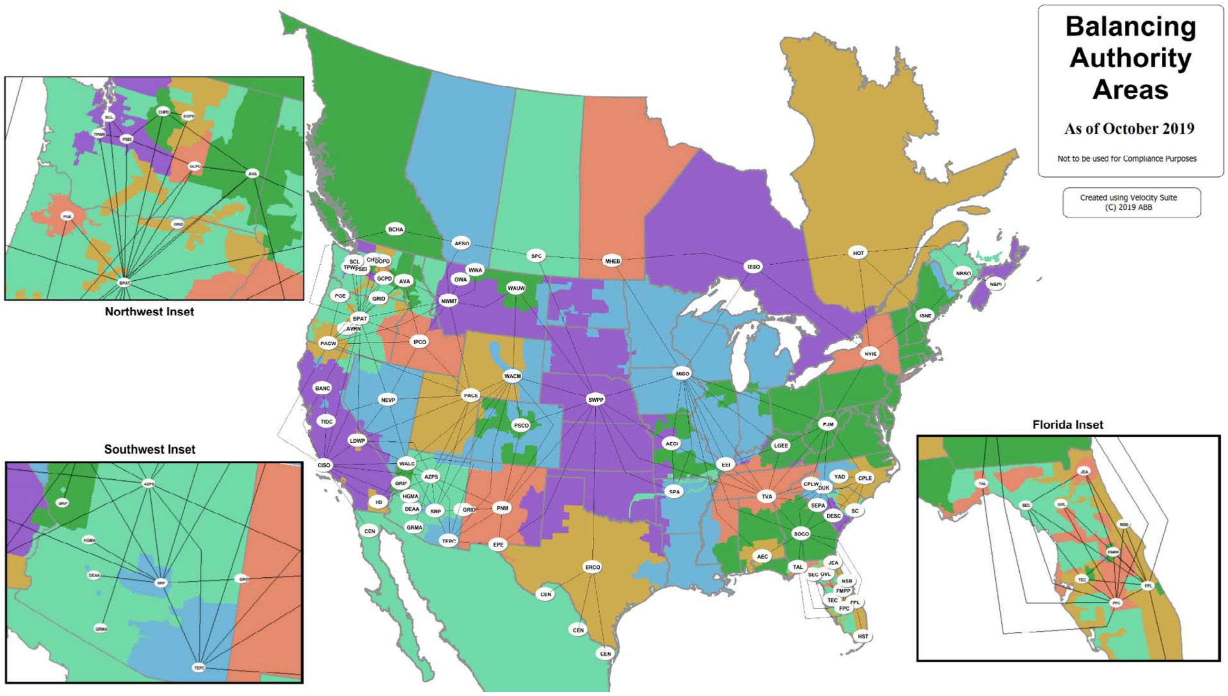
RESOURCE NERC Regional Entities

Inside each Regional Entity is a set of **Balancing Authorities (BA),** which are the grid operators responsible for balancing electricity generation and electricity demand. They do this by dispatching generation inside their BA and/or adjusting "interchange" (buying or selling energy) with their neighboring BAs to ensure there is exactly enough generation available to serve the demand in their system. BAs are the primary entity that must ensure their system operates within NERC reliability standards. Most BAs perform operations and planning functions. BAs can be small organizations of only a few employees to over a thousand employees. **Most transmission planning is conducted at the BA Level.**

RESOURCES

The role of a Balancing Authority

List of Balancing Authorities in the US


Balancing Authority Areas
As of October 2019
Not to be used for Compliance Purposes
Created using Velocity Suite (C) 2019 ABB
Northwest Inset
Southwest Inset
Florida Inset
BCHA
AESO
SPC
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IESO
HQT
NBSO
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ISNE
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MISO
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ERCO
TVA
SOCO
WACM
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LGEE
CPLW
DUK
YAD
CPLE
SEPA
SC
SCEG
AEC
TAL
SEC
JEA
GVL
NSB
FMPP
TEC
FPC
FPL
HST

Typical transmission organization structure

Each BA organization is organized a little differently, but generally they are either part of a transmission owner/electric utility organization or part of an Independent System Operator (ISO) or Regional Transmission Organization (RTO).

RESOURCE Power Markets in the US

The functions of the transmission organization are generally divided into "operations" and "planning" functions.

The role of a transmission operator

VIDEO "A Day in the Life of a Dispatcher"

Transmission operators operate the transmission system in real time and plan for system operations over the next year. Their work is heavily regulated and monitored using recorded lines and reporting to their NERC Regional Entity. Transmission operators are hosted in secure locations, sometimes including armed guards, and their data is highly restricted because there are both public safety risks and market manipulation risks if operations data were to be disclosed. For this reason, there is not much advocacy work done at the Transmission Operations level, other than post-mortem analysis, which is completed after major events once the data becomes public.

EXAMPLES

Advocacy work using market operations data

MISO Public OASIS site

Unfortunately, all OASIS sites are organized a little differently. However, typically, the only important data that advocates may need can be found on these sites by looking for transmission notices, transmission reports, and interconnection studies. Transmission Owners are required to list major transmission

The transmission operations data that is shared must be posted publicly and therefore available to all energy market participants at the same time. This is done using the Open Access Same-Time Information System ("OASIS"). OASIS sites are divided into public and restricted areas. Generally, advocates will only have access (and will only need access to) the public OASIS sites.

studies, including generator interconnection studies, and allow interested parties to request access to these reports. The process differs for each entity, but there is usually contact information provided if one needs support.

Electricity market data is also consolidated and reported at the ISO/RTO level. Each region has its own way of reporting this data, and it is ultimately consolidated by the Energy Information Administration. However, GridStatus.io is easier to use and provides an API to support market data analyses.

RESOURCE Grid Status

The role of a transmission planner

Transmission Planning is the practice of modeling the transmission system, projecting what a future system will look like 1 to 20+ years in the future, identifying credible reliability risks (such as the potential for blackouts, equipment failures, or overloads), and proposing solutions to mitigate the risks identified. Transmission Planning includes studying generator interconnections, large load interconnections, and long-range system planning.

Introduction to Transmission Modeling

Electric Transmission Basics

The electric transmission system operates in accordance with the laws of physics. These laws explain how electricity moves through the grid and why the system works the way it does — no matter who's running it. There are generally three "laws" of electricity that are used in power system analysis:

Ohm's Law:

Voltage (V) = Current (I) x Resistance (R)
Power in an electric circuit can be calculated as Voltage (V) x Current (I)
Using mathematical substitution and Ohm's Law, power can also be calculated as I^2R or V^2/R

VIDEO Explaining how to calculate power in electric circuits

In Transmission System Analysis — which deals with how electricity flows over long distances — power is generated at "generators" (such as power plants) and consumed by "loads" (like homes, factories, and data centers). The calculation of this power transfer is more complex in three-phase AC power systems (the standard for transmission grids), but Ohm's law is always obeyed.

Kirchhoff's Current Law:

The sum of the currents entering a node equals zero.

This is a way of restating the principle of conservation of energy for electric circuits. Said another way: all electric current entering a point in the circuit (called a node) must also leave that point.

In Transmission System Analysis, this shows up as power (voltage times current) flowing into and out of nodes — called "busses" in the high voltage context — in the system. The only way for power to enter the transmission network is from "generators" and the only way for power to leave the network is through "loads" (where energy is consumed, essentially electricity customers of all sizes) or through "losses", which are small amounts of power lost as heat in the transmission lines.. This means that power (measured in megawatts, or MW) must always be balanced between generation, loads, and losses in power system models. Stated as an equation:

Power in = Power out, or
Generation = Loads + Losses

Kirchoff's Voltage Law:

The sum of the voltages around any closed electric loop is zero.

In Transmission System Analysis, the key concept is that voltage in a transmission network is a function of the source (the generators), the resistance (or more accurately, impedance, which also accounts for reactance), and the nature of the loads. In AC systems, voltage is changing constantly, so these factors are complex (meaning they are mathematically represented by phasors on the real and imaginary plane). For this reason, AC power flow analysis requires network modeling to accurately estimate the system's performance.

But in a simplified way, here's what this means: As electricity moves around a circuit, the voltage provided by the source is **distributed across** the components in the loop — like resistors, transformers, or loads. By the time the electricity completes the loop, all of the voltage has been **accounted for** through these voltage drops. Nothing is lost or left over. Think of it like going on a round trip where all the elevation gains and drops add up to zero — you may go uphill and downhill along the way, but when you return to your starting point, your total change in height is zero.

Recommended Resources:

- **VIDEOS**
  How Electricity Works (Induction and Transformers)
  Three-Phase Power Explained

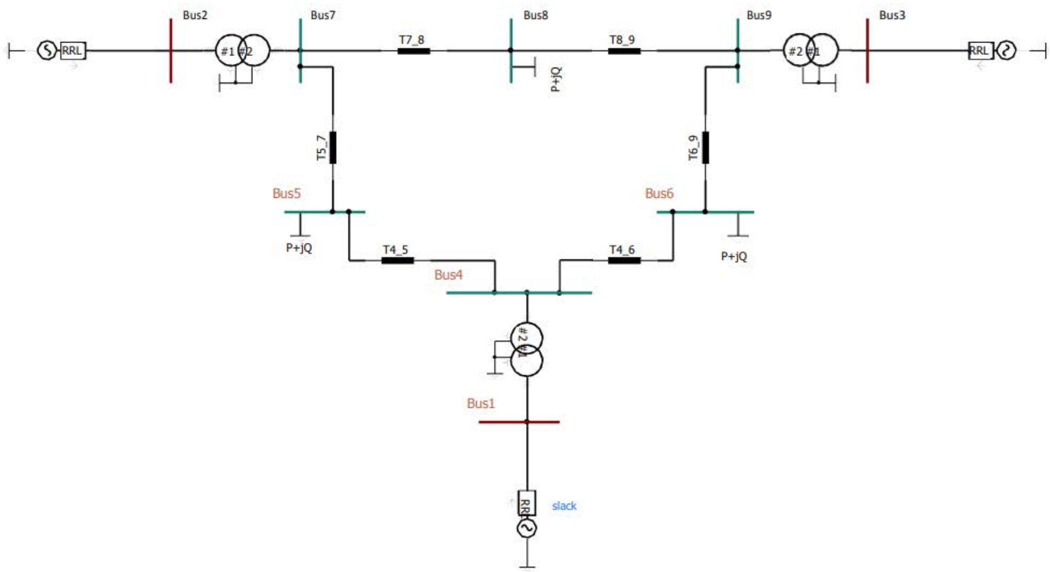
- **RESOURCE** How Transmission Works

AC and DC Transmission Systems

Electricity can be transmitted as direct current (DC) or alternating current (AC). In DC systems, electricity flows in a single, constant direction. In contrast, AC systems involve a continuous reversal in the direction of current flow. Most of North America's electric transmission system uses three-phase AC, a standard that enables efficient power delivery over long distances. While the technical workings of the three phases are complex, what is most relevant is that this approach helps maintain system stability, improves the balance of electrical loads, and minimizes transmission losses.

The goal of transmission system modeling

Transmission system modeling is a process of simulating the AC electric transmission system (typically 69 kV and above) using electrical engineering techniques to equivalence the system and create a network model. Three-phase transmission system modeling is done by solving the "power flow" equation. This model is mathematically represented as a matrix with tens of thousands of values that describe voltages, currents, and flows at different points on the system. This matrix can be solved using a variety of numerical methods. In most cases, the matrix is presented in the form of a "one-line" diagram (a simplified graphic that shows the electrical components of the system) to display the model to make the results more visually intuitive. An example of a one-line diagram is shown below. This diagram represents the IEEE 9-bus benchmark case, a standard test system commonly used for simulation and analysis, and is available in PSCAD.



Transmission System Modeling

The general process of conducting a transmission study is the following:

1. **System Modeling:** Historical load data, generator data, and transmission system data are collected, usually from a variety of departments and sometimes other companies. This data is incorporated into a system model referred to as a "base case."

2. **Load Forecasting:** Future load demand is forecasted based on historical data, economic factors, and weather patterns. This load forecast is then simulated in the system model.

3. **Generation Forecasting**: Integrated Resource Plans and/or interconnection queues are used to build out a future generation portfolio for the period being studied.

    a. The generation dispatch (which generators are turned on, which are turned off, and how much each injects into the system) is dictated by the type of study being conducted. In some cases, the dispatch is set by the economics or predicted weather conditions, in other cases the dispatch is tuned to evaluate system performance under rare, but possible, conditions.

4. **Powerflow Analysis:** Powerflow analysis (a.k.a. "load flow") is performed to determine the flow of electricity through the transmission system under various operating conditions.

5. **Contingency Analysis:** Contingency analysis is performed to identify potential problems that could occur in the transmission system, such as the loss of a transmission line or a generator.

6. **Mitigation Planning:** Mitigation plans are developed to address any potential problems identified in the contingency analysis.

- **VIDEO** explanation of transmission system modeling

The electric transmission system operates according to fundamental physical laws that determine how electricity flows across the grid. Concepts like Ohm's Law and Kirchhoff's Laws help engineers ensure the system is balanced and reliable. Most of the grid in North America uses three-phase alternating current (AC), which allows for efficient long-distance power delivery. To plan and operate the system, engineers create mathematical models and use simplified visuals like one-line diagrams to represent how power moves from generators to consumers.

Transmission system analysis

Once a transmission model is built, Transmission Planners conduct a series of analyses on the model to evaluate system performance. Currently, transmission models are only capable of simulating a "snapshot in time," where the performance of the system is simulated for approximately 0-20 seconds. There are emerging techniques and software aimed at simulating the transmission system performance over a greater time period, but generally transmission planning is conducted using a series of "snapshots" of stressful conditions to probe for problems on the system.

Steady State Analysis

a. "**Reliability or Contingency Analysis**"

The most common form of Transmission Analysis is "contingency analysis" where the transmission planner takes a base case, simulates outages of one or more system elements (such as lines or transformers) to observe how the system would respond. The planner only observes a single snapshot of the system under steady (i.e. not changing) conditions and then a new snapshot following the contingency to look for how the system would perform. The goal of this analysis is to stress test the system and determine what events could trigger reliability problems for the transmission network. To guide this effort, all transmission providers in CONUS must follow NERC standards, notably NERC TPL-001-5, which outline the performance requirements of the system following defined perturbations.

1. The conditioning of the case is essential to getting accurate results. Transmission Planners will tune the case to represent the most stressful, yet credible, conditions. For example, typically the cases represent the highest loading conditions expected during the year ("summer peak" or "winter peak") and then simulate the loss of the largest generator or transmission line on the system. If the loss of this element causes other network elements to overload or indicates that load could be lost, then a mitigation is needed.
2. Increasingly, transmission planners are also testing "low-load, high generation" conditions to identify emerging reliability risks during seasons when load is low, but intermittent renewable generation is high.

3. The typical reliability risks identified in this process include thermal overloads or voltage excursions beyond predefined limits.

    a. **Thermal overload** - too much power is being sent through a line or transformer, and the ensuing heat could hurt the equipment or risk failure (failure could mean serious risk to public safety, including sparking fires or risking electrocution). Note that this does not always mean the equipment could fail due to heat, but often the heat results in lines expanding or "sagging." If lines sag beyond National Electric Safety Code clearances, there is risk that the electricity could flash over into vegetation or structures. Line thermal ratings are based on both the material and clearance of the structures.

    b. **Voltage excursion** - The voltage at a point on the system exceeds the safe operating range. If voltage is too high, there is risk of "flashover" where the insulating equipment can fail. If voltage is too low, electric motors will start to stall and the system risks "voltage collapse." The specific voltage limits for safe operation are usually defined by the regional Independent System Operator (ISO) or Regional Transmission Organization (RTO).

4. The identification of reliability risks under NERC standards does not include economic inputs like Capacity Expansion Modeling or Production Cost Modeling. The dispatch of generation may be informed by economics (planners will turn on more efficient generation before turning on less efficient "peaker" generation), but Transmission Planners are charged with ensuring the system can operate under all credible dispatch scenarios. For this reason, **advocates may come across non-intuitive results where transmission planners are requiring mitigation for scenarios that are exceedingly rare.**

5. Generally, transmission planners do not incorporate the natural gas - electric interface into their reliability analyses. However, grid planners are starting to investigate this risk vector because it was a primary cause of electric outages during both Winter Storm Uri and Winter Storm Elliot. Current Transmission Planning practice is to assume that natural gas fired generators operate independent from one another (if one generator goes out, another can be brought online). However, since many of these plants are fed from the same pipelines and/or natural gas basins, this assumption is hiding inherent risks to the resiliency of the energy system.

b. **Deliverability Analysis** is a process used to assess the ability of the transmission system to deliver power from generators to load centers. It is performed to ensure that the system can meet the forecasted demand for electricity while maintaining reliability standards. This is a special version of contingency analysis where the generator dispatch is set to simulate stressful conditions for specific network zones.

c. Software tools:

There are a variety of software tools used to perform powerflow analysis. Most Transmission Owners in the US use commercial tools, but there are emerging open source analysis tools that continue to be developed.

Commercial Tools

GE PSLF
Siemens PSS/E
PowerGEM TARA
PowerWorld
DSA TSAT
DigSilent PowerFactory
MatLab Simulink

Open Source Tools

PyPSA
NREL Sienna
GenX

Dynamic/Transient Analysis

After completing steady state analysis described above, the next more detailed analysis is dynamic and/or transient analysis. The goal of dynamic/transient analysis is to observe the dynamic response of the transmission system to faults and disturbances between steady state conditions (0-20 seconds). This is similar to contingency analysis, but instead of looking at static snapshots before and after an event, dynamic analysis captures the system's behavior in real time — including how quickly it recovers, whether it oscillates, or becomes unstable. This analysis helps identify reliability risks that do not appear in steady-state models, such as voltage or frequency instability, generator tripping, or control system failures.

a. **Transient Stability** - AC power systems require "synchronism" between different elements. This means that grid disturbances cannot change the grid conditions too quickly or it risks disrupting the stability of the system. The grid is made up of electrical and magnetic connections (such as the connection between a generator rotor and stator or two adjacent electric motors) that all operate at the same "rhythm." If one element starts to move faster or slower than the other elements, it can cause grid reliability issues. This is sometimes referred to as "angular instability." The metaphor commonly used is a bicycle drivetrain. If the two cogs on the bicycle rotate with the same frequency, the chain spins and the bicycle moves forward. However, if the rear tire gets stuck and the rider continues to pedal, the front cog will keep moving while the rear cog stays stationary. The "angle" between the two cogs will diverge, and if this continues too far, the chain will slip off the cogs.

b. Dynamic and Transient Stability analysis can identify reliability risks that could occur in fractions of a second due to inadequate grid inertia, improper generator controls, or lack of proper voltage support.

c. These risks can be mitigated with a variety of tools including

   i. Advanced synchronous generation controls

   ii. "Dynamic reactive support"

      1. Static VAr Compensators (SVCs)

      2. Synchronous Condensers

      3. STATic synchronous COMpensator (STATCOMs)

   iii. Remedial Action Schemes (RAS)

d. Transient Stability is a broad topic and includes in-depth analysis including voltage stability, small signal stability, controls, and oscillatory analysis.

RESOURCES

Transient Stability explained

The Grid Forming Inverter Landscape

Power Quality Analysis

Power quality analysis is essential for ensuring the reliable and efficient operation of electrical systems. Poor power quality can lead to equipment malfunctions, reduced lifespan of sensitive devices, data loss, and even costly downtime for industrial and commercial users. By analyzing power quality, utilities and system operators can identify underlying issues, protect infrastructure, maintain regulatory compliance, and ensure a stable supply of electricity that meets the needs of all customers.

The following types of studies are conducted by Transmission Planners and control engineers to determine if the dynamic (changing) behavior of loads cause issues that could impact all grid users.

Transient analysis can identify issues that require mitigations. However, assertions that "synchronous generation" (which typically means natural gas or coal fired generation) is needed to address these concerns often ignore advanced dynamic reactive support tools or the stability benefits provided by inverter-based resources. In particular, Grid Forming Inverters (GFM) tied to battery storage can provide primary frequency response (sometimes referred to as "synthetic inertia"), fast frequency response, voltage support, damping, and other services to ensure grid stability.

1. **Flicker Study**
    a. If the demand on the system changes rapidly, system voltages can change rapidly in response. Colloquially, this is referred to as "flicker" where lights will change brightness in response to rapidly changing system voltages.
2. **Ramping Study**
    a. Generators and loads historically did not switch on and off at the full power rating instantaneously. Coal plants take many hours to "ramp up" to full rated power and legacy large load customers like smelters, mines, and manufacturing plants would take days to weeks to ramp up to their full load. This fact is changing on today's grid with the growing interconnection of inverter-based resources and demand from datacenters (which can ramp up within seconds to minutes). Transmission planners will use powerflow models to evaluate risks associated with plant ramping on an ad hoc basis, and if needed determine ramping schedules to avoid impacts on the greater grid.
3. **Harmonics Analysis**
    a. Harmonics in the transmission system are currents or voltages with frequencies that are integer multiples of the fundamental frequency 60 Hz. For example, the second harmonic would be 120 Hz, the third harmonic would be 180 Hz, and so on. Harmonics are primarily caused by non-linear loads that draw current in a non-sinusoidal fashion, leading to the generation of harmonic frequencies. Common examples of non-linear loads include power electronic devices like variable frequency drives, rectifiers, and inverters. Transmission planners and operators use various techniques to mitigate the effects of harmonics:
        i. Harmonic Filters: These devices are designed to absorb or block specific harmonic frequencies, preventing them from propagating through the system.
        ii. Transformer Connections: Certain transformer connections, such as delta-wye, can help to reduce the flow of certain harmonic currents.
        iii. Active Filters: These use power electronics to actively cancel out harmonic currents.
        iv. Harmonic Studies: Power system studies are conducted to analyze the levels of harmonics in the system and identify potential problems.

Protection Analysis

Protection analysis (sometimes referred to as "Short Circuit Analysis" or "Fault Duty Analysis") includes the study of how the transmission protection systems will operate in response to a fault or grid disturbance. Transmission protection systems are designed to automatically protect public safety and the greater grid when a line or other grid element fails. The protection system does this primarily through the use of relays and breakers (and in rare cases fuses) to sense the grid disturbance and “trip” (or open) the circuit. Protection engineering is a complex discipline that must balance the need to keep circuits functioning as much as possible, but also be ready to cut power within a fraction of a second to avoid equipment failures from threatening public safety or damaging the grid.

a. System protection analysis is similar to powerflow analysis, but zoomed in on only a few lines or substations to ensure that protection system settings are set properly.

b. In addition, these studies are used to ensure that substation breakers, buses, and other equipment are adequately sized to withstand short, but powerful bursts of “fault current” that occur when high voltage equipment faults. Rather than being rated in a unit of energy (e.g. megawatts), substation equipment is rated in amperes (typically kiloamps or “kA”), which is the unit of current.

c. Modern system protection equipment relies on high-speed telecommunications (often fiberoptic or microwave) to operate. While these technologies improve the performance of the protection system, they often trigger costly telecommunications upgrades that can delay grid investment.

d. Generally, thermal generation is known to contribute up to 7x the normal current during faults (meaning that a generator that contributes 10A normally may contribute up to 70A during a fault condition). Conversely, inverter-based resources only supply approximately 1.5x the rated current. In one way, this is an advantage for inverter-based resources because they can be connected with less risk of overloading breakers during fault conditions. However, fault current is also used as a signal to open breakers, and if there is not enough fault current, a poorly designed protection system may not operate even if there is a system fault.

e. Software tools:

   i. ASPEN

What advocates need to know

There is a growing risk on the grid of power quality issues due to the increased penetration of large data center loads and electronically switched systems. At the same time, these risks are well understood and can be mitigated if adequate control engineering is conducted and operational steps are taken. It is important to understand that power quality analysis helps ensure electricity is reliable and safe for everyone, preventing problems like equipment damage or unexpected outages.

Electromagnetic Transient Analysis (EMT)

The most detailed transmission planning method is electromagnetic transient analysis. In some cases, the simplified "positive sequence" model of the transmission system— which assumes balanced conditions across all three phases — is used in power flow and dynamic studies. While this approach is effective for most planning scenarios, it can mask reliability risks, especially those involving unbalanced faults or fast electromagnetic interactions, that can only be observed by testing more highly detailed EMT models. Sometimes referred to as "Switching Studies," Transmission Planners investigate operations that occur in fractions of a second (such as the operation of a single breaker or the functioning of an automatic control system) using models that include all three phases and all breakers. This type of modeling is referred to as "node-breaker," instead of the equivalenced "bus-branch" one-line model used in steady state and dynamic planning studies.

What advocates need to know

System protection is the "network behind the network" aimed at reducing outages and containing grid problems if they arise. The cost of protection systems is typically an order of magnitude less than the grid equipment they protect. However, designing and installing protection systems and telecommunications needed to support them is an important part of any grid upgrade scope.

a. During certain grid operations, the physics of the substation equipment starts to drive the local behavior of electricity more than the prevailing grid. Issues like ferroresonance and insolation coordination can be observed and mitigated.

b. EMT studies are currently the cutting edge of Transmission Planning methods, and for that reason, it is unlikely that advocates will be heavily involved in disputing EMT study results.

c. Software tools:

   i. PSCAD

   ii. EMTPWorks

What advocates need to know

Inverter-based resources are increasingly being asked to provide EMT models so that transmission planners can evaluate whether any risks are being introduced. This step is needed to ensure that the future grid which will rely on inverter-based resources is built in a reliable way. These EMT models typically reflect the same original equipment manufacturer (OEM) hardware used in the field, and their performance should closely match how the equipment behaves in real-world conditions. This level of fidelity is important for accurately identifying and mitigating potential reliability issues before they occur on the physical grid.

Generator Interconnection Studies/ "Cluster Studies"

Transmission Planners are tasked with completing generator interconnection studies. In many cases, these studies include evaluating a group of proposed generators in a "cluster."

VIDEO The Interconnection Process

System Impact Study

Transmission Planners assess the impact of a proposed generator on the power system using steady state, dynamic, and protection analysis. The interconnection customer supplies a model of their proposed generator to the Transmission Planning entity, and a series of studies is conducted. A Transmission Planner will start with a base case that represents the current transmission system and then simulate the addition of the proposed generator(s). The planner then conducts contingency analysis to evaluate if any new thermal violations, voltage violations, short-circuit violations, or dynamic stability violations are observed. A System Impact Study report is then provided that outlines the mitigations required, if any, to allow the generator to interconnect. The System Impact Study report will include a good faith estimate of the costs and timing of required mitigations, but these estimates are later refined in the Facilities Study.

System Impact Study Key Terms:

Interconnection Queue - The "line" for getting connected to the grid. The queue is managed by rules established in each transmission owner's tariff, and one's place in the queue can have a profound impact on the cost and timing required to interconnect.

Point of Interconnection (POI) - the point on the transmission system where the proposed generator is connecting. This is typically a substation or point on a transmission line where a new substation will be built.

Serial - The original process of studying generator interconnection proposals was to study the proposals "serially" or one at a time. The advantage of this process was that it was fast and that individual interconnection applicants could be relatively certain that the Network Upgrades identified in their interconnection study would not change unless there were major disruptions in the interconnection queue ahead of their project. The disadvantage of this process was that if a major Network Upgrade was identified (e.g.

a new transmission line requiring hundreds of millions of dollars in costs and 7-10 years to complete) the burden of that upgrade fell on whichever project triggered it, and following projects could "free ride" on the Network Upgrade funded by the prior project.

Cluster - In an aim to mitigate the problems caused by the serial process, most Transmission Owners RTOs/ISOs have adopted a cluster study process. Generators that are proposed in the same "application window" will be studied together in a cluster. The advantage of clusters is that Transmission Planners can study all of the proposed generator interconnections together to identify the system-wide upgrades that will be needed, rather than the piecemeal upgrades identified in serial studies. It also allows for the sharing of costs of Network Upgrades that are triggered by multiple interconnection requests, rather than the first plant in line being burdened with the entire cost of major Network Upgrades.

Network Upgrades - the transmission system upgrades required to mitigate the violations caused by the connection of the new generator(s). When generators are studied in "clusters" the cost of these network upgrades will be shared in accordance with the cluster rules. When generators drop out of the cluster, the network must be re-studied, and the network upgrade costs must be re-allocated. This is what has historically caused much of the interconnection queue delay.

Cost Allocation - Determining who pays and how much for the required grid upgrades varies from region to region, but generally, the goal is to allocate costs based on the "cost causer" or the grid element that is causing the need for the upgrade. This is an area of constant debate because transmission upgrades seldom benefit a single grid user. Each region may also have varying Network Upgrade cost payment methods, such as requiring cash upfront, which is refunded as transmission credits, or requiring security (e.g. letter of credit) and returning the security once the project reaches commercial operation. The cluster process has also introduced penalties and minimum contribution requirements to continue through the interconnection process.

Distribution Factor (DFAX) - The percentage of a new generator's power injection that flows onto a specific transmission line, essentially indicating how much a new generator contributes to potential overload on a particular grid element, thus helping to identify which lines might need upgrades to accommodate the new generation source; it's a key metric used to allocate costs for necessary grid upgrades among different interconnection projects.

Facilities Study

Once a System Impact Study is completed, interconnection applicants may choose to move on to the Facilities Study. The purpose of this study is to take the results from the System Impact Study and determine costs and schedule with sufficient accuracy that a

Large Generator Interconnection Agreement (LGIA) can be created and the project can be built and connected. In addition, this study will determine more detailed engineering requirements for ancillary system upgrades needed, such as metering, telecommunications, and system protection. Evaluation of land acquisition and permitting feasibility is also a key component of this process to accurately estimate the construction timeline. Ideally, this study will include engineering fact-finding up to and including site visits to evaluate the health of equipment at the Point of Interconnection to avoid surprise upgrade requirements.

What advocates need to know

Interconnecting a generator is more complex than just the electrical connection to the grid, and the Facilities Study introduces a whole team of engineering and construction professionals that may identify issues not readily known during the System Impact Study phase.

Large Load Studies

Transmission Planners are also tasked with studying the impacts of large load additions connected to the transmission system. Increasingly, this process is being modeled after the generator interconnection process, where loads are being queued and studies are being conducted serially to determine what network upgrades are needed to serve these loads. **An important difference between Large Load Studies and Generator Interconnection studies** is that Large Load studies are not regulated by FERC and are typically governed by state rules for cost allocation. For this reason, the large load study process varies widely across the country. However, generally Transmission Planners use steady state and power quality analyses to determine what system upgrades are required to allow the large load to connect. Increasingly, dynamic analysis is needed to evaluate how large high-tech manufacturing and datacenters load connections are impacting the health of the grid.

RESOURCES

Grid Planning an Operation of Large Loads

2024 National Load Growth Report

Load interconnection requests are getting larger and that the industry is playing catchup with how to study these requests. These requests simultaneously drive new transmission and generation needs, and there is not yet a widely accepted best practice on how to co-optimize system planning to provide the requested service.

Economic Analysis

Resource Adequacy and Production Cost Benefits

Resource Adequacy refers to the ability of the power system to meet the expected electricity demand of its customers reliably and consistently, even during periods of peak demand or unforeseen events like equipment outages or extreme weather conditions. Resource Adequacy is a balancing act of procuring enough resources to meet demand, while avoiding unnecessary overinvestment.

RESOURCE Resource Adequacy Metrics Explainer

Production Cost Modeling refers to simulating the operation of a portfolio of power generation to optimize the system around cost. All generators have characteristics that drive the ultimate cost to create energy. Production Cost Modeling aims to model these characteristics and optimize the dispatch of these energy resources to minimize costs to the end user.

RESOURCE Production Cost Modeling Explainer

Transmission Planners do not regularly engage in Resource Adequacy or Production Cost Modeling directly, but instead are often tasked with developing transmission project proposals to access new resources that will increase Resource Adequacy or reduce the system-wide costs. For example, Resource Planners may identify an area with outstanding wind resources and ask Transmission Planners for an estimate of the transmission investment needed to unlock interconnection of wind generation in that area. Alternatively, Resource Planners may identify reliability or cost savings opportunities with expanded energy trading capacity with neighboring areas. In these cases, Transmission Planners may be asked to estimate the transmission investment needed to increase the interchange capacity between the two areas. Given this information, Resource Planners can estimate a resource adequacy and production cost benefit of the transmission line based on the cost difference between the current system and a system that includes the project.

In most cases, the transmission upgrades will be bespoke and not easily transferable to other similar sized projects. For example, increasing transmission capacity by 1,000 MW across the Rocky Mountains will be different than increasing transmission capacity by 1,000 MW across the Great Plains. This can delay analysis significantly because transmission projects are not interchangeable and Transmission Planners must run new transmission analyses for each proposal.

Losses

Most powerflow models calculate losses based on the system impedance and flow patterns. Thus, the decreased losses attributable to proposed transmission projects can usually be calculated directly with high accuracy. However, these calculations are only accurate under the generation dispatch and load profile input into the powerflow snapshot. As a result, when asked to calculate the loss reduction benefit of a transmission project, Transmission Planners will probe a series of snapshots (whether manually or through an automated redispatching tool) to estimate the lifetime loss reduction benefit of a new transmission line.

What advocates need to know

Economic analysis of transmission is a new but growing discipline. In some cases, when transmission is used to unlock new lower cost generation the benefits can be easily calculated. In other cases, benefits like increased reliability are highly sensitive to assumptions about the value of lost load and likelihood of outages. In almost all cases, the transmission solution will be custom, making direct translation between transmission projects difficult.

What can powerflow analysis tell you?

Powerflow analysis can accurately identify major transmission system vulnerabilities under specified conditions. The equivalencing techniques and numerical methods used to solve the models are well understood and have been used for decades to predict and mitigate transmission risks. Historically, the transmission system only needed to be designed to meet the highest load period of the year and withstand the loss of 1-2 elements. As a result, powerflow analysis uses highly detailed models to "stress test" the system under these extreme conditions. In addition, powerflow analysis can help planners test proposed mitigations to vulnerabilities by allowing planners to simulate system upgrades and accurately determine whether the upgrade solves the problem.

What can powerflow analysis not tell you?

By design, powerflow analysis is a highly detailed "snapshot" of the transmission system aimed at determining reliability risks under extreme conditions. As a result, there are not yet best practices or software tools for studying the transmission system over long periods of time. Since transmission elements typically serve multiple purposes throughout their lifetime (whether it is reliability for the load, reduced losses on the system, increased interconnection capacity for lower cost generation, improved switching capability etc.) many of the benefits of transmission are understated or not well understood.

One of the key blindspots of powerflow analysis is that the model does not include any economic analysis. The generator dispatch is done manually by Transmission Planners looking to stress the system, not operate it in an economically optimal way. Recently, some techniques like Security Constrained Economic Dispatch ("SCED") have been developed to reduce this blindspot, but these tools remain largely in the operations field more than planning. Furthermore, the universe of potential mitigations to solve transmission risks is nearly infinite and the costs of transmission upgrades are not fungible as they can vary widely depending on the unique situation of each project. This makes "optimization" of the transmission system difficult because grid planners cannot test every possible solution and do not easily know which solution will meet the need at lowest cost. Thus, proposed mitigations are limited to the Transmission Planner's experience and the toolkit of available solutions in each organization.

Tools in the toolbox

VIDEO Four ways to increase transmission

RESOURCE PJM GETs and HPC explainer

Controlling the flow

Power in the transmission system flows according to the laws of physics. In most systems, the only way to adjust powerflow is to adjust the dispatch of generation or the pattern of load. However, there are advanced (i.e. expensive) tools that can help control the flow of power on the network.

Phase Angle Regulators/Phase Shifters - These are advanced transformers that adjust the impedance in the circuit to either increase powerflow on the circuit it is in series with or push power around it to other circuits. These devices operate in a matter of minutes and can help mitigate overloads if powerflow on a circuit reaches dangerous levels. However, a key limitation of phase shifters is that they introduce significant losses into the system and can only move power around, not increase or decrease power on the system overall.

Flexible Alternating Current Transmission Systems (FACTS) - This is a category of high-speed powerflow control devices that can help system operators run the system more efficiently and avoid reliability issues. The operating mechanics of these devices varies, but generally they can be used to increase the rating of transmission paths (when they are rated below the thermal rating), increase the stability of the system, and provide levers to move power away from the weaker parts of the system.

There are ways to control the flow on the transmission system to avoid overloads and other reliability risks. However, these tools are expensive and do not address mismatches between generation and load which can cause system reliability risks. Therefore, these are usually tools that only make sense on highly networked, high-voltage (345kV+) systems.

Increasing capacity

There are a variety of ways that Transmission Planners can increase the capacity of the transmission system. The following chart provides an overview of the tools with a qualitative outline of how these tools perform *generally*. It is important to note that these tools do not work everywhere and in some cases work better than presented in this chart. The only way to test whether these solutions will work to address transmission system reliability risks is to conduct powerflow analysis.

ADVANCED TRANSMISSION TECHNOLOGY	DEVELOPMENT TIME	TYPICAL CAPACITY INCREASE	PERMITTING SPEED	DESIGN SPEED	CONSTRUCTION SPEED	VIABLE OPPORTUNITIES	COST
GETS including Dynamic Line Ratings	3+ MONTHS	10-30%	●	●	●	MOST	$
(FACTS) Flexible AC Transmission Systems	8-18 MONTHS	30-50%	●	●	●	MORE	$$
Reconductoring w/ Advanced Conductors	18 - 36 MONTHS	50-110%	●	●	●	MOST	$$
Tower Raising	2-4 YEARS	10%	●	●	●	LEAST	$$
Double Circuit Towers	2-4 YEARS	80-100%	●	●	●	MOST	$$$
Advanced Tower Design	2-4 YEARS	30-100%	●	●	●	MOST	$$$
Voltage Uprate	3-5 YEARS	100-300%	●	●	●	LEAST	$$$
HVDC Conversion	5-7 YEARS	100-300%	●	●	●	LEAST	$$$$
Greenfield Transmission	5-15 YEARS	N/A	●	●	●	LEAST	$$$$

RESOURCES

GETs Explainer
High Performance Conductor/Advanced Conductor Explainer
HVDC Explainer

Greenfield Transmission

Greenfield Transmission, or building a new line where one does not currently exist, is typically the most time consuming option to deploy but also provides the greatest system value. New greenfield transmission requires significant planning and permitting effort to construct and the model for cost allocation can become complicated quickly. For this reason, Greenfield Transmission can take 10-20 years or more to be completed. At the same time, new transmission capacity is desperately needed to promote reliability, provide economic development opportunities, decrease costs, and increase penetration of renewables. Thus, there are many efforts underway to expedite the construction of new transmission lines.

The stakeholder engagement process to select solutions is new and often not robust. Frequently, impacted communities are resistant to the projects and are not adequately consulted with prior to project selection. In addition, there is a regulatory gap in transmission planning where neither FERC nor state regulators have adequate oversight of "local" transmission projects. This is the forefront of advocacy work in transmission planning.

Planning

Long-Term Transmission Planning

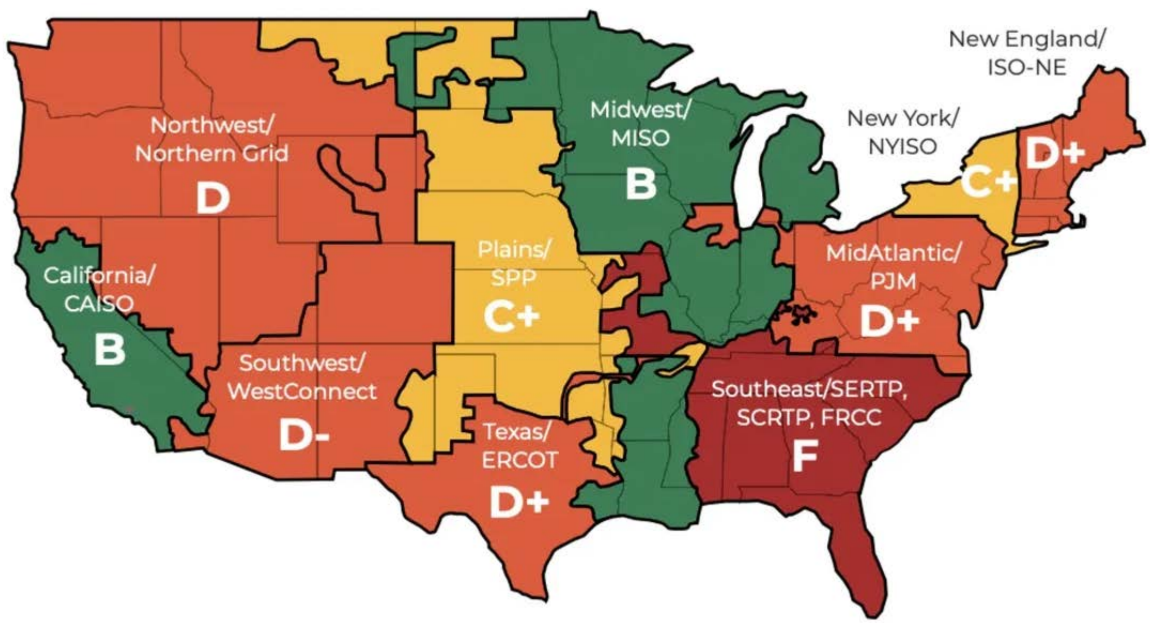
Most long term transmission planning is done at the ISO/RTO level, or in non-ISO regions at the local Transmission Owner level. Every Transmission Planning group has a process to convert the identified needs of the transmission system into a list of proposed transmission upgrades based on priority. Whether the projects are driven by reliability ("NERC projects"), generator interconnection, or load increase, these projects cannot all be constructed simultaneously. When building out a transmission investment plan there are binding constraints in terms of capital, labor, outage scheduling and supply chains that must be considered. In addition, transmission plans are often not as accurate as they are often presented because of the uncertainty in generator and load forecast assumptions. Nevertheless, transmission plans are needed to indicate where future grid investments are likely to occur.

Once a grid need is identified, there are several models for proposing solutions. In some cases, transmission developers will propose solutions that are then evaluated by the Transmission Planners to determine whether the proposal mitigates the grid problem. In other cases, the Transmission Planners will directly prescribe the required solution, and it will either be constructed by the Transmission Owner or a third party contracted with the Transmission Owner.

Regional Planning

Regional Transmission Planning is the act of different Transmission Owners developing a coordinated regional transmission plan. In some cases, this work is completed by the ISO/RTOs, but in non-ISO regions this work is completed by regional planning organizations. The goal of this effort, as launched under FERC Order 1000, is to find regional transmission needs and solicit competitive bids from transmission developers to meet those needs. The regional planning process was aimed at jump-starting development of larger, multi-BA projects instead of each BA planning their system independently.

It is generally accepted that implementation of FERC Order 1000 has not resulted in the transmission development needed for the country to maintain reliable and cost-effective power. The failure of these planning processes was outlined by Americans for a Clean Energy Grid and GridStrategies's regional planning report card:



Source: Regional Transmission Report Card

There are many explanations for why FERC Order 1000 has not been successful, and to address these failures FERC released Order 1920 in 2024, which aims to correct the shortfalls of Order 1000 and encourage the regions to develop long-range (20+ year) multi-value transmission plans to drive development.

■ **RESOURCES**

[FERC Order 1000](#)
[Resource: FERC Order 1920](#)

Interregional Planning

Interregional planning refers to Transmission Planning between the Order 1000 regions and across the interconnections (West, East, and ERCOT). Interregional planning is not done regularly by ISO/RTOs nor is it considered by most independent Transmission Owners. However, the US Department of Energy and NERC have been tasked with studying the needs of the US transmission system and how interregional planning can bring outsized benefits to communities.

■ **RESOURCES**

NREL Seams Study
NERC Interregional Transfer Capability Study (ITCS)
GridUnited Project Map (one of the few transmission developers proposing projects across the interconnection seams)

Permitting

Permitting is often the most time consuming part of developing Greenfield Transmission. Currently, most transmission lines must be permitted state-by-state and jurisdiction-by-jurisdiction, creating a long list of opportunities for stakeholders to slow or kill the project. Unfortunately, a transmission project can negatively impact the communities and environments it traverses while not directly providing benefits in return. However, transmission projects do provide large benefits to the region as a whole. This leads to a classic public policy problem when the benefits of a policy are broadly distributed but the costs are concentrated to key decision-makers. There is movement to solve this problem in two ways:

1. **Community Benefit Agreements** where transmission providers involve the affected communities prior to planning the transmission line and offer to share some of the benefits of the line with the community.

2. **Permitting Preemption** where either the state government approval preempts local government disapproval or federal government approval preempts state disapproval.

FERC's cost causation principle is the fundamental underpinning of most cost allocation methodology for transmission. It states that customers who cause a utility to incur costs should be responsible for those costs. This means that filed rates should reflect the costs caused by the customers who pay them. This principle will be the key driver of regional transmission development.

Paying

Transmission investments are typically hundreds of millions, if not billions of dollars. As a result, only a few entities have the capital structure to finance these projects. Nevertheless, these projects can earn an outsized, FERC regulated return to encourage investment. The key financial barrier is determining who will ultimately pay the transmission rate that funds these projects. Answering this question is called cost allocation, and is a broad topic that necessitates an intense stakeholder process.

GridLAB

GridLab is an innovative non-profit that provides technical grid expertise to enhance policy decision-making and to ensure a rapid transition to a reliable, cost effective, and low carbon future.

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