DESIGN OF A MACROGRID TO SUPPORT HIGH LEVELS OF CLEAN ELECTRICITY

ESIG
ENERGY SYSTEMS INTEGRATION GROUP

Macrogrid Design Studies Scoping Team

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Macrogrid Design Studies Scoping – Project Team

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Foreword

This slide deck was developed through a collaborative process by the scoping team over a period of approximately three months. This and earlier versions were shared with a task force convened by the Energy Systems Integration Group to help oversee this work. Much of the final report for this effort was drawn from these slides and the material therein.

There is some detail in this slide deck that does not appear in the final report, which is the purpose for making this material available. This presentation should be viewed as the working notes of the scoping team.

Introduction

Origin of this effort

- Current studies of U.S. clean electricity and/or clean energy all highlight the attendant need for massive expansion of U.S. bulk transmission infrastructure to deliver clean energy and support system reliability
- Conclusions and observations from ESIG Fall 2020 Transmission Workshops:
  - Transmission expansion in most clean energy studies has been conceptual and high level
  - Such a transformation of the bulk electric system would have implications far beyond energy transport only
  - More detailed transmission system designs can inform technical and policy discussions
- Scope of challenge
  - Detailed study of transmission expansion across the contiguous 48 U.S. states will be a massive undertaking
  - Defining the suite of studies needed for bulk transmission transformation is itself challenging

The national direction forward

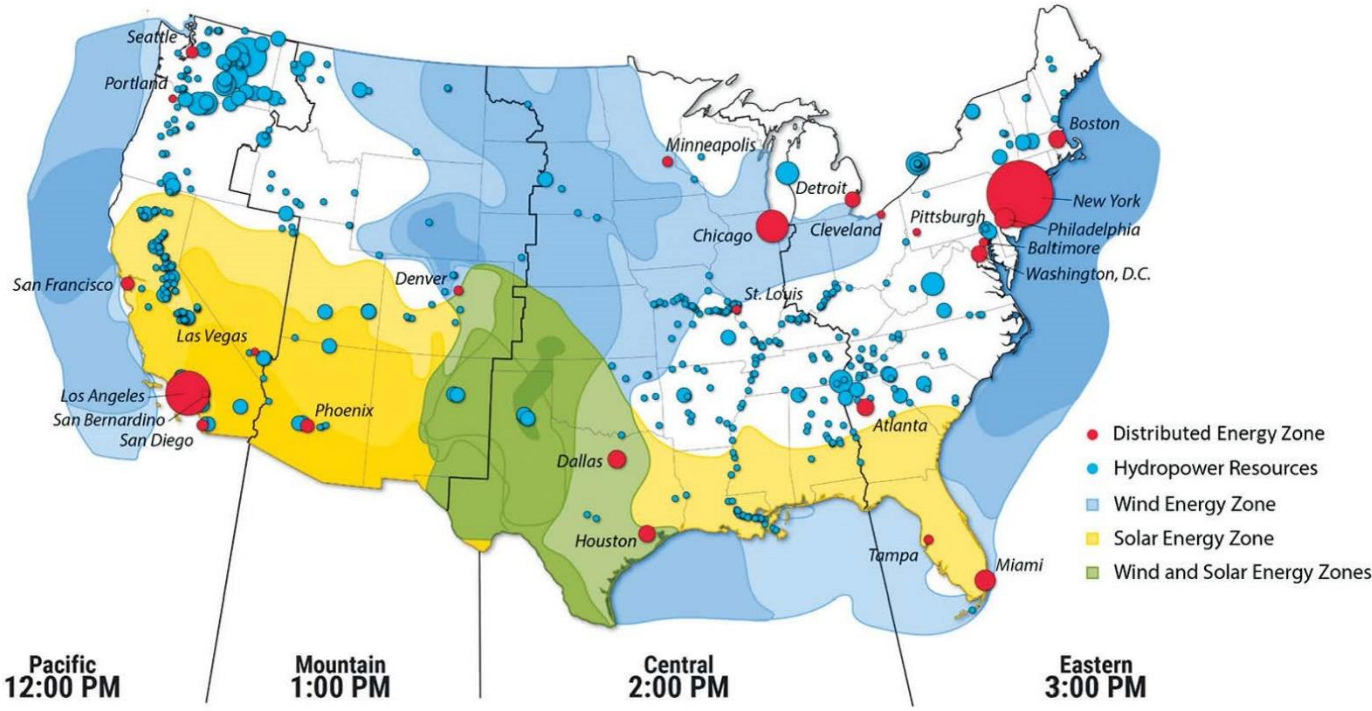
- Biden administration objectives
- DOE focus on high levels of clean electricity, transmission expansion to support
- NREL/PNNL directions, activities
- FERC: All parts of the country benefit from broad interregional transmission development

Current perspective

- The scale of reaching very high clean electricity (>90%) and decarbonization goals is immense
- There is skepticism about whether conventional expansion of the bulk transmission system can meet the need
- It is time to articulate and explore innovative transmission expansion concepts for this once-in-a-century opportunity
- All parts of the country benefit from macrogrid development

Resources and loads

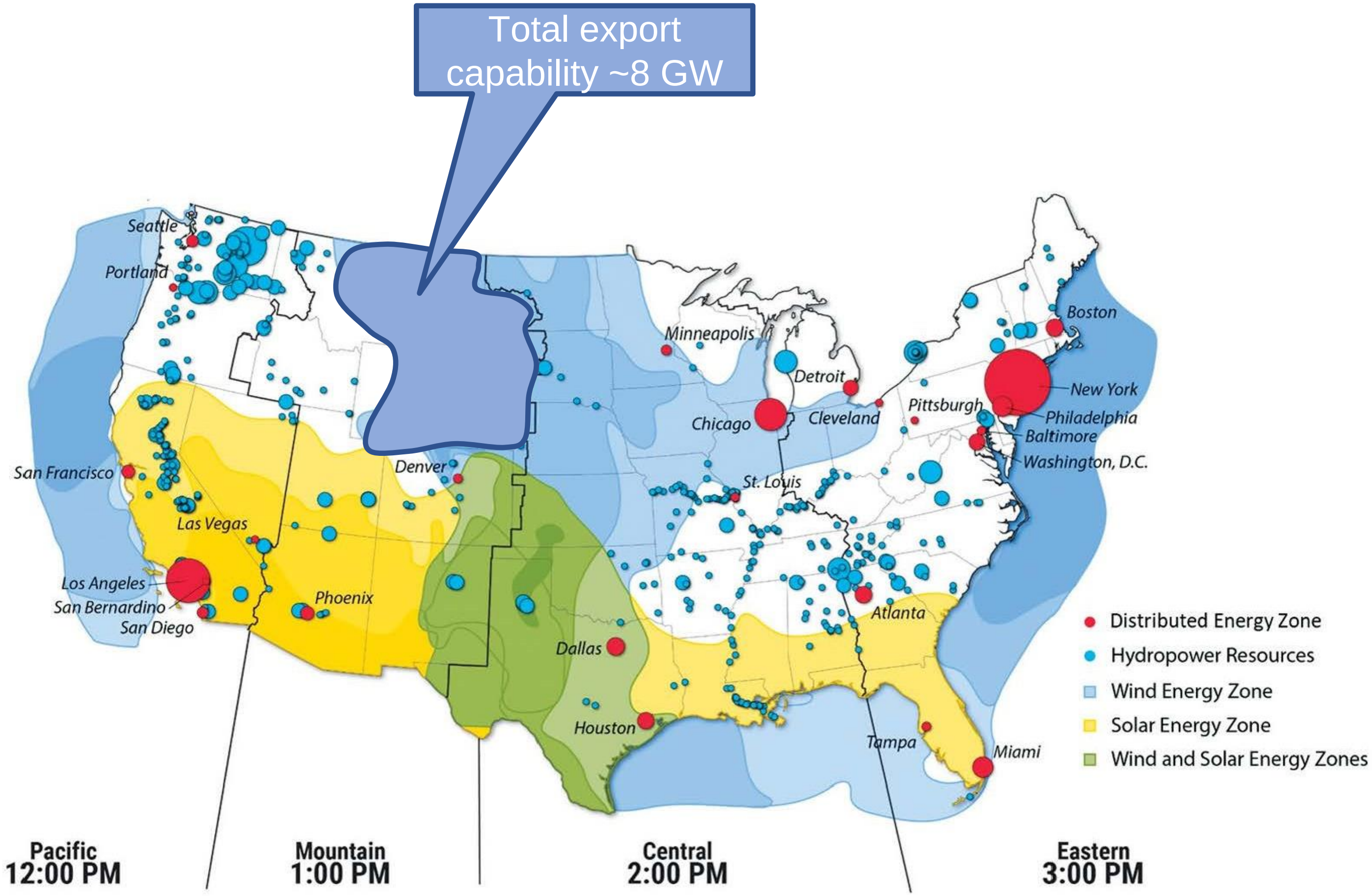
- We have a good idea of where good clean energy resources are located.
- Some will be near the population centers (and travel locally), but much of the clean energy resources aren't near the load.
- We have to move lots of energy, capacity, and services over long distances from sources to loads.
- Great reliability and diversity benefits are gained from transmission that links regions to cross time zones and weather systems.
- We don't have to be exact to understand the scale of this problem and the opportunity…



Source: Energy Systems Integration Group.

Resources and loads

- Consider, for example the wind-rich region centered in Wyoming and Montana
- ALL the transmission today allows about 8 GW of export (from shaded area)
- Clean energy plans project additional wind generation many times this limit in just this area
- New approaches are needed



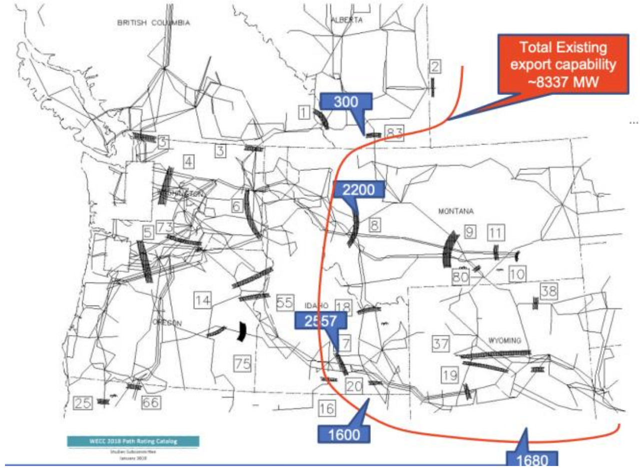
Source: Energy Systems Integration Group.

What difference could a macrogrid make?

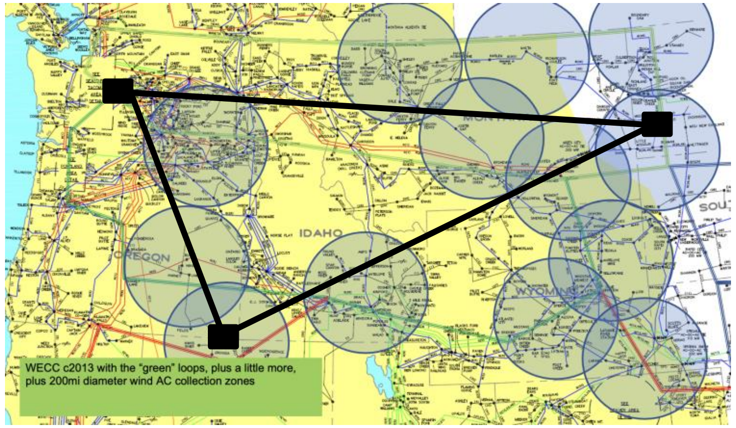
Consider the Pacific Northwest. Current HVAC infrastructure delivers 8,337 MW. The region shown has probably 10x that amount of developable clean energy potential.

- Additional interregional HVAC – maybe with additional interregional and local HVAC lines -- could deliver a portion of this capacity, but could take decades to build and be very complex with respect BPS security
- But building new interregional HVDC lines supported by local interconnection lines could deliver more economically, and be developed more quickly with fewer lines and land use.

Current Pacific Northwest Transmission



Potential Pacific Northwest Macrogrid



Blue circle = gen collector zone
Black line - HVDC

Why a macrogrid?

- Previous studies referred (explicity or implicitly) to a macrogrid that overlays the existing AC bulk system
- Would help overcome challenges with incremental expansion of bulk AC transmission systems and with current transmission planning processes
  - Difficult to fundamentally change the capabilities of AC system with incremental expansion – Large single EHV AC lines don’t buy much
  - Current planning processes use shorter time horizons and are bound by benefit-cost methodologies that do not consider all future benefits
  - A macrogrid moves energy, but equally important, it moves capacity and services, and it moves all three (energy, capacity, services) both near and far.
- Value of “top-down” vs. “bottom-up”
  - A thorough top-down examination of the desired bulk power system long-term ***end-point*** could redirect and improve bottom-up system planning efforts
  - Effectively a single-step system expansion from present to clean electricity or clean energy
  - Macrogrid design would be based on sound transmission planning principles, but likely require developing some new approaches because of its novelty.

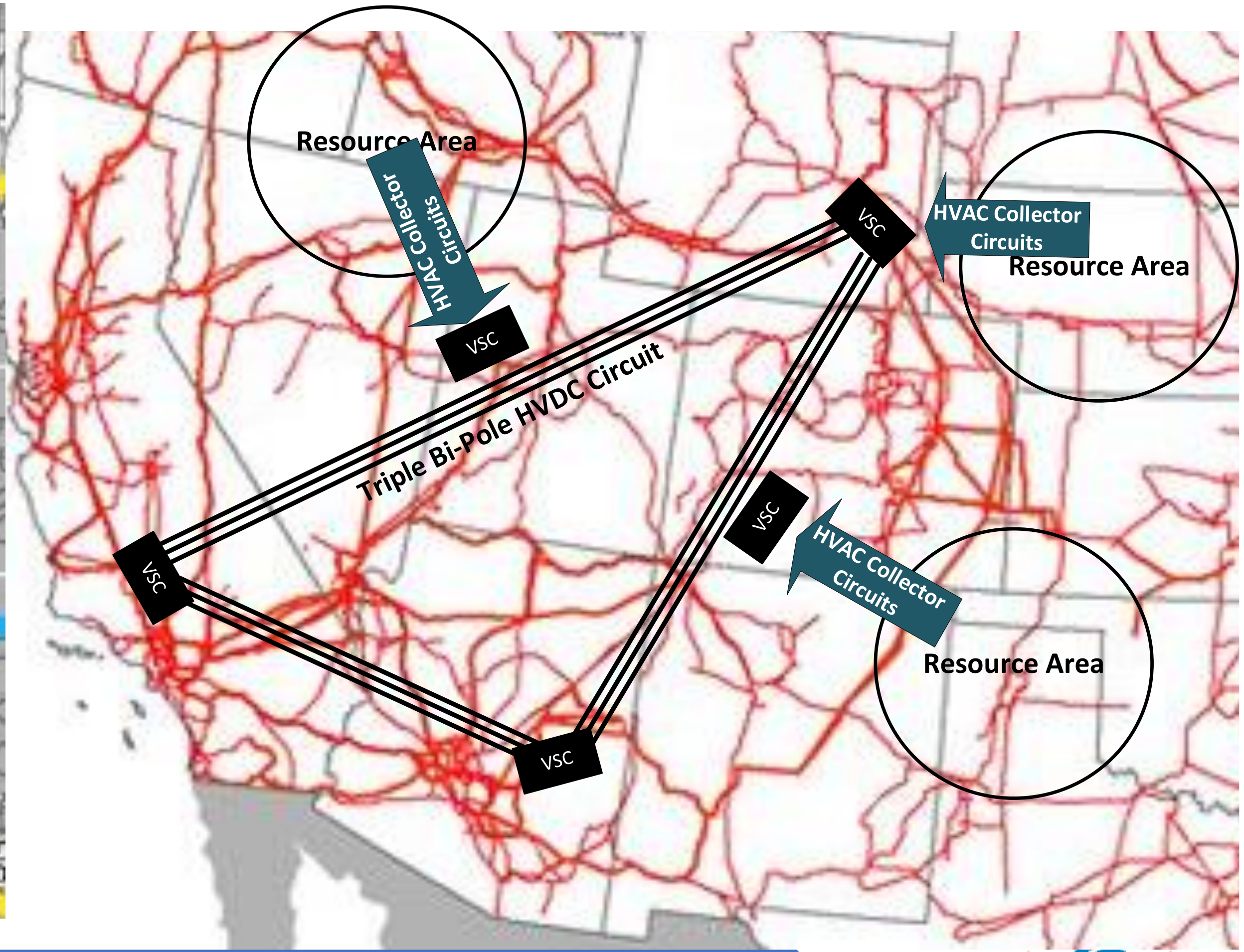
Some macrogrid attributes

- Not just “bigger pipes” for moving clean electricity, but an overlay of HVAC and HVDC lines and terminals that connects clean energy-producing and consuming regions across the entire nation (perhaps serving most of the continent)
- Leverages diversity in demand and clean energy production over maximum geographic scales – beyond neighbor-to-neighbor
- The entire macrogrid would be self-redundant, with limited interactions with the underlying bulk AC transmission system
- Mixture of conventional and new technologies – e.g., multi-terminal HVDC with shunt-connected VSC converter stations
- Can be leveraged to improve or enhance operation of bulk AC grid
- Operates in coordination with underlying bulk AC system, in ways that maximize reliability and economic benefits

What do we mean by innovative macrogrid architecture?

Conceptual western portion of macrogrid

More detail on single “loop” segment of macrogrid



Why are we recommending these studies?

- Previous studies that addressed possible transmission expansion to support high levels of clean electricity, including macrogrid overlays, are excellent works, but
  - Did not (apparently) incorporate important transmission planning principles that would result in a reliable system
  - Left out important technical details of how an overlay could be built and how it might be operated
  - Stopped short of addressing how an appropriately designed and constructed macrogrid could transform the operation of the bulk power system (BPS) in the U.S.
- A macrogrid concept that incorporates available but still novel technologies should be evaluated at a similar level of detail (and possibly beyond) as other more conventional options for expanding the bulk electric system to support a new future

How could the macrogrid change the BPS?

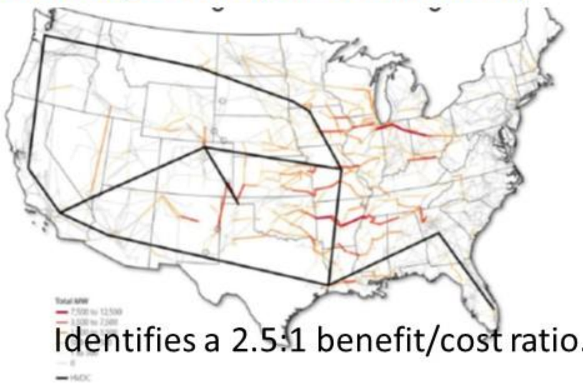
1. The most economically attractive resources (bulk generation and storage, for energy and ancillary services) can be dispatched to cover energy demand across 4 time zones to serve all regions and customers.
2. Energy, capacity, and ancillary services are deliverable from any region of the country to any other region, not just between neighbors.
3. A system of diverse resources significantly improves reliability and resilience on a continental scale.
4. Macrogrid terminals offer very large control opportunities for grid management and enhancing system security during routine and high-consequence climate-induced and other severe events.
5. Utility-scale wind and solar plants can be either AC- or DC-connected. The ability to connect wind/solar plants at DC changes fundamentals of converters and collection circuits used at these plants.
6. A central operator sees the nation's entire grid and coordinates with regional grid operators.
7. A macrogrid is the only approach that has the scale necessary to meet societal decarbonization objectives. It's not that incremental approaches (local build-outs, packing more onto existing lines and ROW, use of advanced technology, DER, energy efficiency, etc.) are wrong – they are necessary, but insufficient.
8. This isn't just once-in-a-generation opportunity, this is a once-in-a-century opportunity that must be started immediately to transform the industry and to combat climate change.

Getting the macrogrid right will create local benefits

- Expanded market footprint for buying/selling energy, capacity, and services
- Converter station control provides increased local and regional reliability
- Cross-continent assistance enhances local resilience to extreme events

References

Interconnections Seam Study, 2018
www.nrel.gov/analysis/seams.html



Identifies a 2.5:1 benefit/cost ratio.

MIT – Decarbonization value of transmission, 2020
https://doi.org/10.1016/j.joule.2020.11.013

Finds that an "every state for itself" approach has a levelized capital/O&M cost of $135/MWh which can be halved with interregional transmission expansion.

Q. Zhang, J. McCalley, et al., "Primary frequency support through North American Continental HVDC Interconnections with VSC-MTDC Systems," IEEE Trans. Pwr Sys, 2020. vol. 36, no. 1, Jan. 2021. https://ieeexplore.ieee.org/document/9154589.

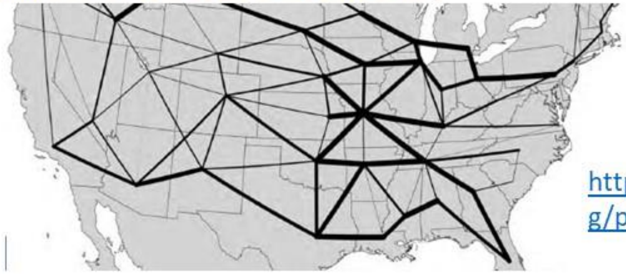
Cross-seam control significantly improves frequency response.

Proposed US HVDC, 2021,
ACEG, MacroGrid Initiative

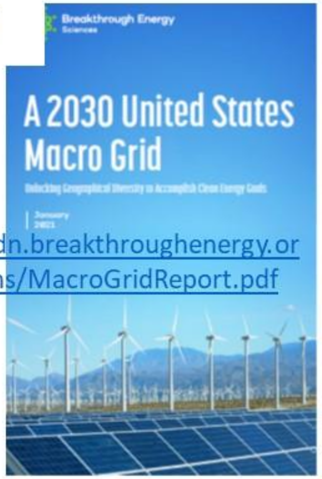
https://cleanenergygrid.org/wp-content/uploads/2019/04/Transmission-Projects-Ready-to-Go-4.1.21.pdf/

...these lines increase the transmission system's transfer capacity by about 11-12%, and enable a 50% increase in domestic wind and solar generation...

Zero by Fifty, 2021
https://www.esig.energy/wp-content/uploads/2021/02/Transmission-Planning-White-Paper.pdf
https://www.vibrantcleanenergy.com/media/reports/zerobyfifty/



Finds that if a macro grid is NOT built, it costs an additional $1 Trillion to get to 100% clean energy by 2050.



https://bescdn.breakthroughenergy.org/publications/MacroGridReport.pdf

Macrogrid Design Studies Overview

Purpose of this initiative

- Very high clean electricity (>90%) is becoming a common target for states, regions, and industry sectors of the U.S.
- There is growing recognition that transmission expansion is a key element for achieving clean energy goals.
- Analysis should be started now to determine key engineering, design, cost and benefit issues that must be resolved to support future transmission build-out for clean energy needs.
- The better we understand the desired transmission and clean energy end-point, the better we can structure an effective vision and direction for near-term work and the path to achieve that endpoint.
- This document offers a framework and guidance for technical activities to better determine the architecture, costs, benefits, and elements of a macrogrid.

Relation to ongoing national efforts

- DOE has launched 100% Clean Electricity study through NREL and PNNL.
- The overall scope for transmission expansion in these efforts should include detailed evaluation of a macrogrid alternative for transmission development.
- Macrogrid design effort would utilize scenarios developed through DOE efforts.
- Focus should be on the endpoint – e.g., 100% clean electricity; design macrogrid to meet needs.
- Macrogrid expansion would be compared to possibly more conventional alternatives developed in likely DOE/lab scope.

Michelle Manary of DOE spoke at CREPC. She is only at DOE for a 2 year assignment. They renamed her resilience department to Transmission Deployment.

*Michelle said that **NREL is undertaking a 100% Clean Electricity study**. OE has subcontracted NREL **and PNNL to do transmission planning scenarios** which include different policy approaches including nuclear, renewables, different levels of electrification, demand response, etc. Then OE will go to each region and test those scenarios with stakeholders. They will mesh the lab and industry tools together so that there will be a national transmission map that is driven by regions to meet 2035 goals. She wants to use **upgrades on the existing system, GETs and other technologies.** They will identify no-regrets transmission lines from the different scenarios.*

*She said DOE wants to partner with states. They want to help with analysis or funding. They **have state funding for transmission studies and building transmission in the infrastructure bill**.*

In one year, she will have an outline of a national transmission roadmap showing what each region is doing.

Elements of macrogrid design

- Focus on architecture and design of a fully developed macrogrid as it would exist in the future for supporting target level of clean electricity/energy (e.g., >90% clean electricity) – start at the end point, single-step expansion from present to that future
- Main study elements
  - Initial macrogrid designs
    - Scenario development
    - Extension of transmission planning principles
  - Resource adequacy analysis
  - Reliability analysis (steady-state and dynamic)
  - Resilience assessment
  - Operability
  - Economics
- Iteration and sensitivities – what about decarbonization, or what if we don't get to >90% clean electricity?
- How does the macrogrid option compare to other approaches?

Study execution

- The first step is to develop initial macrogrid design(s) that serve the articulated clean electricity vision for defined future scenarios
- Parallel study tracks (reliability, operations, resilience, economics) dig into details with likely overlaps between study tracks
- The entire study effort should be conducted as an open process, with frequent review and input from industry experts
  - RTOs, regional planners
  - Technologists (e.g., HVDC, TL design, transmission economics)
  - Policymakers
- Considerations for major study elements described in following sections

Work Scope for Macrogrid Design

Initial macrogrid design: Objective

- Based on defined target scenarios, develop macrogrid designs that support the delivery of electric energy from all sources to all sinks, at a very high clean electricity level (>90%)
- Based on our assumptions of DOE intentions, other transmission expansions will be explored (all under very high clean electricity levels), and likely include:
  - **BAU1** (reference): probable result of current transmission expansion planning processes, but no macrogrid
  - **BAU2:** BAU1 with "no regrets" lookback (e.g., replace some conventional expansion with HVDC)
- The macrogrid expansion represents the **Innovative** scenario
  - Extensive use of self-redundant, multi-terminal VSC HVDC
  - HVAC expansion for collection and local/regional delivery of clean electricity that is needed at times at demand centers remote from sources
- With multiple end-point scenarios, "no regrets" lines and system elements that are highly valuable across many scenarios can be identified

Transmission planning principles

The process of moving from concept to preliminary design will involve more than just sizing elements to transport energy. Because this effort is focused on the macrogrid as it would exist after many years of development, we have the opportunity to develop new engineering principles and approaches for design and operation of an advanced transmission system:

- New concepts for appropriate mixes of technologies: line-commutated converter HVDC (LCC-HVDC), voltage source converter HVDC (VSC-HVDC), HVAC "collector lines," and AC grid reinforcement
- Exploring issues related to low- or zero-inertia power systems, the value of grid-forming technologies for VSC HVDC terminals, and utilization of multi-terminal HVDC concepts
- Identifying engineering design considerations, such as design principles, modularity, equipment ratings, circuit configurations, expandability, embedded VSC-HVDC considerations, HVDC system protection, HVDC to HVAC system interactions, and others
- Assessing robustness and optionality in the face of significant uncertainty of future resource and load development paths due to: (1) evolving electricity supply and storage technology and cost options, (2) varying levels of electricity demand associated with end use efficiencies, (3) demand response and electrification paths, and (4) policies and costs associated with distributed energy resources

Analytical assumptions

1) Minimum levels of power system reliability from the resource adequacy and operational perspectives, such as expected unserved energy (EUE), will be built into the analysis as requirements to be satisfied rather than as outcomes that could vary as a result of system design and budget constraints. A uniform reliability requirement will apply to all scenarios and we can choose how to meet that reliability requirement using local vs. distributed resources, energy efficiency and macrogrid transmission. Costs (fixed and energy production) and macrogrid designs will be analytical outcomes rather than constraints.
2) The set of scenarios analyzed for each goal will contain a BAU (no macrogrid) scenario, to estimate the consequences and opportunity costs of using only current transmission technologies and processes to achieve the desired power system transformation.
3) And others…

Multiple transmission expansion approaches will provide value

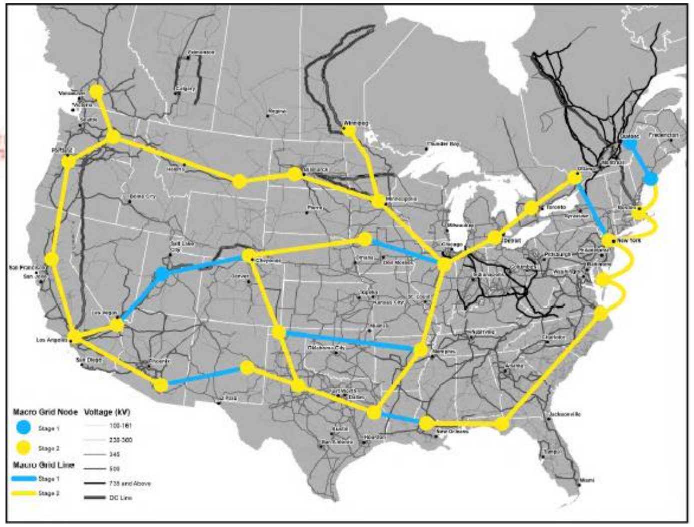
- We recommend the development, analysis, and assessment of at least three different designs, illustrated on the next slide.
- We assume that something resembling the first option (or a "hybrid" as mentioned previously) will come out of existing planned efforts.
- Evaluation of the multiple designs will provide insight into not only costs and feasibility, but the strengths and weaknesses with respect to reliable and secure bulk transmission systems.

Three design concepts

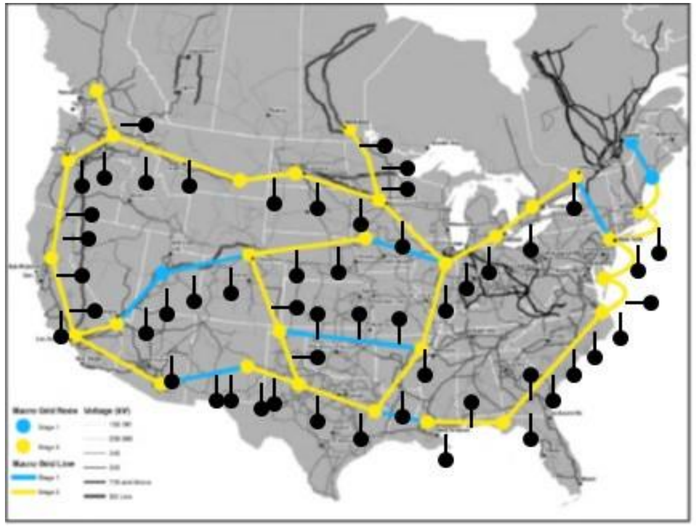
DESIGN 1: All AC: No macrogrid; reference case. This design is suggested because it represents a BAU or reference case to which the other two designs can be compared in order to identify their benefits. It is expected that the cost of reaching >90% clean electricity in this design would be very high relative to the other two suggested designs.

Requirements for all designs:

- Achieve very high (<90%) clean electricity..
- Any new AC transmission should maximize power density, e.g., HSIL on double circuit towers
- Use existing ROW whenever possible



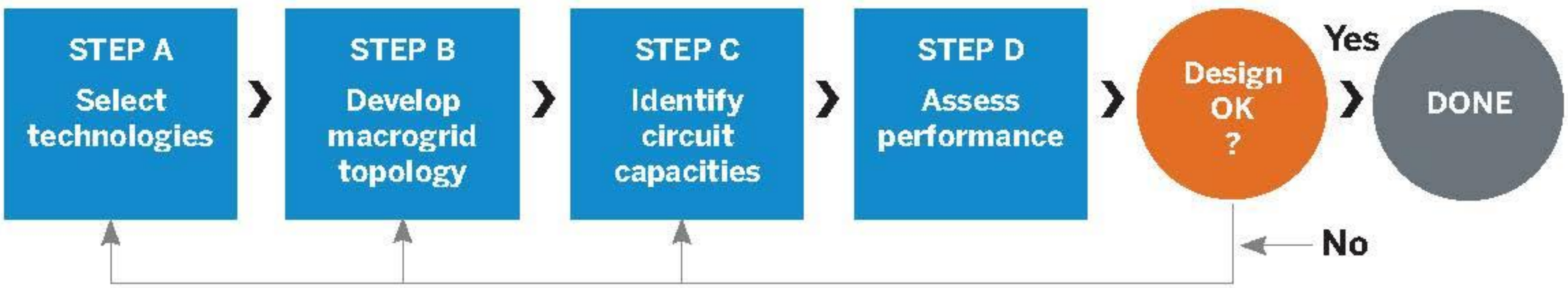
DESIGN 2: Macrogrid w/AC collection: May be VSC, LCC, or hybrid. Only macrogrid segments are HVDC; collection done w/ AC. ~40 converter nodes (collectors, load centers).



DESIGN 3: Macrogrid w/ AC+DC collection: VSC multi-terminal HVDC. ~40 converter nodes (collectors, load centers) plus 100 DC nodes (collectors only, 40/40/20 in 3 grids).

Note: The figures on this slide are not intended to prescribe macrogrid topology; it is expected that reassessment and further development of topology would occur in future studies.

High-level view of macrogrid design process



Macrogrid design: Data and tools

Macrogrid (MG) Design Step		Data/Information Needed	Tools Needed
Step #	**Description**		
A	Select technologies.	Converter station capabilities and costs. HVDC and HVAC/EHVAC transmission costs.	
B	Create macrogrid topology	Load centers, renewable resource quality by location, ROW data.	Top-down design requires experience and system familiarity at the national level. Bottom-up design requires specialized graph-search tools.
C	Identify circuit capacities. 1. Create existing grid (EG) reduced model 2. Develop scenarios and constraints; 3. Expand/ assess using reduced model.	Power flow and production cost data for existing Eastern, Western, ERCOT grids. Scenario definition. Capital costs for all viable generation and transmission technologies. Hourly load and *forecasted* (not historical) wind, solar, hydro production data for final year.	Network reduction. Co-optimized expansion planning.
D	Assess using full model.	Power flow, production cost, and dynamic data for full model.	Tool to translate generation and transmission investments to full model. Production cost simulation*.

*Production cost simulators need to account for near-zero marginal energy costs (some nuclear and carbon-capture-fossil may remain); dispatch is performed based mainly on the provision of ancillary services (regulation, contingency, and ramping) and variable O&M.

Step A: Select technologies

DC instead of AC: Reasons for selecting DC in macrogrid design are as follows:

(1) There is no minimum capacity above which is required for stable interconnection
(2) It offloads the underlying AC system, allowing increased AC interconnection of renewables
(3) It improves AC system performance in terms of voltage, frequency, transient, and oscillatory stability via converter control
(4) Its power density (MW per ROW area required) is greater than AC
(5) DC cost per MW-mile for long-distance transmission is less than AC
(6) HVDC losses are less than AC, for the same transfer capacity and distance

Although future studies should carefully consider the various technology options, we recommend the adoption of a state-of-the-art innovative option of a VSC-based multi-terminal HVDC network with grid-forming converters.

A hybrid design consisting of LCC and VSC may also be considered. An example of a hybrid design is provided in:

- H. Rao, Y. Zhou, C. Zou, S. Xu, Y. Li, L. Yang, and W. Huang, "Design Aspects of Hybrid HVDC System," *CSEE Journal of Power and Energy Systems* 7(3)(2021): 644-653. http://dx.doi.org/10.17775/CSEEJPES.2020.00980.
- J. McCalley and Q. Zhang, "Macro Grids in the Mainstream: An International Survey of Plans and Progress," Nov. 2020, p. 42. https://cleanenergygrid.org/macro-grids-mainstream/.

Step B: Topology design

Make key design decisions on technologies (point-to-point, multi-terminal network, or hybrid).

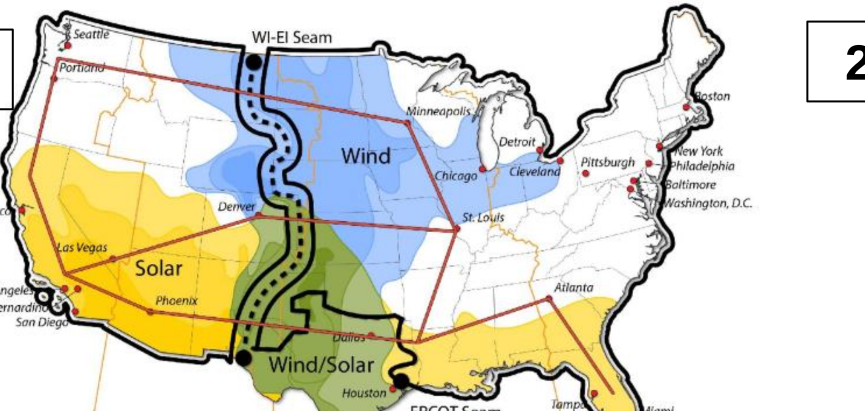
Identify topology (specification of macrogrid candidate segments between candidate nodes) and routing. Two complementary approaches:

1. **Top-down (experience-driven) topology design**: Developed based on understanding of where load centers and renewable resources are located and basic design rules such as the rule of three. This approach identifies topology (but not routing).
2. **Bottom-up (data-driven) topology design**: Includes cost-weighting to reflect ability to obtain ROW, accounting for terrain, use of existing ROW (rail, lines, interstate), and underground vs. overhead. This approach identifies topology and routing.

Final design for each macrogrid topology is obtained via sensitivity studies applying bottom-up results to refine top-down designs.

B1. Top-down (experience-driven) topology design

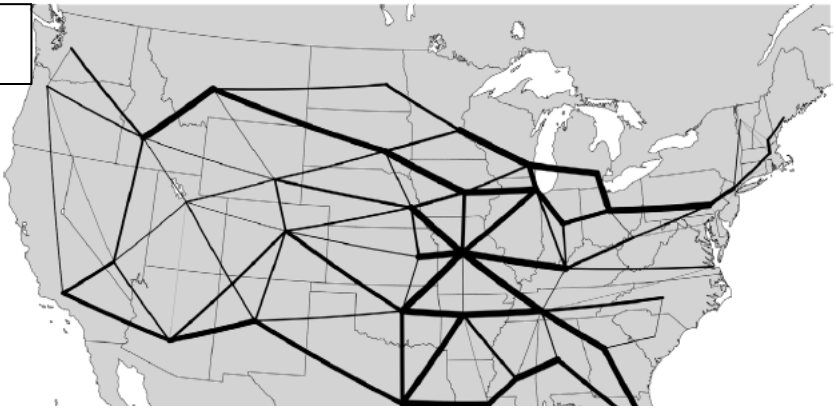
1



A. Figueroa-Acevedo, J. Bakke, H. Scribner, A. Jahanbani Ardakani,H. Nosair, A. Venkatraman, J McCalley, A. Bloom, D. Osborn, J. Caspary, and J. Okullo, "Design and Valuation of High-Capacity HVDC Macrogrid Transmission for the Continental US," *IEEE Trans on Power Systems*, 2021.

Website of the NREL Interconnection Seam Study: https://www.nrel.gov/analysis/seams.html.

2



C. Clack, "The role of transmission in deep decarbonization," presentation slides, March 29, 2021, https://vibrantcleanenergy.com/wp-content/uploads/2021/03/VCE-COPUC03292021.pdf.

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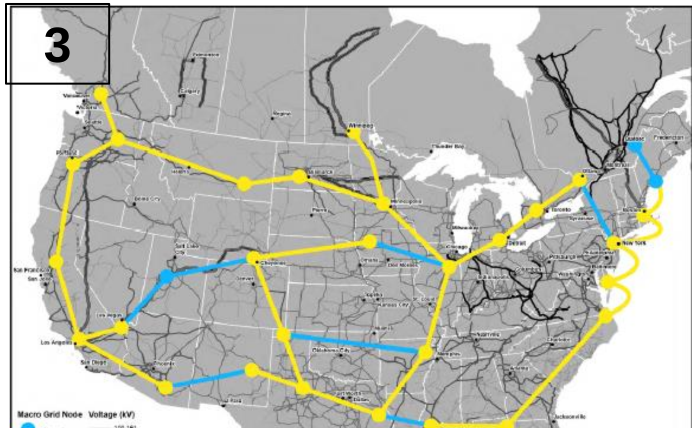
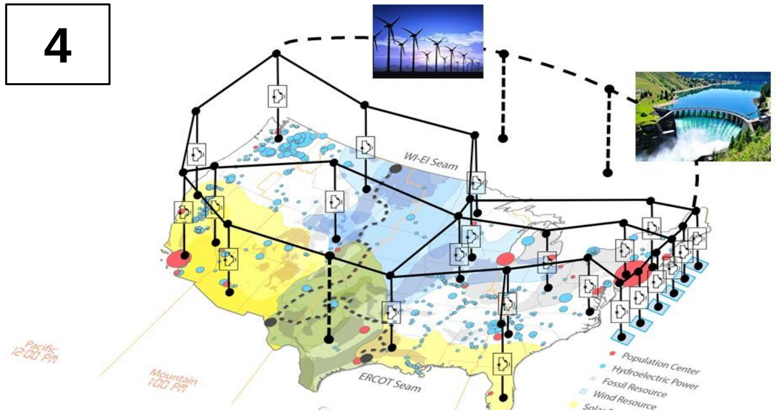


Energy System Integration Group. "Transmission Planning for 100% Clean Electricity," [Transmission Planning for 100% Clean Electricity – ESIG](#).

4

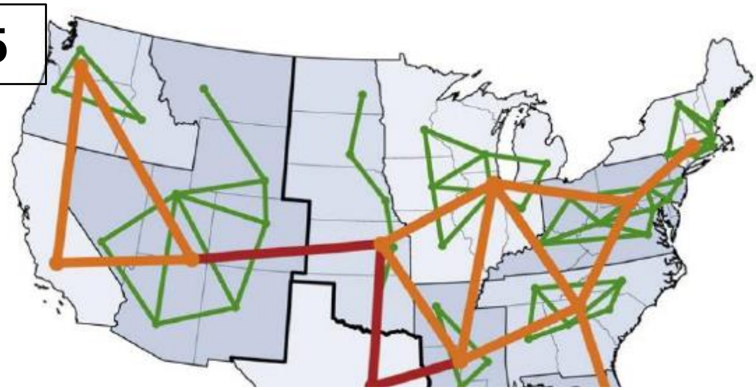


J. McCalley and Q. Zhang, "A Macrogrid Design for the 21st Century," Energy System Integration Group Blog, https://www.esig.energy/a-macrogrid-design-for-the-21st-century/.

These are some of the recently-proposed top-down designs; #1, 2, 4, 5 have been studied.

Note: This slide summarizes previous macrogrid work reflecting the most recent thinking in regard to macrogrid topology design.

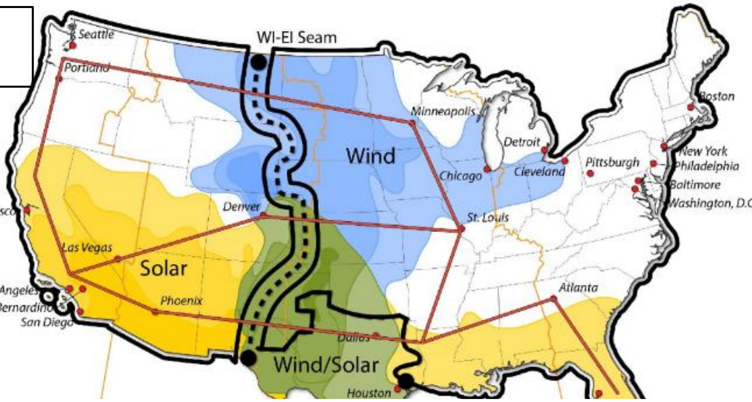
5



P. Brown and A. Butterud, "The Value of Inter-Regional Coordination and Transmission in Decarbonizing the US Electricity System," *Joule* vol. 5, issue 1, 20 January 2021, pages 115-134.

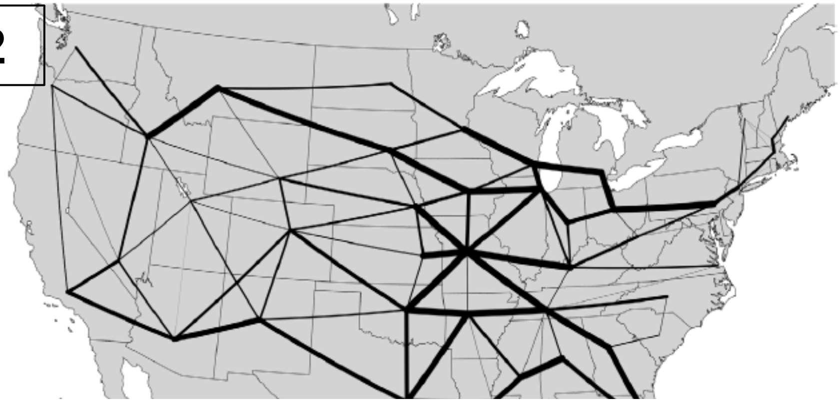
B1. Top-down (experience-driven) topology design

1



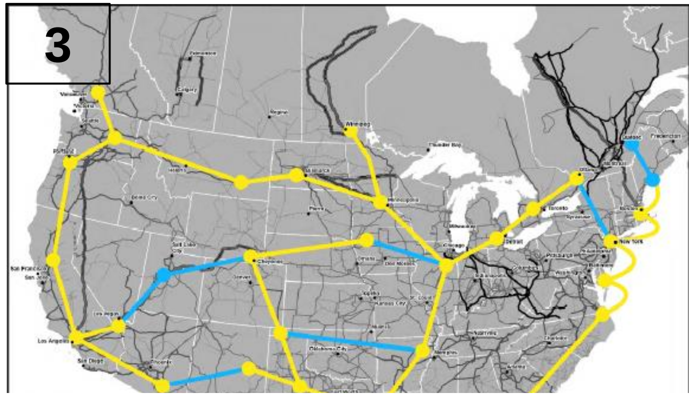
Northeast US omitted assuming offshore wind & Canadian hydro dominate that region.

2



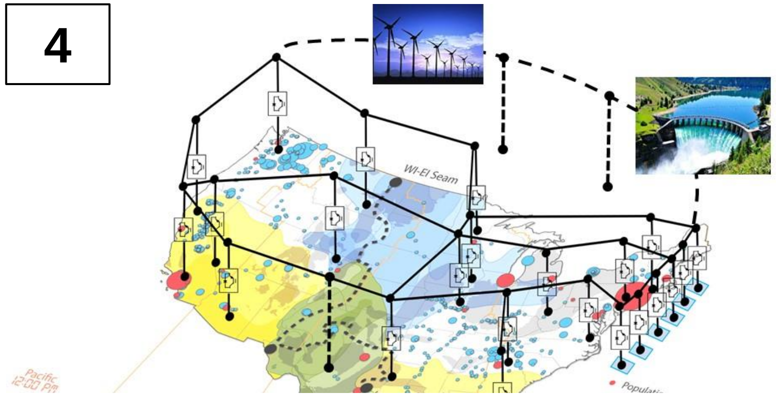
A node in every state avoids flyovers & may have good policy implications.

3



Designing it to be built in stages has advantages.

4



This design provides intentional focus on East Coast offshore & Canadian wind/hydro.

Each design identifies unique features and/or raises important questions. None have yet to be optimized for ROW feasibility & cost.

Note: This slide is summarizing previous Macogrid work in order to provide the most recent thinking in regard to macrogrid topology design..

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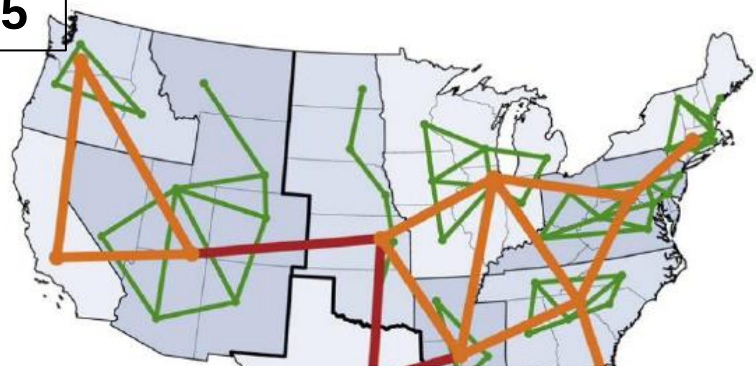


This design provides major loops and minor loops.

B2. Bottom-up (data-driven) topology design

Bottom-up design: Begins with a set of N candidate nodes and then assesses all possible N*(N-1)/2 branches between those nodes, accounting for routing information

Key features:

- Includes routing influences in its identification of topology
- Results used to refine top-down topology designs to obtain final macrogrid topology

Final macrogrid topology:

- Self-contingent: survives loss of any single branch without impacting underlying AC system
- Includes candidate nodes and branches
- Co-optimization in Step C identifies optimal topology from candidate nodes and branches

Step C – Identify circuit capacities

C.1 Create reduced model of existing grid

Steps:

- Join Eastern, Western, and ERCOT power flow models; results in ~120k buses
- Add economic data for generation and loads (VOM and costs of providing ancillary services)
- Reduce to ~500 buses (because co-optimization expansion planning tool is computationally intensive).

Reduction:

- Perform Kron reduction, modified to estimate flow limits for equivalent branches.
- Given analysis is on future-year only when zero-carbon is achieved…
    - Move renewable generation on eliminated nodes to retained nodes
    - Remove all carbon-producing generation

Step C – Identify circuit capacities

C.2 Develop scenarios and constraints, expand/assess using reduced model

Scenarios: Assumptions are made based on future conditions to be modeled, in terms of:

- Investment costs of technologies (e.g., wind, solar, storage)
- Demand growth
- Demand-control capability of providing ancillary services
- Forecasted meteorological conditions

Constraints: In addition to standard network operational constraints, we add constraints to explore solutions not otherwise identified based on economics alone, e.g., solutions having very high offshore wind.

C.3 Expand/assess using reduced model:

- Apply *co-optimization expansion planning (CEP)* on reduced model
- CEP identifies generation and transmission investments that result in least cost for investments + operations
- Copper sheet analysis not needed as CEP optimizes both generation and transmission simultaneously
- Identify macrogrid benefits associated with resource adequacy and resilience

Step D: Assess performance

Translation:

- Investments identified in Step C on reduced model, where buses and paths are equivalents
- Translation identifies investments on the physically existing buses and paths of the full model

Production cost simulation (PCM):

- PCM enables study of how the zero-carbon system operates
- However, a zero-carbon system will have a near-zero marginal energy costs and therefore will be dispatched based on VOM and ancillary service costs

Steady-state, control design, and dynamic analysis:

- Steady-state (AC power flow) contingency analysis for overload and voltage analysis
- Control design — using converters to improve frequency, voltage, transient, and oscillatory response
- Dynamic analysis — to ensure satisfactory dynamic performance for disturbances of concern

Macrogrid Reliability Framework

Macrogrid reliability assessment: Objective

The objective of the reliability analysis will be to assess relatively common, conventional events or issues that could cause disturbances on a grid with high levels of renewables. This would include, but not be limited to, concepts such as:

- Ways in which a macrogrid changes or supports system response to major disturbances
- Opportunities brought by the existence of a macrogrid for new bulk grid control paradigms (e.g., with extensive and embedded controllable HVDC)
- Opportunities for the macrogrid to improve the more localized performance of the existing AC grid
- The degree to which a macrogrid allows for sharing of services, such as reductions in contingency reserves
- A macrogrid's benefits for system performance for a grid with high levels of renewables and very low inertia
- Role of new technologies, such as grid-forming power electronic converters

Using large-scale power flow and dynamic simulations, these engineering analyses will quantify the system reliability enhancements that could be achieved by effective design and control of the macrogrid.

Reliability of the power system with a macrogrid

This section is limited to considerations of security per NERC

- Most reliability considerations are extremely design/detail-specific.

- This effort will focus on illustrating the security of a national BPS with a macrogrid overlay, by carefully investigating all the types of reliability concerns and opportunities that will arise.

- The approach must be demonstrably complete in the depth of the analysis: i.e., the details of the tests. It need not be exhaustive in the geographic scope, i.e., there is no need to prove that every potential problem is resolved, or that every potential benefit is quantified, rather that every potential type of benefit or problem has been examined.

- Particular attention will be given to:
  - Finding and mitigating failure modes associated with the macrogrid and its interaction with the BPS
  - Finding ways in which the macrogrid may enhance the performance or value of the underlying BPS grid

NERC defines a reliable Bulk Power System (BPS) as one that is able to meet the electricity needs of end-use customers even when unexpected equipment failures or other factors reduce the amount of available electricity.

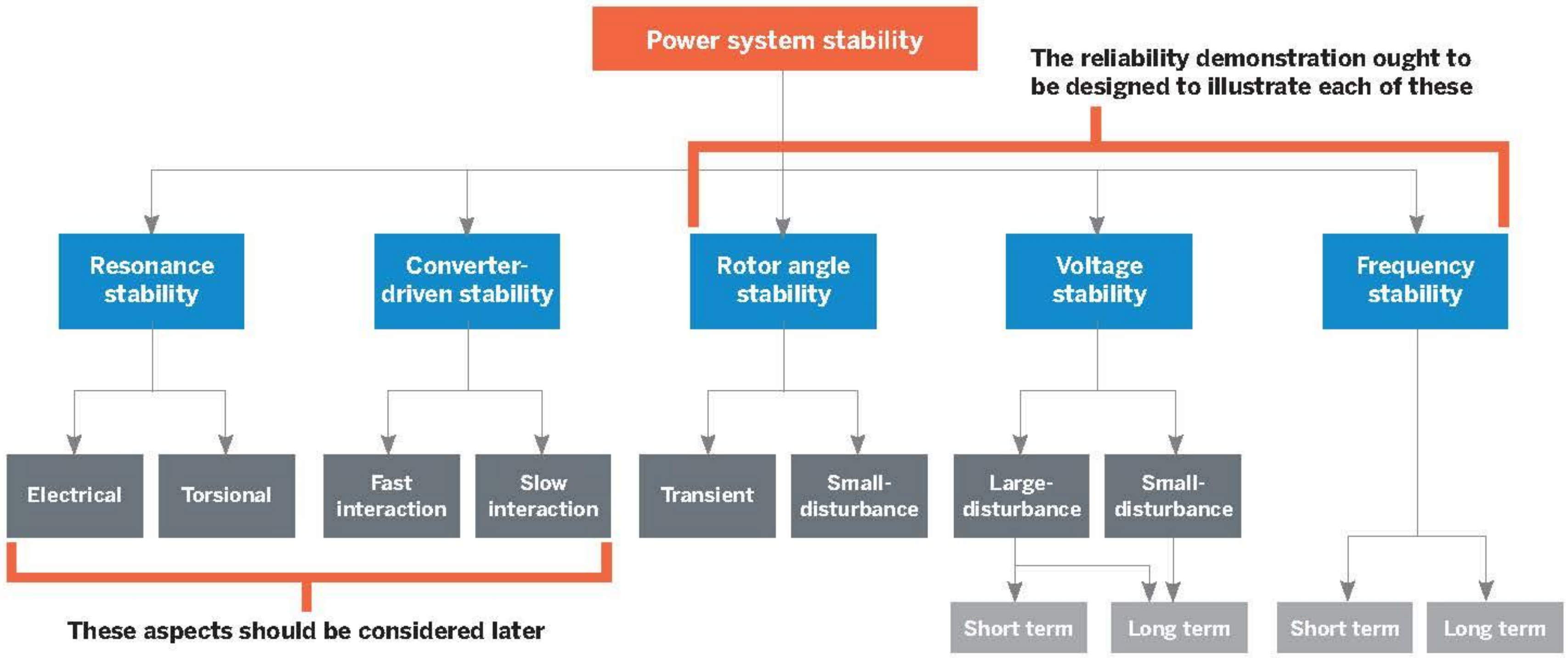
NERC divides reliability into two categories:

- Adequacy: (elsewhere in this effort)
- Security: the ability of the BPS to withstand sudden, unexpected disturbances, such as short circuits or unanticipated loss of system elements due to natural causes, and manmade physical or cyber attacks (paraphrased)

Pushing the envelope

- This exercise sets, as a minimum, the objective of showing that a macrogrid overlay system "can work" with sensible engineering and available technologies. But the study must also show whether the macrogrid system works better and makes the *existing* power system better.
- This study should provide quantitative insight into which practices should be retained, modified, or abandoned in the context of the fundamental structural changes that will accompany addition of a macro grid.
- A starting point should reflect minimum NERC reliability criteria. Because the BPS must be "fail-safe," consider modifying this criteria to reflect the macrogrid's potential for higher-consequence failures. Challenge criteria that have been traditionally enforced, but yield poor efficacy (i.e., impose a high cost for poor return on reliability benefits).
- Design the study to test, challenge and demonstrate reliability and to explore opportunities of the macrogrid to provide performance benefits (via control capabilities) not currently available. (For examples, see "local" and "share" slides later.)
- Some questions and solutions are likely to be outside the "normal" planning regime, and may possibly challenge existing rules or entrenched practice. The investigation must address these, recognizing but not necessarily be rigidly constrained, by existing practice and rules.

Stability



Adapted from N. Hatziargyriou *et al*., "Definition and Classification of Power System Stability – Revisited and Extended," in *IEEE Transactions on Power Systems*, vol. 36, no. 4, pp. 3271-3281, July 2021, doi: 10.1109/TPWRS.2020.3041774.

Getting the macrogrid right will create local benefits

- In some regards, the macrogrid will provide a solid “anchor” against which existing and new local/regional AC systems can lean. This will provide performance (and economic) benefits beyond the transfers on the macrogrid.
- The reliability investigation must design tests and demonstrations to explore these opportunities.
- For example:
    - Advanced controls of the macrogrid, that respond to disturbances on the supporting AC grid, should be able to relieve (some) performance constraints on it (e.g., increase path limits), increasing utilization, saving costs, reducing the need for more ROW for supporting AC circuits.

Sharing services: Frequency response, reserves, and inertia

- These issues will tend to be geographically broader or systemic, compared to transient and voltage stability.
- The macrogrid will tie regions together in ways that should facilitate better overall performance and economic sharing of resources.
- Security performance, particularly the response to events that unbalance the system – causing frequency and intertie violations – will be altered.
- The security investigation must design experiments to test existing and new types of systemic stress and make demonstrations of possible benefits from the macrogrid.
- For example, the macrogrid should allow for sharing of primary frequency response, delivery of fast frequency response, and more economic compliance with frequency response obligations. Novel controls may be needed to fully realize some potential benefits.

Technology opportunities: Grid-forming functionality, grid-enhancing technologies, energy storage, energy systems integration

- This aspect of "security" complements the macrogrid, specifically:
- The entire system, including the balance of the AC grid, and the mix of resources, such as massive IBRs buildout, new energy storage resources, electrification of new sectors, will be different.
- Reliability performance demonstrations should start with an assumption of best available and appropriate technology. For example, high functionality IBRs, best practice protection, high function reactive compensation, dynamic line rating, VSC HVDC, etc.
- Investigation must be designed to allow for refinement and addition of new (but reasonably well established) technologies. These can be used to mitigate problems or improve performance. Focus should be especially those which are currently projected to grow in the near future, including large-scale energy storage (with reliability centric controls), active electric vehicle infrastructure, and newly electrified industrial segments.

Disturbance response

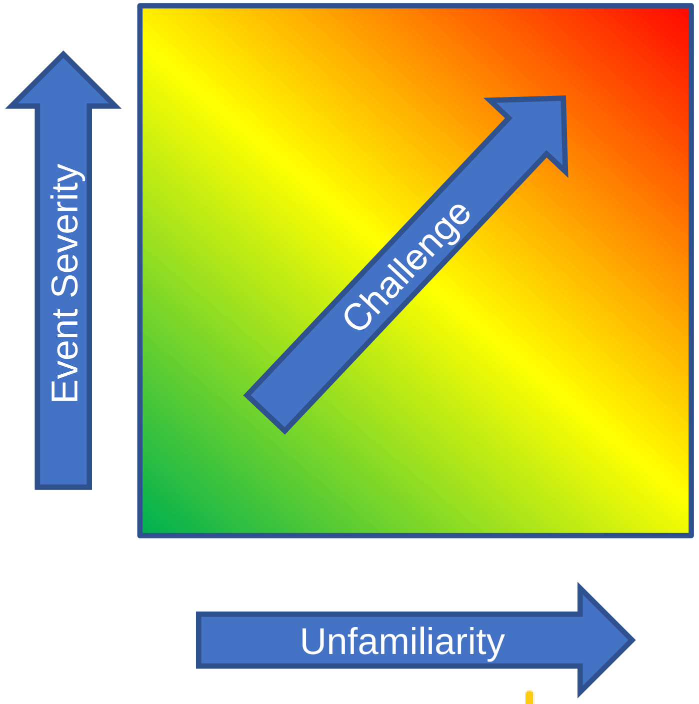
Severity

- "Normal" disturbances, for which there should be no (or very limited) customer impact. AKA N-1 planning paradigm.
- "Extreme" disturbances, including:
  - HILF (high-impact, low-frequency) and HIMF (high-impact medium-frequency) events
  - Common mode failures, i.e., events that are likely to cause significant customer impacts but for which the grid remains intact in its entirety.
- There are established rules and art addressing event impact severity. A starting point is to use them as-is, but since threats are changing, analysis of future severe disturbances should be flexible as well.

Familiarity

- Familiar territory (concerns that are characteristic of "conventional" transmission expansion)
- Standard planning paradigm
- New ground (concerns unique to the character of the macrogrid)
- New behaviors and responses

This is complex, including classification of events and allowable response to those events; it should even explore whether the existence of the macrogrid could enable new or different events. The IEEE stability classification provides context for the types of stability-based reliability concerns that should be addressed.



Events (transient and voltage stability)

At the least, the investigation should consider the classes of disturbances discussed here. Each type includes some points of technical concern. This list is not exhaustive, but represents the minimum set of events that should be considered. Also see “Frequency Stability and Sharing Services” and “Designing Reliability Tests” that follow.

1. **Fault, trip DC bi-pole:** Should be self-contingent. Other bi-poles pick up power. Will systems at nodes (nearby or otherwise) be affected? Will AC reactive support change? With VSC and big ratings, this is new ground

2. **Fault, trip AC collector line:** Will perturb other plants; DC will “see” disturbance. Depending on Node s/s configuration existing grid may see. Pretty standard stability questions, but novel controls on DC might provide performance improvements that allow heavier loading/better use of this new AC infrastructure.

3. **Fault, trip existing AC intertie:** Presence of DC will alter BPS behavior for critical (often studied) faults. E.g., stability of Colstrip line has been critical for decades; flows on existing AC are limited by stability for faults like this. Again, DC will “see” disturbance. But, again, novel controls on DC might provide performance improvements that allow heavier loading/better use of this existing AC infrastructure.

4. **AC fault in node substation**: This is extreme. Will presumably result in loss of “collected” plants. Must not result in cascading failures. Loss of MW from trip of plants will make this both a transient stability *plus* a frequency event. How will DC respond? Are strategies obvious? Are some better than others? How?

5. **Clear node:** This is extreme. Presumably this is *not* self-contingent. Again, cascading failure is not allowed. What strategies result in the least bad outcomes?

6. **Clear DC ROW:** This is extreme. Is it worse or better than 5 (clear node)? Are strategies different? What does AC system see, during and after the DC fault?

Events (frequency stability and service sharing)

Investigation of interconnection wide behaviors, as distinct from more localized stability concerns, are needed as well.

1. **Fault, trip largest units:** For example, a trip of 2 Palo Verde NPS units is a design basis event. The Eastern Interconnection and Texas Reliability Entity (TRE) have similar design basis events. This is basic, but very important. Design of experiment must consider the expectation of lower system inertia, and the potential for a wide range of resources to provide primary frequency response, fast frequency response, and other related frequency response services.
2. **Loss of infeed events (new):** The macrogrid is expected to be self-contingent. As noted on the previous slide, transient and voltage stability issues may arise from more extreme events. Similarly, power unbalances that will stress frequency and the delivery of service may result from more extreme failures. New risks of this category must be examined.
3. **Regulation sharing:** This is an intersection with stability constraints, and requirement for self-contingent management of the macrogrid. This applies to large discrete events and the next topic.
4. **Abrupt weather events:** Will perturb the system over relatively brief time frames, but ones that are longer than those normally considered in the context of stability. The risks associated with these events blurs the line between stability and operability in ways that were largely absent in thermal dominant systems. Ramping reserves and sharing need to be demonstrated. Systemic response to (for example) ramping events must not push the system into conditions of security risk, even temporarily. Consequently, attention to stability risks as capacity and service expectations with the macrogrid are set is necessary.

Designing reliability tests

- In many regards, the reliability study has the characteristics of a "design of experiment."
- Established (e.g., NERC) practice sets the starting point, but is insufficient to fully evaluate the radically different paradigm of a macrogrid.
- Reliability study must deliberately seek tests, disturbance and beyond, to stress various known reliability risks.
- A test regime, perhaps along the lines of this matrix, would be appropriate.

Class of stability concern	Disturbances that might precipitate	What might be different with macrogrid (what to look for)	Attributes of good test	Candidate mitigation
Transient (1st swing) loss of synchronism				
Power swing oscillations (rotor angle variety)				
Transient voltage collapse				
Transient overvoltage				
Transient frequency failure				
Emergency thermal failure				

Distilling insights from reliability tests

(for problems and solutions, for a given scenario/topology)

- The illustrative investigation will need to distill and extract insights that can guide broader discussions, as well as future macrogrid analysis.
- To that end, reliability investigation reporting must facilitate identification and mitigation of reliability challenges, not just show success or failure of the specific system illustrated.
- Researchers should plan to parse results. The table suggests one possible approach.

Recommended minimum points to study and report

Where the disturbance happens

- On the macrogrid
- On the major feeds between the resources and the macrogrid
- At the new resources
- At the receiving end, load centers
- Common-mode

What type of disturbance

- AC Faults; line trips; plant trips; other?
- macro grid: pole trip, bipole trip, station trip
- Severity of event

What type of problem

- Per IEEE stability hierarchy

Basic technology questions may require attention during the reliability study phase. For example:

Is there sufficient institutional understanding of what happens when a DC line faults in a multiterminal VSC grid? e.g., what does the nearby AC system "see", if anything?

If there is insufficient technical understanding in the industry for such questions (this is just an example), then entirely "separate" research efforts may be needed.

This reliability study should identify and advise the industry and research affiliates of technology research gaps and needs.

Macrogrid Resilience Framework

Goal and context

Goal – We must use consistent analytical and evaluation techniques for all of the macrogrid studies and analyses. Macrogrid proposals should be evaluated to determine whether they improve resilience as well as reliability (which will be incorporated into the macrogrid engineering design framing).

Context – Extreme weather events have historically been the most frequent causes of widespread electric distribution, transmission, and generation failures. Looking ahead, threats to the power system, citizens, and communities are expected to increase due to climate change (becoming high-impact, medium-frequency (HIMF) events) and potential attacks.

- Extreme weather situations and event recovery issues fit within NERC's legal obligations and responsibilities for reliability, even though the word "resilience" does not appear in the Federal Power Act legislation that gives FERC and NERC their powers.
- But recent atypical extreme weather events and reasonably possible HIMF and HILF events require a different analytical approach; they must be addressed through credible scenarios because extensive historic data and past system performance are not yet available.
- Assume standard reliability using historical data on load and generation patters (as defined and operationalized in NERC-FERC context) will be built into and frame the macrogrid engineering design framework.
- Design and construction of macrogrid must reflect future extreme weather threats and be hardened to ensure system ability to operate under extreme conditions when it is most needed for human safety and national security.

Reliability and resilience

Reliability = Meet standards of service based on historical statistics of load and generation
Resilience = Maintain acceptable levels of service during reasonably possible high-impact, low-frequency scenarios beyond just historical patterns, and reducing consequences and recovering quickly when service is interrupted

Customer view of resilience: make outages as infrequent, small and short as possible

Customers don't care why the grid goes down

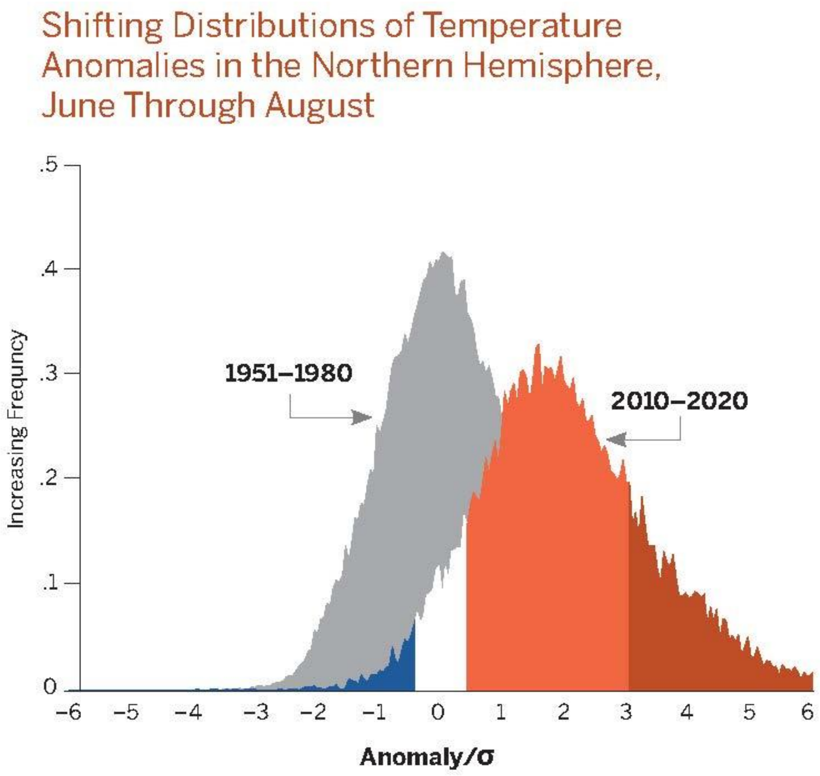
- >90% of all outages due to distribution-level problems*
- Typically <10% of all outages due to major events*
- Most major power outages due to severe weather*
- Before Winter Storm Uri, <0.0001% of customer outage-hours due to generation shortfalls or fuel supply problems.

Standard industry measures for reliability assessment exclude major weather events and use customer value of lost load (VOLL) estimates based on happily short outage events and ignoring lost productivity, morbidity, and mortality -- so irrelevant for evaluating current and future conditions and threats.

Wealthier customers are self-providing resilience (PV, batteries, generators) so their VOLL survey answers don't represent actual perceived costs or value of reliability.

*** Data from before 2018 and start of recent escalation of climate change-exacerbated wildfires, hurricanes, heat waves…**

Climate change and extreme weather



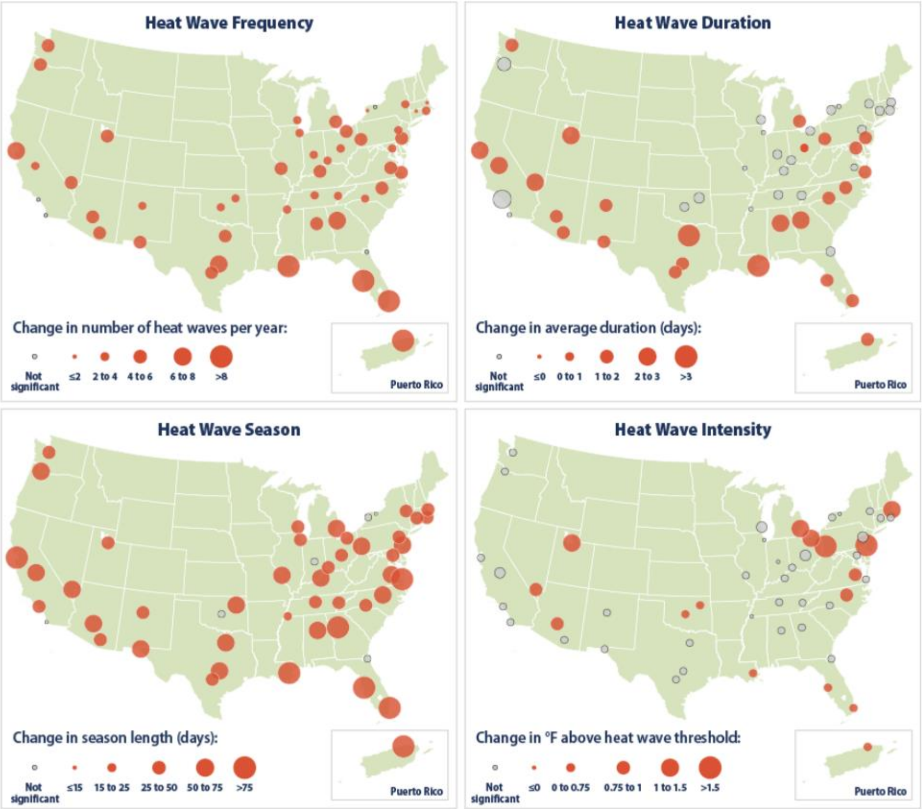
Source: Makiko Sato and James Hansen, Columbia University.

The historical, “normal” conditions and patterns we built and funded this grid for are no longer relevant (e.g., California, New Orleans, Houston, Puerto Rico)

Extreme weather changes

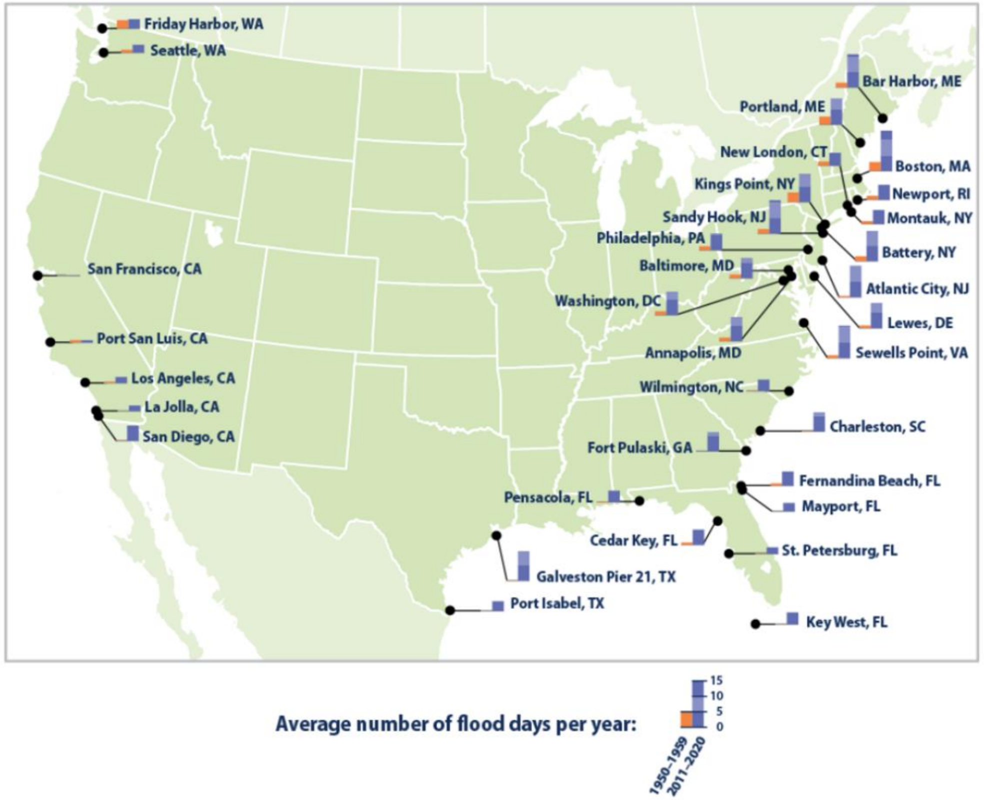
Heat waves worsening

Figure 2. Heat Wave Characteristics in 50 Large U.S. Cities, 1961–2019



Coastal flooding accelerating

Figure 1. Frequency of Flooding Along U.S. Coasts, 2011–2020 Versus 1950–1959



Also:
- Hurricanes
- Precipitation
- Inland floods
- Wildfires
- Droughts

Source: https://www.epa.gov/climate-indicators/climate-change-indicators-us-and-global-temperature

Implications for reliability and resilience

Higher risk to grid and society from climate change (also human threats)

- Historical ("normal") weather conditions not a relevant guide for current and future conditions
- Extreme weather no longer HILF events but high-impact medium-frequency events
- Higher risk = (higher frequency of extreme weather events) x (worse weather events causing more grid and societal damage)

Challenge for current grid assets

- Lesser ability to withstand harsher extreme weather conditions (asset destruction, condition deterioration, overloading)
- Lower performance capability (equipment deratings, low hydro output, faster time to failure)
- Limited ability to replace, upgrade, or expand asset base to meet challenges
- Restoration challenges – wider damages require more time, equipment, crews, $$$

Resource adequacy

- Higher demand levels (extreme weather, electrification) even with energy efficiency
- Harder to grow and operate grid supply side – complicated by evolving resource mix – to meet demand under extreme or surprise weather or supply failure conditions

Resilience characteristics and metrics

- Qualitative and quantitative assessment of the system under each defined extreme event, comparing the macrogrid to BAU scenarios
- Metrics for measuring the system's performance during an extreme weather scenario
  - Loss of load expectation (LOLE)
  - Expected unserved energy (EUE). Feed this into economic and reliability section by designing the system to meet a target EUE and assessing the cost of doing so.
  - Economic value of expected lost load using EUE times VOLL. Feed this into economic section.
  - Other quantitative and qualitative measures of performance of alternate portfolios under a wide variety of adverse conditions. Test alternate grid designs and resource portfolios under multiple severe conditions/threat scenarios.

Optionality and insurance value

How transmission creates optionality

- Allows better reliability and economic outcomes in both planning and operating timescales from better ability to respond to uncertainties including fuel costs, generator capital costs, and load patterns
- Enables large quantities of power delivery to support the most affected region, using available supply from neighboring areas, since severe weather events tend to be most severe in regions that are geographically smaller than the full interconnected network
- Measures of uncertainty and insurance value
- Explain insurance value
    - Note Winter Storm Uri and extremely costly possibilities.
    - Tie to other examples with which people are familiar, e.g., the average person has about 2 car accidents in their lives but they pay for insurance for 50 years. In 24 out of 25 years they pay insurance and get no benefit, but in one of the 25 years the insurance premium pays for itself.

Resilience evaluation methodology

Hypotheses for macrogrid resilience contributions (informed by historical event examples)

- Geographic load diversity during extreme events
- Geographic supply diversity and deliverability during extreme events
- Imported energy capability (as to make up for localized demand spikes and inability of in-region generation to perform due to storm impacts) with and without a macrogrid
- High-impact medium-frequency = the collected, credible set of high impact extreme weather events. Ask DOE and FERC to help get NOAA or IPCC modelers to provide 10, 20, 30 year forward datasets on type, magnitude, frequency, locations of these extreme events for standard analytical use.
- Imported capacity (as to meet summer or winter peak loads)
- Black-start capability
- Ancillary services (mostly frequency response)
- Reduced risk from portfolio diversity
- Reduced risk from increased operational sources and tools
- Potentially faster outage restoration
- Non-extreme events covered in standard reliability and economic sections

Sources and references

- Goggin/ACORE ***Transmission Makes the Power System Resilient to Extreme Weather*** released in July posted at: https://www.ferc.gov/february-2021-cold-weather-grid-operations-preliminary-findings-and-recommendations
  - During February 2021 Winter Storm Uri, an additional GW of connectivity between ERCOT and the Southeast could have saved nearly $1 billion. SPP and MISO-South each could have saved in excess of $100 million with an additional GW of transmission ties to power systems east.
  - During Texas August 2019 heat wave, an additional GW of transmission tie capacity to the Southeast could have saved Texas customers nearly $75 million.
  - During the "Bomb Cyclone" cold snap across the Northeast in December 2017 – January 2018, New England, New York, and the Mid-Atlantic region suffered cold weather for nearly three weeks. Each of these regions could have saved $30-40 million for each GW of stronger transmission ties among themselves or to other regions. The regions typically switched between importing and exporting, demonstrating that transmission benefits all users across broad geographic areas.
- PJM 2017 resource diversity analysis: https://www.pjm.com/~/media/library/reports-notices/special-reports/20170330-pjms-evolving-resource-mix-and-system-reliability.ashx
- "Planning for Resilience in High Renewable Power Systems," NICHOLAS W. MILLER, CIGRE GENERAL SESSION E-MEETING 2020 SC C4, Paper 121 7-9-2020
- "Assessing Transmission Investments Under Uncertainty," https://www.energy.gov/sites/prod/files/2013/09/f2/1-2013RMReview-Hobbs.pdf
- "Engineering-Economic Methods for Power Transmission Planning under Uncertainty and Renewable Resource Policies," https://hobbsgroup.johnshopkins.edu/docs/FD_Munoz_Dissertation.pdf

Macrogrid Operations and Operability Framework

Purpose and objectives

This section facilitates early analysis of the operational needs associated with a future macrogrid (HVDC overlay) across North America, outlining the steps needed to ensure that future operation of the macrogrid is studied and coordinated with existing operational structures and organizations.

<u>Objectives</u>

- Posit options for workable organizational structures and responsibilities for operation of macrogrid overlay
- Assess operational requirements for the macrogrid and how it integrates with and affects the underlying transmission network
- Determine how operations could be coordinated with regional markets and entities
- Identify new tools and approaches that may be required to fulfill national operational mission (e.g., simultaneous transport of energy with reliability constraints)

Operations and operability: General

- A national macrogrid would offer a degree of control over flows of energy from sources to loads. Those flows will be orders of magnitude greater than present power system flows.
- To leverage such control, however, new architectures and methods for grid control may have to be developed.
- Current control structures are based on cooperation mostly between neighbors and within interconnections.
- With a macrogrid, operational concepts and opportunities will extend across interconnections and to neighbors' neighbors and beyond.

Coordinating macrogrid operation

- Select or create an entity that operates the macrogrid to meet reliability/resilience needs and facilitate economic operation of the U.S. electrical infrastructure.
- Determine appropriate mechanisms for technical control and operation of the macrogrid and underlying networks to:
  - Maintain bulk system security
  - Balance generation and load
  - Manage congestion
  - Coordinate between regional and national entities for system operations
  - Conduct long-term resource assessments and planning
- Identify appropriate options to manage power, economic, and market transactions, including:
  - Coordinating renewable energy procurement nationally, both day-ahead and in real time
  - Coordination between regional and national entities regarding commitment and dispatch of all electricity sources, demand response and storage, and market operations
  - Ancillary services management
  - Cost allocation of ancillary services and uplift costs
- Macrogrid economic and operations studies would likely use large-scale production simulations to illustrate both higher-level coordination concepts and issues such as balancing and congestion management.

Approach

- Leverage DOE capabilities, resources, and leadership to identify and begin addressing operational issues and challenges that must be addressed to facilitate design, construction, and operation of a national macrogrid and capture its full benefits. The federal government possesses vast capabilities for studying and improving the power system through the Department of Energy, national laboratories, power administrations, and the Federal Energy Regulatory Commission. These capabilities should be organized and coordinated to facilitate the industry's design, construction, and operation of a national macro grid.
- Collaborate with industry, NERC, and FERC to create research and procedural roadmaps for changes to operational analytics, standards, and performance metrics that will be appropriate for a macrogrid-enhanced electricity system, as well as mitigation needs during the buildout and transition to a fully redundant, self-contingent macrogrid network.
- Develop new tools and capabilities to improve situational awareness, operational support tools including coordination and communications needs in the real-time and operations planning horizons.

Assumptions

- A macrogrid will complement existing networks and markets, and not eliminate the need for regional markets and interregional planning within and across existing interconnections.
- Although existing bulk power systems will integrate with a macrogrid, we will not need to redesign existing AC systems to handle a contingency on the HVDC network.
- The majority of new renewable and associated storage facilities that rely on the macrogrid for regional and interregional delivery will be directly connected to the macrogrid to minimize the impacts to underlying power systems serving regional markets. The macrogrid will be integrated with the existing AC grid strongly enough that it can leverage the benefits of load diversity among regions.
- A macrogrid could allow existing HVDC ties between interconnections to be replaced, expanded, or even bypassed.
- The macrogrid will facilitate the operation of regional and interregional wholesale power markets as a result of its capabilities to provide fast frequency response, contingency reserves, ramping, black-start, and other ancillary services which are currently a burden on the efficiencies of existing grid planning and operations.

MACROGRID MARKET

NYISO

ISONE

BPA

MISO

PJM

WAPA

SPP

TVA

CAISO/EIM

ERCOT

SOUTHEAST

Expected operational benefits

The addition of high-capacity HVDC transmission lines in a self-contingent, high-capacity overlay network can provide a range of operational benefits to system operators by enhancing reliability and reducing the cost of system operations. The operational benefits of HVDC lines, enabled by the projects' converter technologies, include:

(1) provide dynamic voltage support to the AC system, thereby increasing its transfer capability

(2) supply voltage and frequency support

(3) improve transient stability and reactive performance

(4) provide AC system damping

(5) serve as a "firewall" to limit the spread of system disturbances

(6) decouple the interconnected system so that faults and frequency variations between "variable" resources and the AC network, or between different parts of the AC network do not affect each other

(7) provide black-start capability to re-energize a 100% blacked-out portion of the network

(8) with grid-forming control, mitigate localized weak grid issues that limit IBR penetrations

HVDC facilities can redirect power flow instantaneously, which provides tremendous flexibility for system operators to address reliability challenges, system stability, voltage support, improved reactive performance, and black-start capability.

Many current and planned operating protocols, practices, and metrics will be obsolete

- There is broad industry consensus that RTOs/ISOs will need more operational flexibility from resources to reliably serve loads as the resource mix evolves to include more weather-dependent variable energy resources and loads change due to weather-dependent distributed energy resources, electrification, and other factors. This is premised on an incremental view of the current power system with marginal system improvements, not with an HVDC macrogrid network.
- Current protocols, practices, and metrics must evolve. For example, ever-increasing penetrations of inverter-based resources and the retirement of thermal synchronous generators have led many markets throughout the world to adopt minimum inertia requirements. The macrogrid creates an opportunity for bulk power system operators to rethink traditional operating requirements, including whether provision of inertia from traditional resources remains necessary to provide system security. Advanced grid control and monitoring capabilities, combined with high expected levels of distributed energy resources, will provide an opportunity to drastically improve system stability.
- Potential benefits from largely replacing UFLS and AC system Remedial Action Schemes with macrogrid delivery of fast frequency response from inverter-based resources.

Improved operating practices, procedures, and tools are needed

- Improved operating practices, procedures, and tools are critical to integrate variable generation and improve the control performance and reliability characteristics of the power system. System resources supporting reliability, such as flexible generation and responsive load, are finite. Operating practices, procedures, and tools that maximize the effective use of limited responsive resources improve reliability and facilitate variable generation integration.
- Three categories of operations activities support reliability: prepare, observe, and act. These three categories are roughly chronological with preparation occurring first, followed by observation and action when required. The categories are not mutually exclusive; many practices, procedures, and tools useful in preparing for operations are also used to observe and/or to act and manage the grid.

Technology

- Better systems and tools will be required with standardization across the continental grid, to facilitate coordinated operations between system operators using the enhanced controls and services that can be provided by robust HVDC network.
- A well-designed macrogrid – once built out – can be expected to reduce congestion levels during normal system conditions, and can provide significant throughput, flexibility, and resilience benefits during extreme weather events.
- Frequency response, reserves, and regulation can be provided from HVDC nodes and eliminate the need for many complex ancillary services to support markets with high penetrations of renewable resources.
- Not all terminals of the HVDC macrogrid need to built at once, i.e., they can be built in stages, a feature that might facilitate incorporation of coalitions of interested parties who want to focus on certain segments.

Tool development

Better situational awareness tools will be needed to help operators evaluate potential events and contingencies on a complex mixed HVDC and AC system, and give operators guidance on the effectiveness of possible mitigating measures. Operator decisionmaking support tools include:

- Aggregating data on current system status from various sources including EMS/SCADA, load and variable generation forecast systems, and operational planning and/or market results identifying available resources to provide succinct, meaningful displays that support situational awareness.
- Situational awareness will be drastically improved with sensors and enhanced algorithms to manage grid operations as well as operators' understanding of options and services that can be provided via the capabilities of the macrogrid.
- Real-time reliability and risk assessments associated with present and future operating conditions, considering contingencies and elements such as total ramping capability from available resources (supply and demand) and uncertainties in unit availability, load, and variable generation.
- Evaluation and recommendation of mitigating actions that can be implemented to solve potential, predicted or realized reliability/security concerns.

Education

- Control capabilities from the macrogrid need to be understood, appreciated and incorporated into future operating protocols, reliability standards, performance metrics which will affect operating agreements, business practices, and tariff services. These control capabilities will drastically improve frequency stability, voltage stability, transient stability, and oscillatory stability of the existing AC networks. Education of industry staff and stakeholders will be a critical first step in shaping support and getting buy-in to a shared vision of how the future power system needs to be operated.
- Research and document best practices to improve coordinated operations in terms of necessary consolidated and coordinating mechanism; focus on scheduling practices, provision of ancillary services, etc. from a robust overlay integrated into existing and planned AC systems. Expand upon McCalley/ACEG's *Macro Grids in the Mainstream: An International Survey of Plans and Progress*, November 2020.

Lessons learned

- Development and use of a macrogrid will require the bulk power industry to plan and operate the bulk power systems differently. Planning and operating a rapidly changing grid requires time to learn, collaborate, and share experiences. The industry participants and stakeholders must collaborate to develop new policies, processes, and procedures to drive change for the macrogrid.
- Lessons learned should be available from extensive HVDC and UHVAC expansion in China, Supergrid initiatives in Europe, and recent collaborative efforts such as G-PST and CIGRE C1.44.

Questions to be answered...

- How can a macrogrid affect current operating parameters and requirements?
- What is the value proposition of a macrogrid to consumers based on enhanced HVDC controls and capabilities to affect existing BA standards such as frequency response?
- Can existing communication channels and networks support the needs for an effective and efficient macrogrid and its associated control system?
- Is a macrogrid and its associated control system consistent with existing NERC standards?
- How could a macrogrid impact the provision and economics associated with essential reliability services for the bulk power system?
- How would a macrogrid and its associated control system address bulk power system issues such as AC dynamic stability, low frequency oscillations, load shedding schemes, and system black-start?
- How could synchrophasor and other monitoring and analytics efforts be expanded to facilitate the needs of a macrogrid control system and mitigate impacts to the AC systems?
- How would a macrogrid and its associated capabilities impact existing joint operating agreements and coordination requirements between neighboring systems?

Macrogrid Economic Framework

Overview

- Goal: to use meaningful and consistent economic analytical and evaluation techniques for all of the macrogrid studies and analyses
  - Macrogrid costs
  - Macrogrid benefits and benefit distribution by region and customer type
  - Cost-effectiveness
  - Cost allocation, benefits, and equity v. economics
  - Summarize metrics
- Every evaluation of macrogrid costs and benefits has to compare to the costs and benefits of achieving the same goal without use of macrogrid overlay, using only BAU technology, practices, and trends

Costs of macrogrid construction

- Capital costs and ongoing fixed costs for new transmission
- Time and speed to build. Lines that can be built fast with minimal community and landowner opposition – even if they have higher nominal capital cost due to longer mileage or more expensive structures and building for future expansion – are preferable to lines that take longer but cost less, because they could avoid litigation and enable faster realization of economic, reliability, and resilience benefits.

Benefits methodology

- As long as the scenarios and relevant costs and benefits are consistently defined and evaluated, it is appropriate to calculate the differences in costs and benefits between different scenarios and factors
- For most benefits to be studied, the total benefit from a given scenario should be credited to the goal (e.g., 100% clean electricity)
- Look at multiple scales of impact (local/state, regional, national) without restricting benefits to the immediate geographic area around the MG lines.
- Benefits for every scenario should be compared to the impacts of the BAU (no macrogrid) scenario to identify the opportunity costs of not building the macrogrid.

Opportunity costs of not building the macrogrid

Credible analysis of macrogrid options must compare macrogrid costs to the opportunity costs of not building it.

- Define a no-macrogrid or business-as-usual (BAU) scenario and calculate the same cost and benefit metrics for the BAU-no macrogrid scenario as for the various macrogrid scenarios.
- The BAU reference case should achieve and serve the same level of renewables (or emissions) and electricity demand but using more local generation and AC transmission without the macrogrid overlay.
- The no-macrogrid BAU case study should determine whether it is possible to achieve decarbonization goals without a macrogrid, and identify the base reliability and cost levels associated with a BAU buildout.

Cost of inaction (from NETA paper)

"Although large transmission expansion will be expensive, it is less expensive than the alternative—inaction which contributes to worsening climate change, exacerbates the effects of extreme weather events, and fails to enhance grid reliability and resilience. Since the impacts of climate change will be felt by hundreds of millions of people in the United States (and billions worldwide) through this century and beyond, the United States should commit to a federal funding program that pays for a portion of the country's electricity system expansion and improvements, accelerating this expansion and its benefits to all Americans over many decades. Coordinated federal action is desirable because it would better balance costs and benefits, speed infrastructure investment and implementation, and reduce the likelihood of incompatible investments or gaps that obstruct attainment of the full goal. Experience to date shows that decentralized, uncoordinated transmission planning and execution approaches have not effectively built much interregional transmission and cannot address challenges of this scale and importance to the reliability, resilience, decarbonization, economic, jobs, equity, and security functions on which our nation relies."

Benefits of a macrogrid

Electricity system benefits (what FERC is allowed to charge customers for):

- Energy production cost savings
- Saved capital and ongoing fixed costs of generation and transmission
- Level of competition in generation market
- Value of reducing emissions of carbon and other pollutants
- Power system reliability (operating security), including additional reliability improvements leveraging macrogrid-enabled HVDC controls for improved system frequency response, better local voltage control, and enhanced transient and oscillatory stability performance.
- Adequacy -- capacity reduction to achieve the same level of resource adequacy by capturing load and renewable diversity, reducing planning and operating reserve needs (including ancillary services)
- Fossil fuel cost savings (through use of the most economic resources nationwide and reduced energy consumption for fuel transportation, as opposed to use of the most economic resources locally)
- Delivered energy costs (retail bills and distribution adder)
- Greater cost certainty for transmission customers including interconnecting generators
- Reduction in risk from reducing exposure to uncertainties regarding fuel price, load, generator cost, etc. Potentially valued by assigning consumers a risk-averse preference profile, and then probabilistically testing consumer outcomes across a range of input assumptions for uncertain variables (see https://www.energy.gov/sites/prod/files/2013/09/f2/1-2013RMReview-Hobbs.pdf https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2928862)

More impacts and benefits of a macrogrid

- Broader social benefits beyond electricity system benefits
  - Net employment and wages impact
  - Gross domestic product (GDP) impact
  - Tax payments to local and state governments impact
  - Public health

Routing and siting options to speed construction and lessen macrogrid costs

- Highway right-of-ways (ROWs)
- Existing transmission ROWs
- Maximize capability on initial build (ROW width, structure capability, terminal capacity) to enable future expansion
- Longer routes and bigger payments to get around hostile landowners
- Limited selective undergrounding
- Current and retired plant sites and natural gas pipelines

Distribution of benefits

- Determine who benefits and by how much, for use in regulatory proceedings
- Incorporate the broad incidence of benefits including in high-impact low-frequency events, and the option/insurance value of transmission

Comparing macrogrid costs and benefits

- Decision rule: Maximize expected net benefits
- Calculate costs and benefits on local, state, regional, national scales
- Calculate macrogrid costs and benefits for portfolios of lines, not just for individual lines. Transmission is by definition a network commodity, for which the whole exceeds the sum of the parts, so individual lines won't open up the full suite of benefits realizable from building the entire portfolio.
- Explicitly identify and compare location of costs v. location of benefits to show how beneficial impacts spread far beyond where costs are incurred

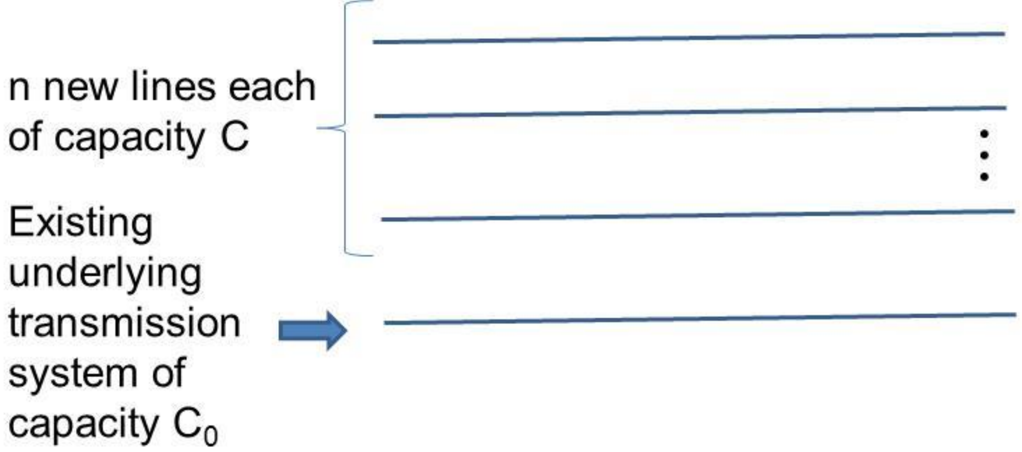
Appendix: Rule of 3

Rule of 3

The rule of 3 is a guideline that says that high-capacity interregional transmission can be built to be (i) self-contingent, and (ii) economically attractive if it is built using at least 3 parallel circuits.

- Self-contingent means that remaining circuits are able to carry the additional loading for loss of one circuit.
- Economically attractive means that, during normal operation:
  - it provides significant additional transmission capacity
  - it can use a high percentage of the invested capacity

Rule of 3 – Development



Define:

C	Capacity of one new line
n	Number of new lines
ΔC	Emergency overload capacity of each new line
C_0	Capacity of existing underlying trans system
ΔC_0	Emergency overload capacity of existing underlying trans system
p	Derating factor: fraction of total trans capacity that can be used without overloading remaining circuits during loss of one new circuit

Total Max Flow Before N-1 Outage ≤ Total Capacity After N-1 Outage

$$pnC+pC_0 \quad \leq \quad (n-1)(C+\Delta C)+(C_0+\Delta C_0)$$

Above inequality can be manipulated to give: $n \geq \dfrac{C+\Delta C+pC_0 - C_0 - \Delta C}{C+\Delta C - pC}$

Rule of 3 – Illustration A, with underlying capacity

Assume:

$$n \geq \frac{C+\Delta C+pC_0 - C_0 - \Delta C}{C+\Delta C - pC}$$

C=3600MW (Capacity of one new line)

ΔC=900MW (25% of C, 20-min emergency overload capacity of each new line)

C_0=1500MW (Capacity of existing underlying trans system)

ΔC_0=375MW (25% of C_0, 20-min emergency overload capacity of existing underlying trans system)

Case A: Underlying system has capacity

n (minimum number of new lines to satisfy inequality at p)	p (derating factor - fraction of total transmission capacity that can be used without overloading remaining circuits during loss of one new circuit)	nC (capacity added, MW)	pnC (total available capacity added, MW)
1	0.37	3600	1323
2	0.73	7200	5276
3	0.88	10,800	9549
4	0.97	14,440	13,925

Economics improve with the ability to use a high % of the investment.

Rule of 3 – Illustration B: no underlying capacity

This is approximately the case, usually, when the new transmission interconnects two asynchronous grids.

Assume:

C=3600MW (Capacity of one new line)

ΔC=900MW (25% of C, 20-min emergency overload capacity of each new line)

C_0=0MW (Capacity of existing underlying trans system)

ΔC_0=0MW (25% of C_0, 20-min emergency overload capacity of existing underlying trans system)

$$n \geq \frac{C+\Delta C+pC_0 - C_0 - \Delta C}{C+\Delta C - pC}$$

Case B: Underlying system has no capacity

n (minimum number of new lines to satisfy inequality at p)	p (derating factor - fraction of total transmission capacity that can be used without overloading remaining circuits during loss of one new circuit)	nC (capacity added, MW)	pnC (total available capacity added, MW)
1	0	3600	0
2	0.62	7200	4500
3	0.83	10,800	9000
4	0.94	14,440	13,500

Economics improve with the ability to use a high % of the investment.