Design Study Requirements for a U.S. Macrogrid

A PATH TO ACHIEVING THE NATION'S ENERGY SYSTEM TRANSFORMATION GOALS

Energy Systems Integration Group

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A Path to Achieving the Nation's Energy System Transformation Goals

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Executive Summary

Several recent, comprehensive studies of a clean energy future for the United States point to the same conclusion: a clean electricity future for the United States will require massive development of the bulk transmission infrastructure.

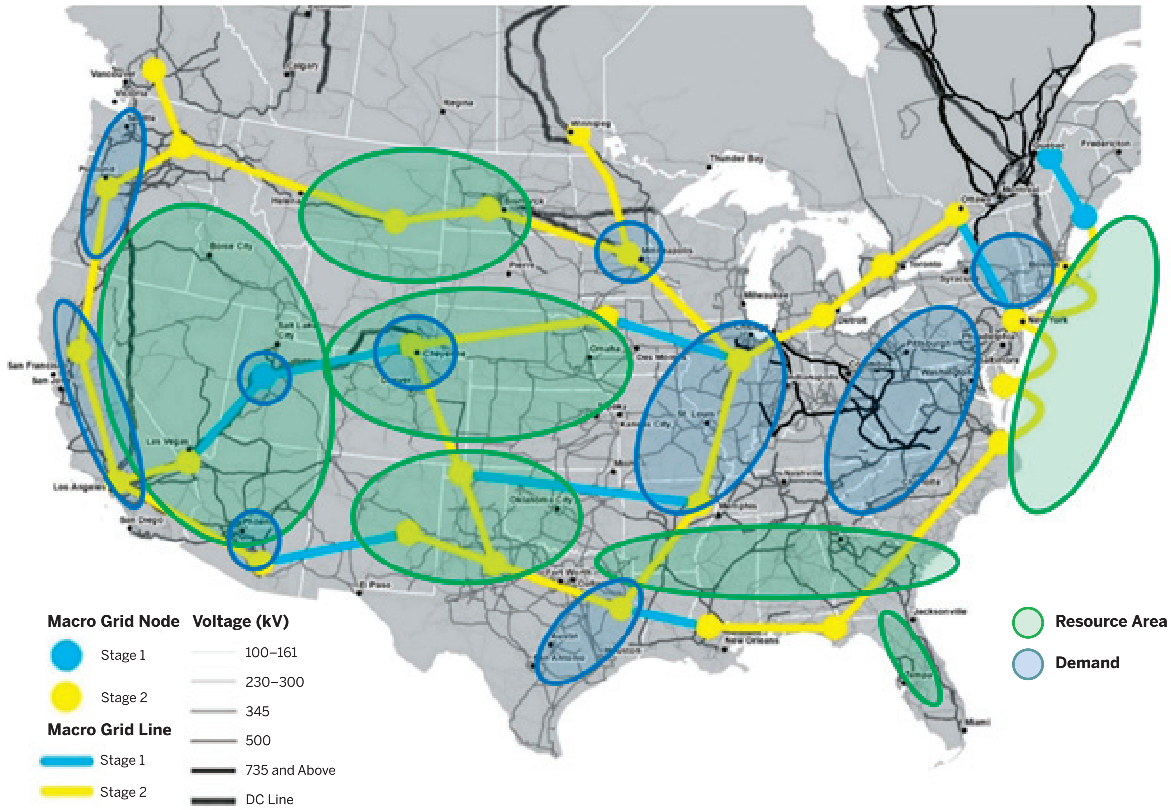
States, utilities, and consumers have significant commitments to rapidly decrease carbon emissions in the power sector and to use more electricity to reduce emissions in other sectors. In the autumn of 2020, the Energy Systems Integration Group conducted a series of virtual workshops to consider the implications of and opportunities highlighted by the above referenced studies. These workshops confirmed that our current transmission development approaches and processes would almost certainly be inadequate for the challenge of growing to enable a clean energy future.

The advanced hybrid grid may be part of the key for the massive transmission expansion required to support very high levels of clean electricity for the United States. Some major features of the macrogrid concept (Figure ES-1, p. 2) are the principle of looped circuits and the interspersed converter stations to either collect clean electricity or deliver it to demand centers.

The macrogrid concept proposed here is more than massive build-out of conventional high-voltage DC (HVDC) lines and converter stations. The macrogrid vision consists of a backbone of long-distance lines composed of networked, multi-terminal HVDC based on voltage source converter (VSC) technology.

FIGURE ES-1

Macrogrid Concept with Overlaid Clean Energy Resource Areas and Locations of Major Electricity Demand



Source: Energy Systems Integration Group.

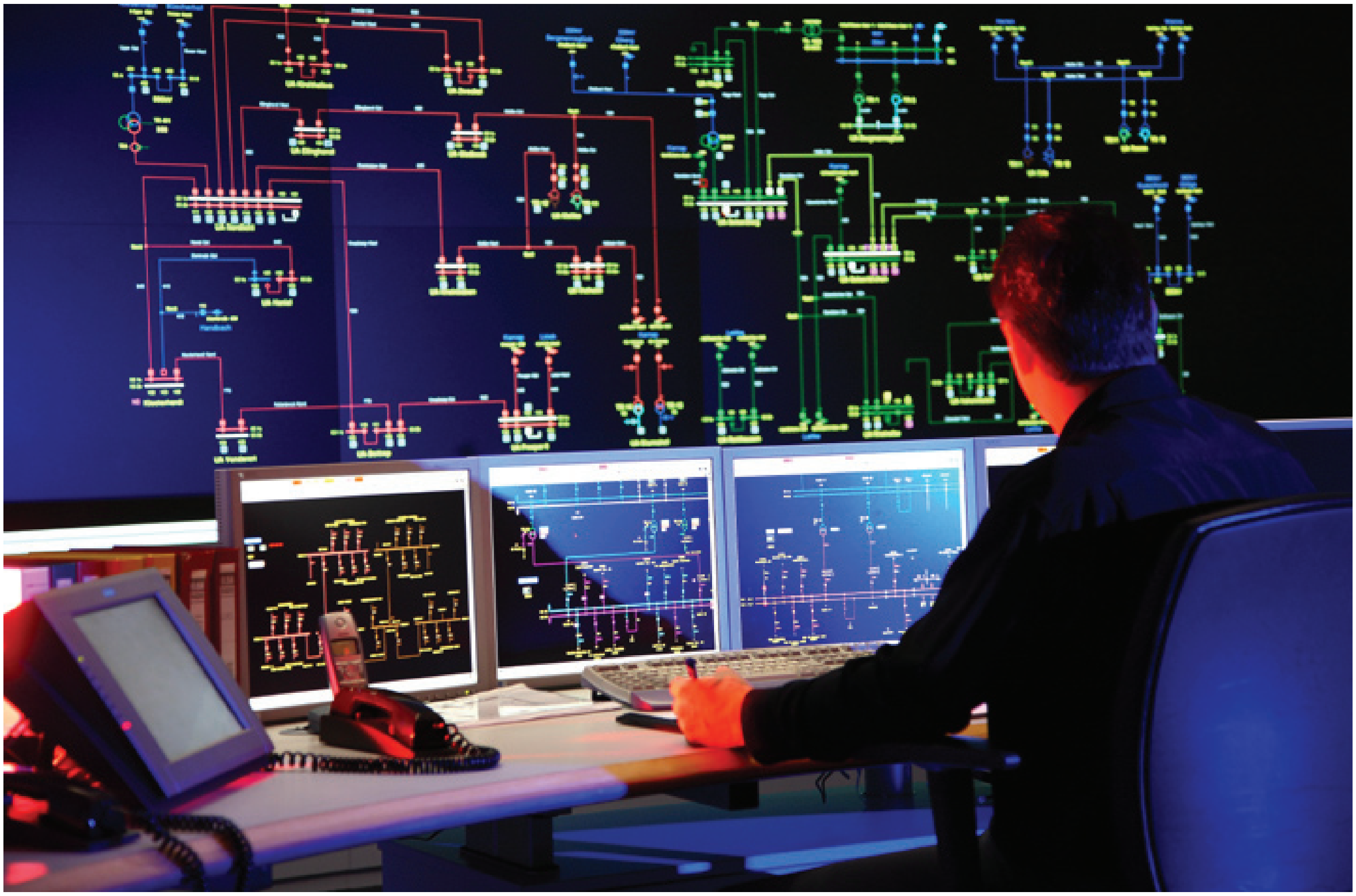
Major Benefits of a Macrogrid

The benefits of a national macrogrid go well beyond simply serving as conduits for moving clean energy from source to load. The general attributes of a macrogrid fall into the following broad categories:

- **Reliability.** The macrogrid's capabilities will be extremely valuable for grid management and security with very high levels of renewable resources to support decarbonization goals. Increased interconnectivity between regions of the United States can contribute to significant improvements in reliability. The technologies comprising the macrogrid—extra-high and ultra-high voltage DC (EHVDC and UHVDC) transmission that can make the bulk transmission network highly controllable—can be leveraged to address long-standing challenges with bulk power system reliability.

  The controls associated with HVDC equipment, and wide-area situational awareness enabled by new connectivity and technology, will tie regions together in ways that facilitate better and more efficient overall grid performance. Energy, capacity, and ancillary services would be deliverable from any region of the country to any other region, not just between neighbors. A macrogrid can provide operational tools and capabilities that not only can reduce the bulk power system's susceptibility to failure, but can enhance outage restoration capabilities and speed, which can be critical during extreme operating scenarios.

- **Resilience.** Extreme weather events, a growing concern in a changing climate, can affect large regions of the country as experienced in California in August 2020 and Texas in February 2021. The scope and scale of the macrogrid will provide interconnectivity that



spans the entire country (and potentially the northern and southern borders as well) and goes well beyond the connections that we have now, between mostly adjacent regions. Such interconnectivity is needed to ensure the resilience of the electricity infrastructure on which the country's residents and economy depend.

- **Economics.** Some recent studies indicate that a macrogrid would substantially reduce the overall cost for a clean energy future, saving as much as one trillion dollars (see, for example, VCE (2020)). Conventional power system planning models under-value transmission, but newer approaches capture the benefits of moving power to balance power systems with dispersed variable resources based on the location and time of output. A macrogrid can facilitate the use of the most economically attractive resources (bulk generation and storage, for energy and ancillary services), which can be dispatched to cover energy demand across four time zones to serve all regions and customers. And HVDC transmission has lower costs when transmitting electricity over hundreds of miles.
- **Operability.** The macrogrid would add an overarching layer on the existing grid management structure, enabling the coordination of national and regional energy flows. The macrogrid's capabilities will be extremely valuable for grid management and security with very high levels of renewable resources to support decarbonization goals. The controls associated with HVDC equipment, and wide-area situational awareness enabled by new connectivity and technology, will provide capabilities that would not only reduce the bulk power system's susceptibility to failure, but also enhance outage restoration capabilities and speed, which can be critical during extreme operating scenarios.

The U.S. Department of Energy, through the National Renewable Energy Laboratory and Pacific Northwest National Laboratory, has launched efforts to explore transmission development for supporting clean electricity futures. We propose that the macrogrid be evaluated in the context of this DOE initiative as an alternate transmission approach for supporting very high levels of clean electricity. Using the clean electricity scenarios developed by the laboratories as the starting point, a quantitative process based on recent transmission expansion planning principles, augmented to accommodate the scale and technologies envisioned for the macrogrid, would be applied. From this initial design, a series of studies would be conducted to elicit the full range of costs and benefits of the macrogrid, along with identification of outstanding questions and recommendations for future research.

Central Tasks in Working Toward a Viable Macrogrid Design

This report explores the central tasks involved in working toward a viable macrogrid design and presents specific steps for addressing them:

- **Technical studies on reliability, resilience, economics, and operations.** A series of technical studies is proposed and described here to design and evaluate the macrogrid alternative for grid expansion. An initial design for the macrogrid would be based on clean electricity scenarios already under development in DOE initiatives. It is recommended that the initial macrogrid design be based on the end-point scenario, and not involve a multi-step incremental expansion exercise. The initial macrogrid design would then be subjected to additional technical analysis to elicit further details on the range of ancillary benefits provided by the macrogrid infrastructure.

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- **Coordination and oversight of the physical infrastructure.** Physical operation of the macrogrid raises a number of technical challenges and questions. Currently, there is no operating entity that has the purview and national scope of the macrogrid infrastructure, or has the tightly coupled operating interactions with the number of entities that would be necessary here.
- **Cost comparisons.** The costs to build the macrogrid are obviously of major importance and would be compared to other alternatives for grid expansion to support the same clean electricity scenario. Against these costs, the full range of benefits—including those related to improved power system reliability and resilience—would be captured and quantified to develop a full picture of the macrogrid economics.
- **Use of rights-of-way.** Acquisition of rights-of-way for new transmission is a barrier to any form of grid expansion. Because of the architecture, the HVDC lines comprising the macrogrid would likely be much longer than new lines that are part of a more conventional grid expansion. Further, utilization in terms of power transfer of the rights-of-way would be much higher. As part of this evaluation, opportunities to use existing or more readily available line routes, such as interstate highways or railroads, would be explored in detail.

The convergence of the national push for very high levels of clean electricity and the advances in HVDC transmission technology of the last decade have created a unique opportunity for a detailed exploration of an alternative to the conventional transmission expansion process to address identified challenges for the U.S. electric power system.

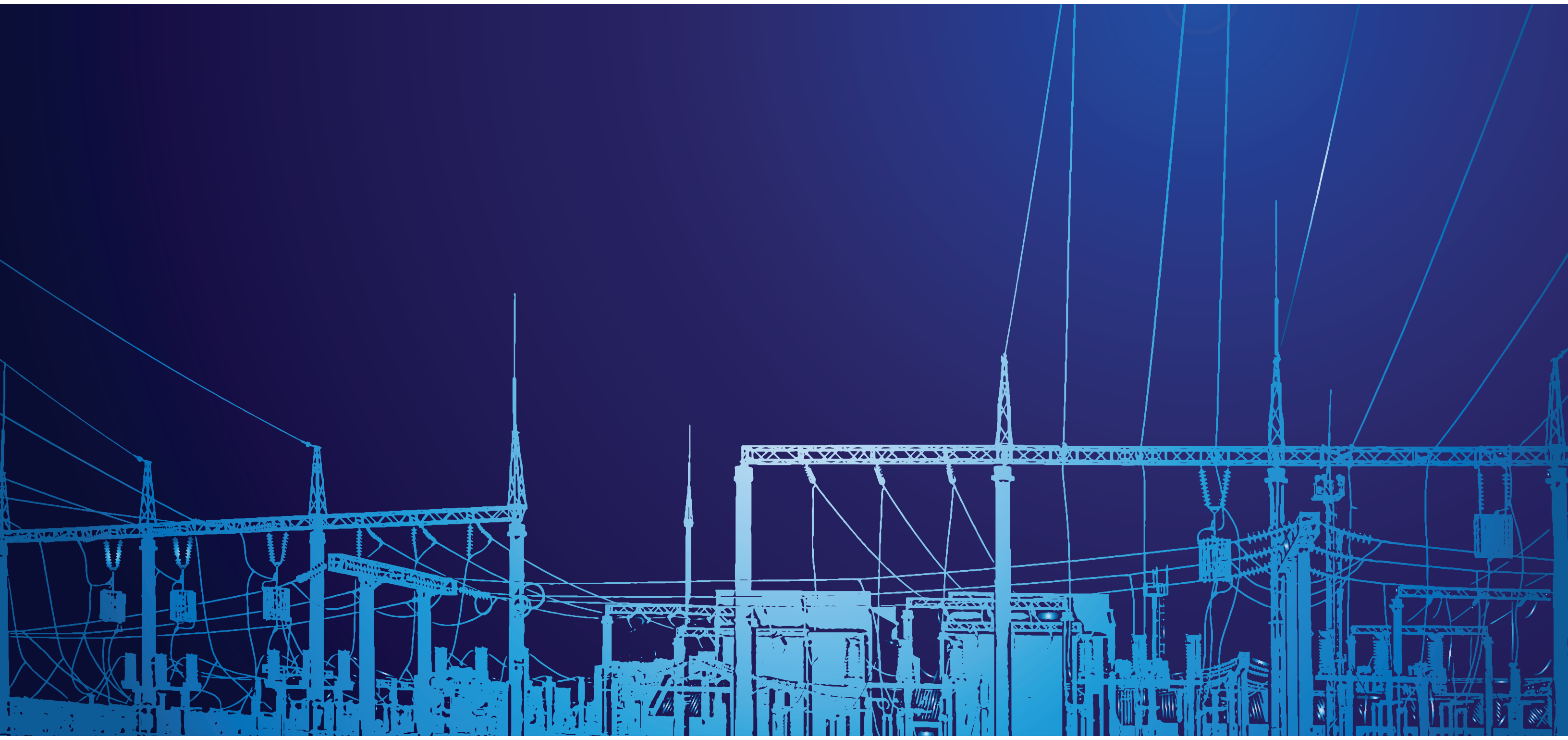
Introduction

States, utilities, and consumers have made significant commitments to rapidly decrease carbon emissions in the power sector and to use more electricity to reduce emissions in other sectors. To achieve decarbonization on the scale these commitments require, very large amounts of clean electricity will need to be moved across the country. Several recent, comprehensive studies of a clean energy future for the United States point to critical importance of transmission: a clean electricity future for the United States will require *massive development* of the bulk transmission infrastructure, spanning large regions of the country and allowing the sharing of clean renewable energy among neighboring grids (Bloom et al., 2021; Brown and Botterud, 2020; MISO, 2017; VCE, 2020).

This report draws from these rigorous studies as well as a series of workshops including technical experts from throughout the industry, hosted by the Energy Systems Integration Group (ESIG). It articulates a set of recommendations for the next stage of proactive transmission planning of a macrogrid covering reliability, resilience, economic, and operational aspects of the design.

Broad Benefits of a Macrogrid

There are many benefits of a nation-wide transmission overlay—a macrogrid—as a system of diverse resources significantly improves reliability and resilience on a continental scale. In some regards, the macrogrid will provide a solid "anchor" against which existing and new



local and regional AC systems can lean. Macrogrid terminals also offer large control opportunities for grid management and enhancing system security during routine and high-consequence climate-induced and other severe events. The general types of benefits offered by a macrogrid include the following:

- **Reliability.** The macrogrid's capabilities will be extremely valuable for grid management and security with very high levels of renewable resources to support decarbonization goals. Increased interconnectivity between regions of the United States can contribute to significant improvements in reliability. The technologies comprising the macrogrid—extra-high and ultra-high voltage DC (EHVDC and UHVDC) transmission that can make the bulk transmission network highly controllable—can be leveraged to address long-standing challenges with bulk power system reliability.

  The controls associated with HVDC equipment, and wide-area situational awareness enabled by new connectivity and technology, will tie regions together in ways that facilitate better and more efficient overall grid performance. Energy, capacity, and ancillary services would be deliverable from any region of the country to any other region, not just between neighbors. A macrogrid can provide operational tools and capabilities that not only can reduce the bulk power system's susceptibility to failure, but can enhance outage restoration capabilities and speed, which can be critical during extreme operating scenarios.

- **Resilience.** Extreme weather events, a growing concern in a changing climate, can affect large regions of the country as experienced in California in August 2020 and Texas in February 2021. The scope and scale of the macrogrid will provide interconnectivity that spans the entire country (and potentially the northern and southern borders as well) and goes well beyond the connections that we have now, between mostly adjacent regions. Such interconnectivity is needed to ensure the resilience of the electricity infrastructure on which the country's residents and economy depend.

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A macrogrid is the only approach that has the scale necessary to meet societal decarbonization objectives, and the deployment of one requires concerted, proactive efforts. Incremental approaches—local build-outs, packing more onto existing lines and right-of-way, use of advanced technology, distributed energy resources, energy efficiency, etc.—are necessary, but they are insufficient. And they are more costly in the long run than proactively planning at a larger scale. An interregional

transmission macrogrid using HVDC technology provides greater benefits than numerous, smaller AC transmission expansions.

Moving Forward with Proactive Planning

In the autumn of 2020, ESIG conducted a series of virtual workshops to consider the implications of and opportunities highlighted by these comprehensive studies. The workshops confirmed that our current transmission development approaches and processes would almost certainly be inadequate for the challenge of expanding to enable a clean energy future, because they have produced little new interregional transmission on the ground over the past decade. The ESIG workshops resulted in a vision of a transmission overlay—a macrogrid—that would connect regions rich with clean energy resources to load centers in a way that would take advantage of the diversity in production, demand, and geography, as well as substantially bolster the operation of the existing AC grid.

Such transmission is crucial to achieving clean energy goals. The white paper developed following the workshops described the critical role of transmission in supporting clean energy goals (ESIG, 2021):

"Multi-regional transmission provides diverse and important economic and reliability benefits at a relatively low cost. It enables deliverability of resources to load; it provides resource and load diversity to facilitate system balancing, enables resource adequacy, and helps the grid weather extreme events; and it helps to strengthen the grid, making it more resilient to operational failures. For example, the ZeroByFifty study found that the United States will need to add about twice as much transmission as we have today in order to fully decarbonize by 2050 [VCE, 2020]. It also found that if we do build a macrogrid, we will save $1 trillion in reaching these decarbonization goals compared to a future where we do not build a macrogrid.

"The Interconnections Seam Study [Bloom et al., 2021], MIT study [Brown and Botterud, 2020], and ZeroByFifty show that an interregional transmission macrogrid using HVDC technology provides greater benefits than numerous, smaller AC transmission expansions. HVDC transmission has lower costs when transmitting electricity over hundreds of miles, and energy flows can be directed to minimize inadvertent impacts on the AC system, for example, to minimize loop flows."

Rethinking Grid Expansion

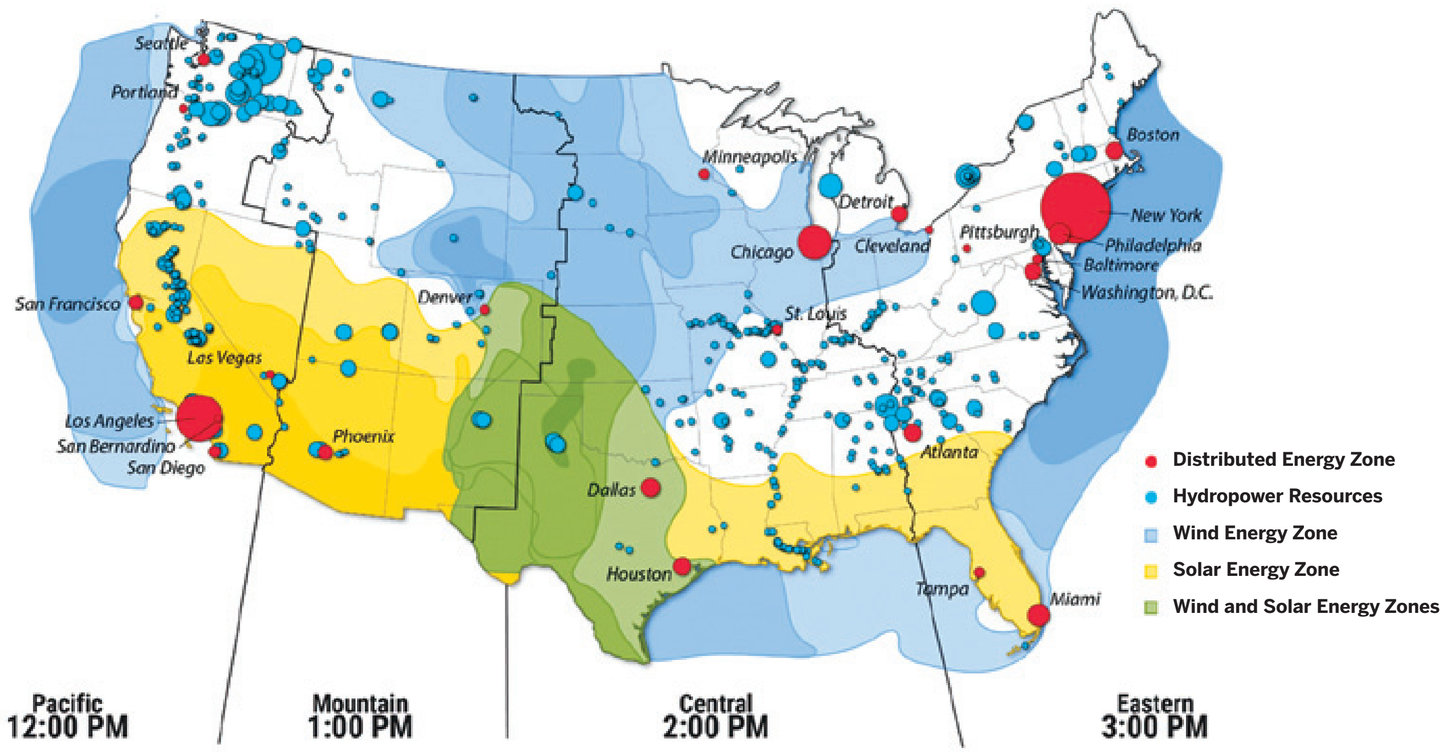
The massive expansion of the bulk transmission system necessary for supporting very high levels of clean electricity in such a relatively short period of time (15 to 25 years) requires a rethinking of and evolution in the way we currently expand the grid. Over the last decade of transmission expansion, most projects have been built to improve reliability locally and to replace assets having reached their end of life. While some expansion was for economic and policy reasons, the headwinds for these types of projects have become increasingly strong. Very little interregional transmission has been developed over the past 20 years.

The sheer scale of the clean electricity targets set in the past 10 to 20 years is hard to fathom. The aforementioned studies agree that a 100% clean electricity target implies about a five-fold increase in wind and solar photovoltaics (PV) generation over 2021 levels. Clean energy targets—decarbonization not just of the electricity system but of the whole economy by 2035 or 2050—could double that. It has taken two decades to install the roughly 200 GW of wind and solar PV in today's fleet. Transmission availability has been a major obstacle to that development most of the way. While distributed energy resources will play a substantial role in the clean electricity future, very substantial development of bulk system renewable generation will still be necessary.

Connecting Areas Rich in Renewable Resources with the Nation's Load Centers

A conceptual map of clean energy resources is shown in Figure 1, illustrating the geographical reality that we face—many of the high-quality wind and solar resources that would need to be developed to reach ambitious clean energy targets are located far from major load centers. Clean resources close to major population centers would be used locally or regionally when available. However, achieving high levels of clean electricity will require exploiting these vast clean energy resource areas and transporting that electricity over long distances to locations of high demand. In order to move massive

FIGURE 1
Clean Energy Resources in the Continental United States



Source: Energy Systems Integration Group.

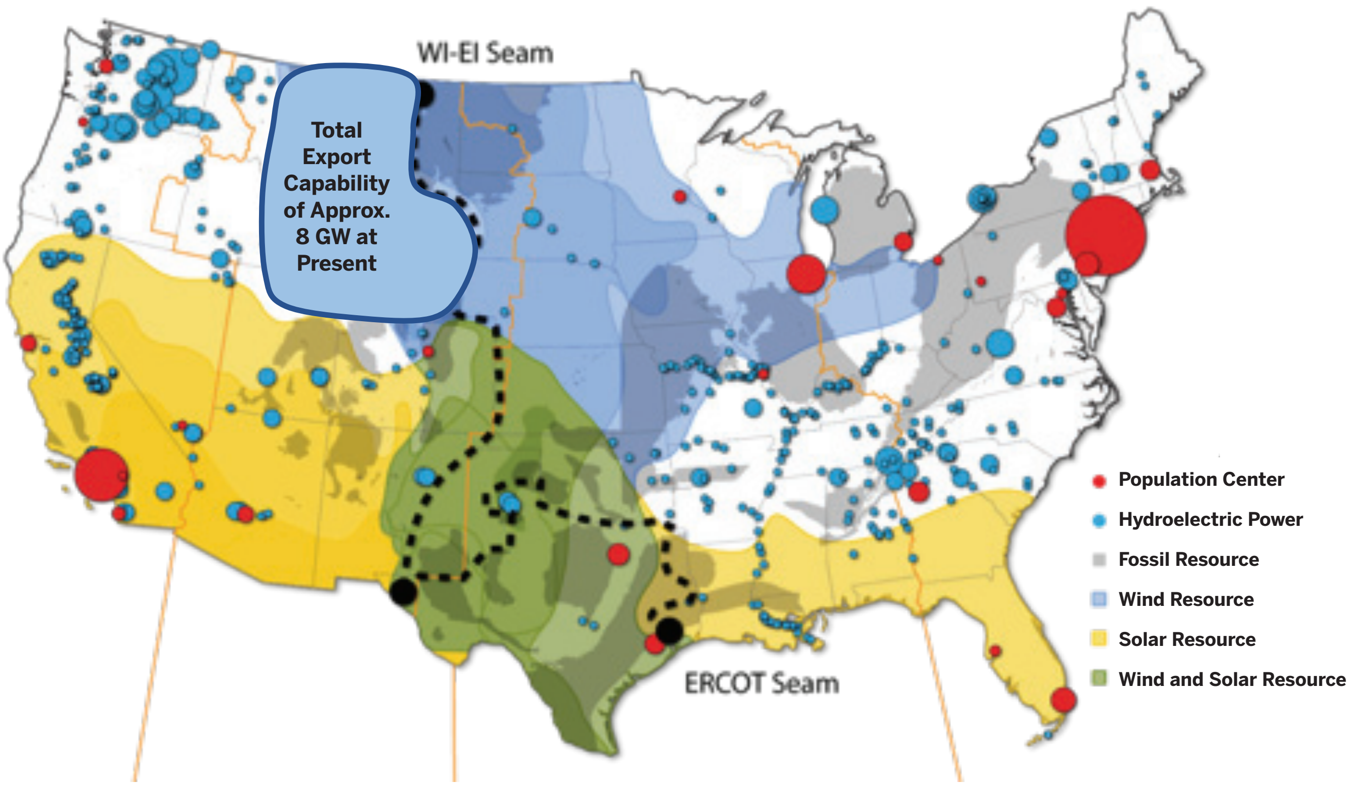
amounts of energy, capacity, and grid services over long distances, we will need a new transmission infrastructure that will offer significant reliability and diversity benefits from linking regions across time zones and weather systems.

The challenge that comes from the conventional view of transmission expansion at this scale is illustrated by an example from the interior west. In today's bulk transmission system, the total export capability from the wind-rich region centered on Wyoming and Montana is about 8 GW (Figure 2). This is a relatively small amount of power given the excellent wind resource in the region, and it is limited by existing Western Electricity Coordinating Council (WECC) path limits. However, if adequate transmission export capability were available, it would likely be economic to develop and export 5 to 10 times this level of low-cost, high-quality wind production, based on the resource availability, and deliver it to customer load centers.

Major expansions of electric export capacity would require additional interregional HVAC and/or HVDC lines. While the example in Figure 2 is for a single region of the country, meeting the nation's aggressive clean electricity and energy goals requires similar considerations simultaneously for all regions of the country. The questions therefore become, how to add these interregional lines, how many to add, when, and at what cost? Our transmission expansion experience to date offers little relevant guidance for such transformational development.

FIGURE 2

Illustration of Transmission Constraints in Clean Energy Resource Regions



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Source: Energy Systems Integration Group.

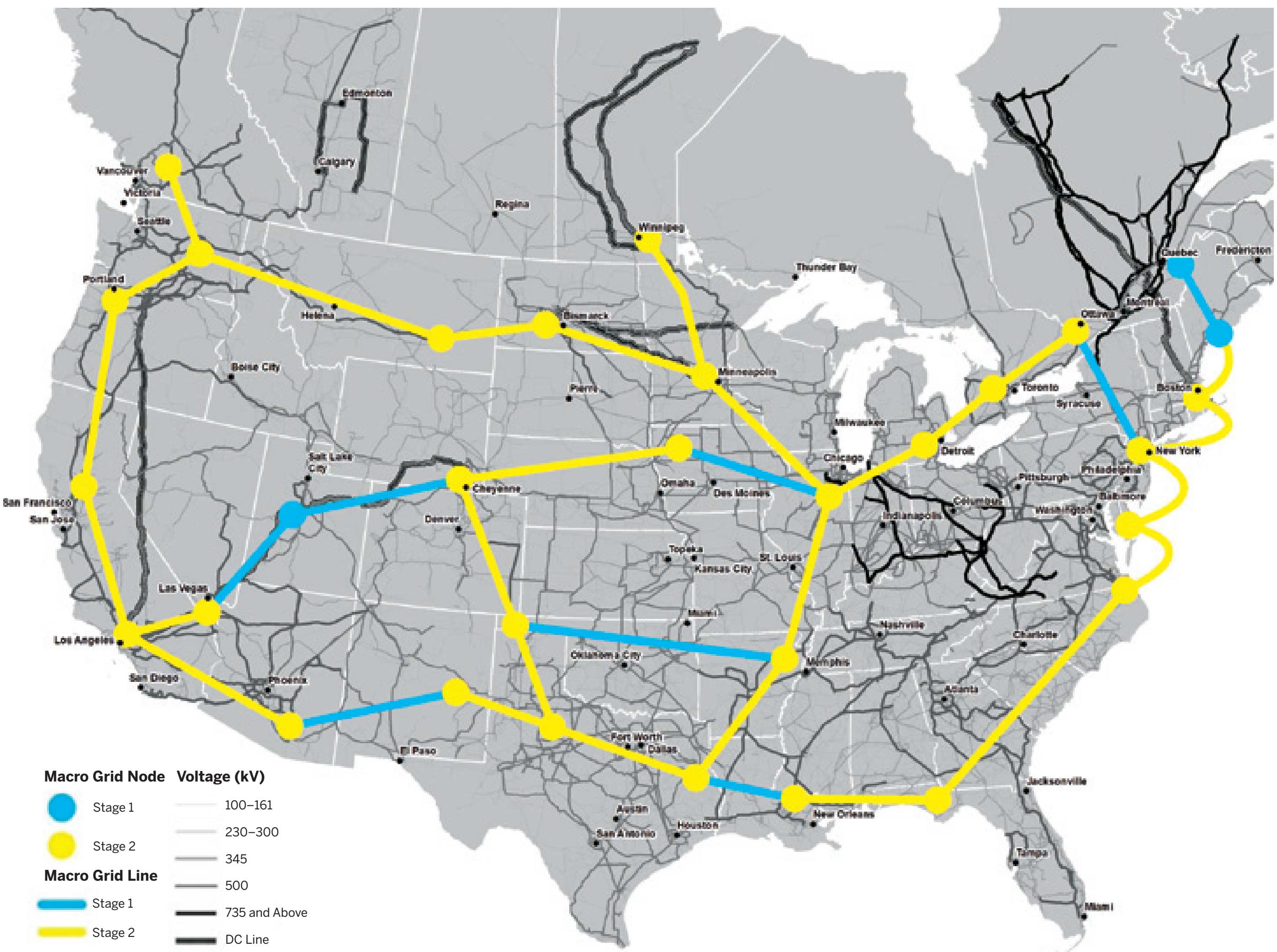
Adopting a National Perspective and Vision

To successfully address and resolve the challenges of massive clean energy development and delivery volumes, distances, and time frames, a national perspective and vision are needed. A national transmission infrastructure would help to maximize the benefits of load and clean energy resource diversity across geographical regions and a multi-decade time horizon. The rationale and conceptual plans for this massive infrastructure have been laid out in several recent studies and were a major outcome of the ESIG transmission workshops (Figure 3). However, the many facets of design, construction, and operation of a macrogrid have received only cursory or qualitative attention.

The ESIG transmission workshops proposed that a cadre of studies be launched to develop the next level of quantitative detail about how a properly designed macrogrid could transform the operation of the electrical infrastructure in the United States. The scale of the grid transformation required for high levels of clean electricity necessitates a rethinking and revision of conventional transmission planning approaches, and we delve into those revised approaches in the sections that follow.

FIGURE 3

Conceptual Macrogrid Layout from Fall 2020 ESIG Transmission Workshops



Source: Energy Systems Integration Group.

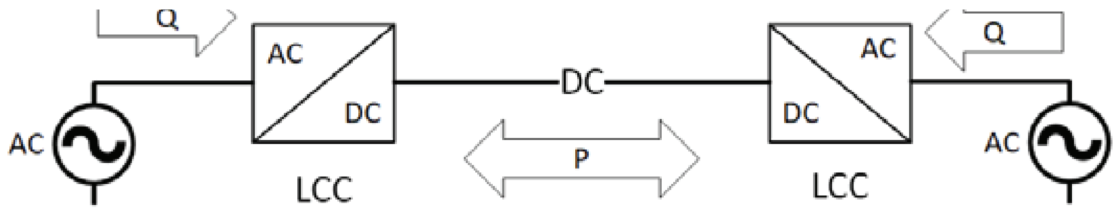
Macrogrid Design and Attributes

The concept of transforming the bulk power system in the United States through the addition of a transmission overlay spanning all regions of the country has been referred to, either explicitly or implicitly, in several recent studies of the United States' clean electricity future. The term "macrogrid" has become part of the current lexicon in technical, regulatory, and political discussions about the future of the grid in the United States, although its definition has thus far remained quite general and fluid.

To transform the U.S. bulk power system in just a couple of decades requires more than evolutionary thinking, however. Our current grid is the product of many decades of bottom-up, incremental development—connecting generation to load centers, then electric company to electric company, followed by transmission to enhance regional aggregations of companies, and, in a few instances, improved connections between the aggregated regional footprints. This continual development over nearly a century has brought us to a place where the electric grid in the contiguous 48 states remains balkanized, with three mostly separate interconnections, and barriers to development of high-quality clean energy resources within each of them.

A properly designed macrogrid has the potential to break through these barriers.

FIGURE 4
Conventional Point-to-Point HVDC Based on Line-Commutated Converter (LCC) Technology



HVDC transmission facilities of the conventional type provide point-to-point connections between separate AC grids or portions of a single grid separated by substantial distances.

Source: Energy Systems Integration Group.

HVDC Infrastructure Built "Over" the Existing AC Grid

The first general attribute of a macrogrid is that it is built "over" the existing AC grid. Its operation would obviously be integrated with the existing, underlying AC grid, but it would operate on its own level, akin to the relationship between an urban freeway and the surrounding (underlying) city streets. A macrogrid is national in scale, so with the required distances and volumes for energy transport, it would be composed substantially of HVDC transmission.

HVDC transmission is relatively common around the world, with more than 100 projects currently in service. Most of these facilities are of the conventional type (Figure 4), providing point-to-point connections between separate AC grids or portions of a single grid separated by substantial distances. These systems allow controllable transfer of power from end to end. The technology comprising the converter stations is based on high-power thyristors, and the DC-to-AC conversion process places some burdens on the connected AC systems. Most prominently, the AC systems must supply reactive power to the converters for their operation. This can be problematic in weak and remote portions of the grid, which can be a significant barrier to the application of the conventional HVDC links. The macrogrid design therefore utilizes an advanced technology for DC-to-AC conversion.

HVDC links using VSC terminals are much more controllable and do not impose reactive burdens on the connected AC network.

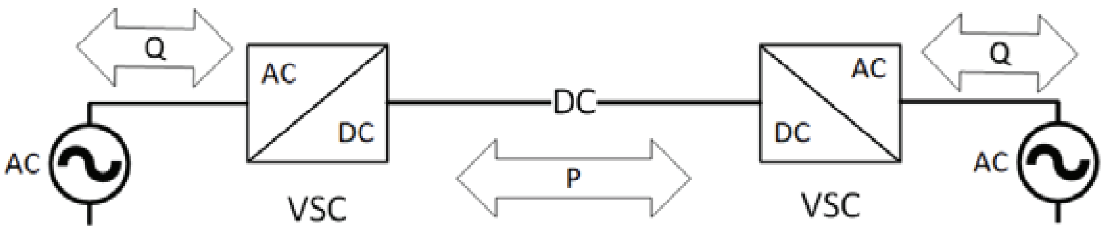
Networked, Multi-Terminal HVDC Based on VSC Technology

Over the past two decades, a new technology for HVDC conversion has emerged and ascended to power levels appropriate for large-scale transmission projects. In the simplest form, the structure of an HVDC link using voltage source converter (VSC) terminals is identical to that of the conventional arrangement except these are much more controllable and do not impose reactive burdens on the connected AC network (Figure 5, p.13). Because of the controllability, in fact, the terminal can provide reactive support and voltage control to a weak AC system.

It has long been recognized that the ability to add a third terminal to a point-to-point HVDC line would be a significant advantage for applications requiring improved flexibility and faster control. A few such systems are in commercial service globally and are technically feasible with either conventional or VSC terminals (Figure 6, p.13).

FIGURE 5

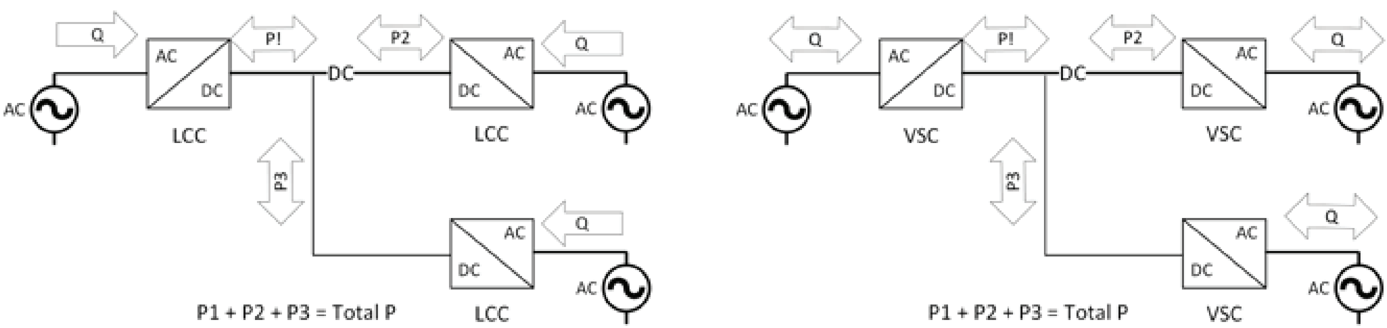
Point-to-Point HVDC Link Employing VSC Terminals



Source: Energy Systems Integration Group.

FIGURE 6

Multi-Terminal HVDC Links Employing Conventional and VSC Terminal Technology



Left: multi-terminal HVDC links employing conventional technology. Right: multi-terminal HVDC links employing VSC terminal technology.

Source: Energy Systems Integration Group.

One disadvantage of the "tapped" arrangement is that all converters must be shut down instantaneously or as quickly as possible in the event of a short circuit on the DC lines. For example, a short circuit on a short tap line would require that all three converters be blocked (shut down) to allow the DC fault current to be extinguished. The protection complications as well as other technical control challenges have been an impediment to significant adoption of multi-terminal HVDC systems.

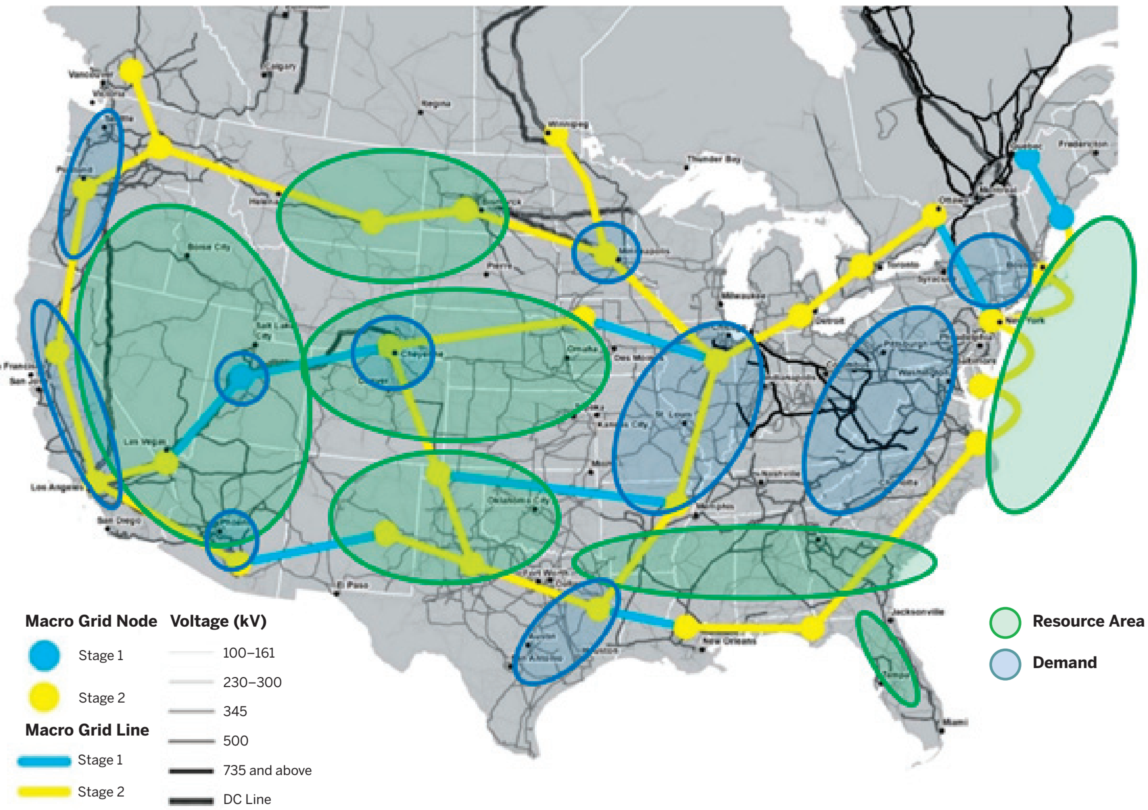
Technological advances for VSC-based HVDC are spurring growing interest in what can be described as truly a next generation of bulk power transmission. These systems will consist of both HVAC and HVDC grids. The hybrid system leverages HVDC for controllability and long-distance energy transportation and the flexibility of HVAC delivery of energy to regional load centers (Rodriguez and Rouzhehi, 2017).

A major challenge for a true HVDC network is the protection of the DC links themselves. Interruption of HVDC currents in the event of a short circuit is difficult, since there are no natural instants where the fault current goes to zero as in AC systems. There are some relatively recent developments, however, that point to the availability of commercial HVDC circuit breakers in the not-too-distant future.

An advanced hybrid grid concept such as described above is key for the massive transmission expansion required to support very high levels of clean electricity for the United States. Some major features of the macrogrid concept are the principle of looped circuits and the interspersed converter stations to either collect clean electricity or deliver it to demand centers (Figure 7, p. 14).

FIGURE 7

Macrogrid Concept with Overlaid Clean Energy Resource Areas and Locations of Major Electricity Demand



Source: Energy Systems Integration Group.

The macrogrid concept proposed here is more than a massive build-out of conventional HVDC lines and converter stations. The macrogrid vision consists of a backbone of long-distance lines composed of networked, multi-terminal HVDC based on VSC technology. It would incorporate important transmission planning principles, including the "rule of three" for transmission expansion, discussed in the appendix.

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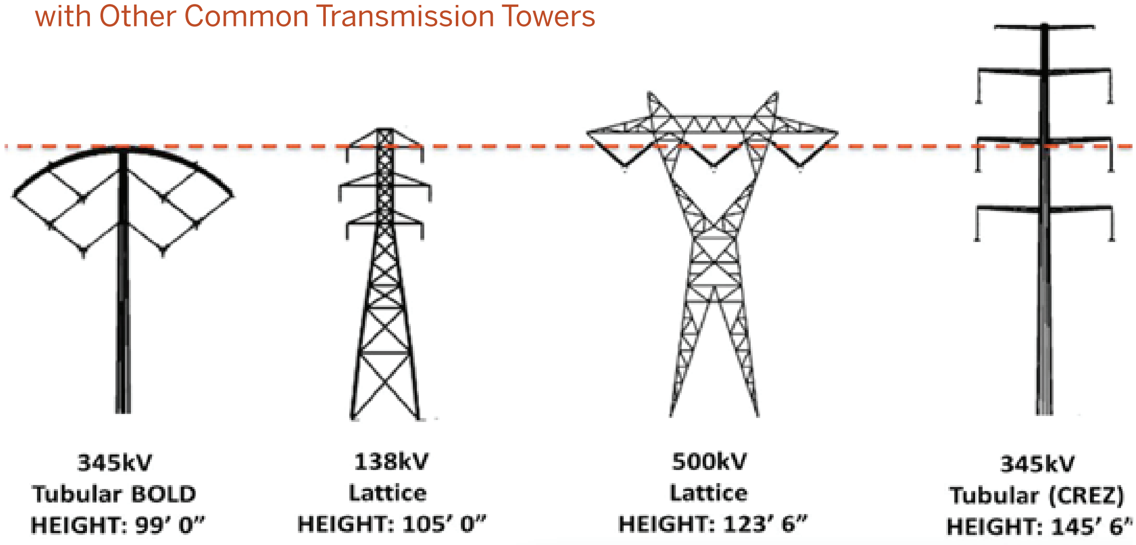
The HVDC transmission paths form a true DC network and are composed of triple bi-pole circuits operating at +/- 800 kV DC. A transmission tower design by American Electric Power (AEP), known as the "Bold" concept, could be utilized for these high-capacity macrogrid transmission line segments. Currently in use as a double-circuit high surge impedance loading (HSIL) line, the structure is more material-efficient, compact, and aesthetic than alternatives (Figure 8, p. 15). With some adaptation it could be used to carry three bi-pole circuits of six conductors total rather than two three-phase AC circuits of six conductors.

VSC converter stations are now available with ratings up to 3000 A. This equates to a 2400 MW rating at 800 kV for a single pole and double that—4800 MW—for a bi-pole configuration. Other needed technologies, such as HVDC breakers, are entering commercialization and can be assumed to be available by the time any procurements would commence.

FIGURE 8

Physical Comparison of Structures for AEP Bold Line Design with Other Common Transmission Towers



Source: American Electric Power.

Higher circuit ratings for the lines make maximum use of rights-of-way and provide flexibility for the evolution of the macrogrid network over time.

Self-Redundancy

The fundamental design for self-redundancy requires that the macrogrid be composed of loops, where at least three terminals are connected by three HVDC circuits. In this way, the outage of a single HVDC line path could be accommodated with built-in reserve capacity.

Further, the transmission paths themselves would be designed so that each bi-pole circuit would have contingent capacity. As an illustration, if a transmission path is delivering 4800 MW on each of the three bi-pole circuits, the total transfer over this path would be 14,400 MW. The loss of one bi-pole circuit could be covered by rating the path at 21,600 MW (7,200 MW per bi-pole circuit times three) to provide additional redundancy.

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On Ramps and Off Ramps Between the HVDC Network and Existing AC System

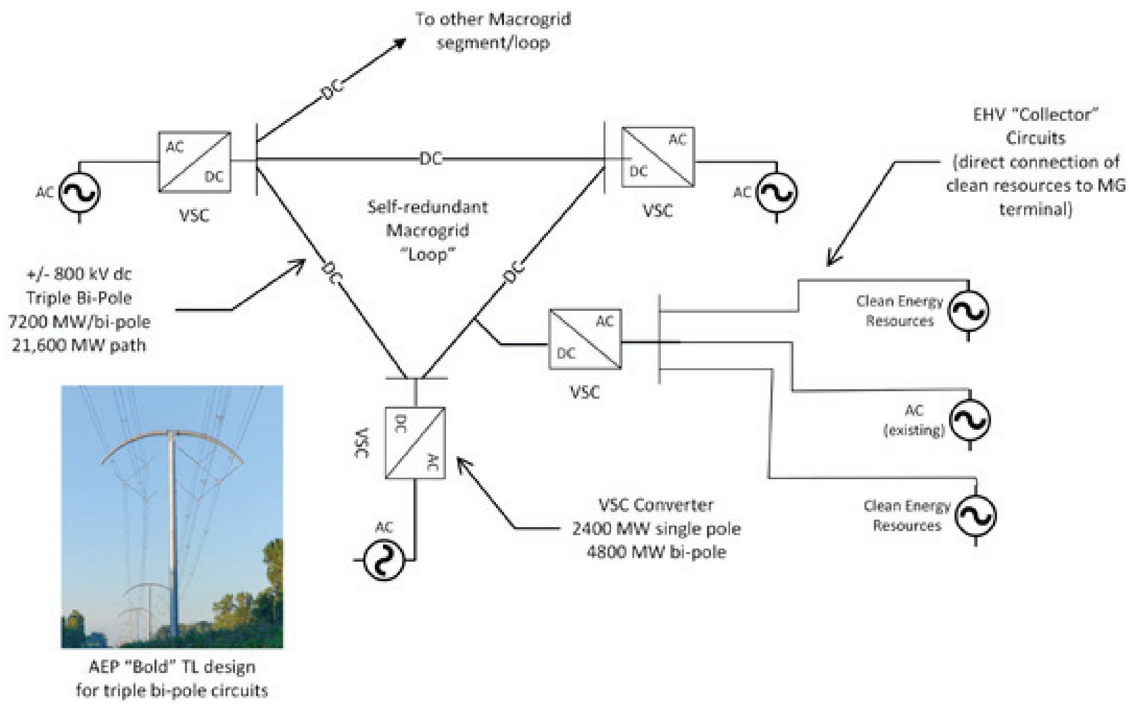
The "on-ramps" for clean electricity would be connected to the existing AC system, if stout enough to carry the clean electricity generated in the proximity. In high clean electricity resource areas with weak AC transmission, the source VSC node could be fed by separate EHVAC (extra-high-voltage AC) collector transmission circuits of up to a couple of hundred miles in length.

"Off ramps" near demand centers would be integrated with the underlying AC system, and appear as large local generators. The flexibility of this design would allow the macrogrid delivery point to be rated up to 2400 MW. Smaller ratings, potentially dictated by local or regional conditions, would also be possible.

These concepts for the macrogrid architecture are illustrated in Figure 9 (p. 16). Because the DC lines form a true network, it would be possible to insert additional converter stations where needed for either collecting or delivering clean energy. This provides a level of modularity and flexibility not available with conventional point-to-point HVDC, but is obviously dependent on HVDC breakers for protection of the HVDC network.

FIGURE 9

Illustration of Concepts for Macrogrid Architecture



Sources: Energy Systems Integration Group (graphic); American Electric Power (photograph).

Rather than requiring reactive power for operation, VSC converter stations could provide voltage support in weak areas of the network. Grid-forming VSC designs could also provide other services, such as black start.

In contrast with conventional line-commutated converter (LCC) HVDC converter stations, the VSC design would impose minimal requirements on the AC system to which it would be connected. Rather than requiring reactive power for operation, as an example, VSC converter stations could provide voltage support in weak areas of the network. Grid-forming VSC designs could also provide other services, such as black start, which would not be possible from LCC HVDC stations.

Addition of an Overarching Layer on Existing Grid Management Scheme

The existing interconnections in the United States are managed through a multi-party and multi-layer control structure that includes embedded competitive wholesale energy markets. The macrogrid would add an overarching layer on this existing grid management scheme, necessitating the coordination of national and regional energy flows, and requiring the creation of an entity to ensure the macrogrid is operated in such a way as to meet reliability and resilience needs and facilitate economic operation of the U.S. electricity infrastructure.

Recommended Macrogrid Design Studies

Synopsis

- Previous studies that addressed possible transmission expansion to support high levels of clean electricity, including macrogrid overlays, are excellent works, and form a solid basis for important next steps:
  - To incorporate important transmission planning principles necessary to ensure system reliability
  - To add technical details of how an overlay should be built and how it might be operated
  - To address how an appropriately designed and constructed macrogrid could transform the operation of the bulk power system in the United States
- 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.

Background and Recommended Technical Evaluations

The U.S. Department of Energy (DOE), through the National Renewable Energy Laboratory and Pacific Northwest National Laboratory, has launched efforts to explore transmission development for supporting clean electricity futures. We propose that the macrogrid be evaluated in the context of this DOE initiative as an alternate transmission approach for supporting very high levels of clean electricity. Using the clean electricity scenarios developed by the laboratories as the starting point, a quantitative process would be applied based on recent transmission expansion planning principles augmented to accommodate the scale and technologies envisioned for the macrogrid. From this initial design, a series of studies would be conducted to elicit the full range of costs and benefits of the macrogrid along with identification of outstanding questions and recommendations for continued research.

To be clear, what we are proposing is *not* an alternative incremental capacity and transmission expansion exercise. The grid expansion, including the macrogrid overlay, would be designed as if the end point is known, based on the scenarios identified through the ongoing DOE efforts. We believe that focusing on the end point would best illustrate the transformative nature of the macrogrid, and allow for quantitative assessment of related benefits for the reliability and resilience of the bulk grid in the United States. From this initial design, follow-on efforts can explore sensitivities to other clean electricity expansion scenarios, including how the macrogrid could be developed over time.

The cadre of technical evaluations being recommended consists of:

- A focus on architecture and design of a fully developed macrogrid as it would exist in the future for supporting a target level of clean electricity/energy (for example, >90% clean electricity). The evaluation would start at the end point, effectively being a single-step expansion from present to that future.
- The following major study elements:
  - Development of an initial macrogrid design that adheres to principles for reliable transmission expansion
  - Reliability analysis (steady-state and dynamic)
  - Resilience assessment
  - Considerations for operability and operations

- Economics, routing, and permitting

- Iteration and sensitivities—what about decarbonization goals, or what if we don't get to >90% clean electricity?
- A comparison of findings here with other transmission expansion options developed through parallel efforts.

The intention is for the initial macrogrid design to be conducted first, and then serve as the object for the subsequent technical evaluations. These follow-on evaluations could probably be conducted in parallel if consideration of the important overlaps between the study tracks is made.

We recommend that the macrogrid study effort be conducted as an open process, with maximum involvement from the energy industry. This includes regional transmission organizations (RTOs) and others in the transmission planning space; technologists (including expert consultants, equipment manufacturers, transmission line designers, energy economists, and others), and policymakers.

The next sections highlight and summarize the individual components of the technical evaluation we believe is necessary to determine how the macrogrid option would compare to more conventional approaches to transmission expansion for high levels of clean electricity.

Initial Macrogrid Design

Objective

- Create macrogrid design(s) for a 100% clean electricity scenario
- Determine the best mix of transmission and other technologies (e.g., storage) that will facilitate transportation of clean energy from source to sinks
- Maintain/enhance bulk system reliability—initial view

- Increase the resilience of bulk electric supply—initial view

Overview

A macrogrid is a high-capacity transcontinental transmission system distinct from, but interconnected with, existing underlying AC transmission. The objective of a macrogrid design is to identify the macrogrid technologies, network topology, and circuit capacities to maximize the derived macrogrid benefits. This section describes a process to achieve this objective, a nascent process that will further develop as experience grows. The design process described here is intended to be one on which further design efforts will build.

Macrogrid design requires understanding and modeling the manner in which the macrogrid will operate. This requires identification of a market construct, including its participants, and how macrogrid operation interacts with the operation of regional markets run by the RTOs. The market aspects are addressed later in the report.

Design Process

The design process is composed of four main steps, as illustrated in Figure 10. An underlying assumption of the process is that the design targets very-high-percentage clean electricity futures (e.g., 85% to 100%). The design process identifies the best mix of macrogrid technologies and AC system generation, transmission, and storage to facilitate the delivery of clean electricity from sources to load centers while enhancing the reliability and resilience of the bulk power system.

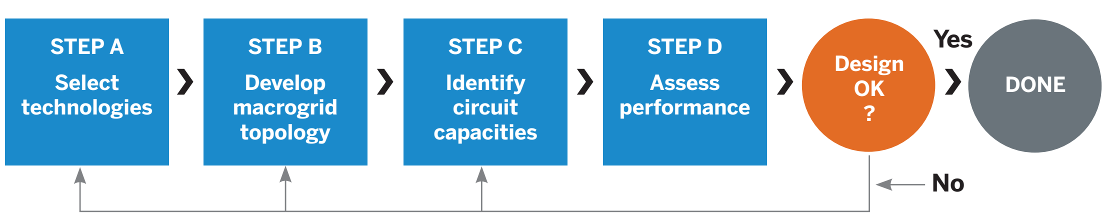
Step A: Technology Selections

Technology selections are made in Step A. This decision may include use of either DC or AC transmission, although most macrogrid design work conducted to date has selected DC, for the following reasons:

- There is no minimum capacity required for stable interconnection
- A macrogrid using DC transmission offloads the underlying AC system, allowing increased AC interconnection of renewables
- It improves AC system performance in terms of voltage, frequency, transient, and oscillatory stability through converter control
- Its power density (MW per right-of-way area required) is greater than AC
- Its cost per MW-mile for long-distance transmission is lower than for AC
- HVDC losses are less than HVAC losses for the same transfer capacity

Assuming the macrogrid is DC, then converter technology must be chosen; options are multilevel voltage source converters (VSC), line-compensated converters (LCC), or hybrid (use of both). Although LCCs provide higher capacity than VSCs, VSCs provide better control, including provision of voltage support and grid-forming capability. In addition, VSCs enable the implementation of a multi-terminal network rather than a series of point-to-point DC lines, offering the ability of the macrogrid

FIGURE 10
Overview of Macrogrid Design Process



Source: Energy Systems Integration Group.

to control DC network to AC network injections rather than only the flows on each point-to-point DC line. Finally, there is the potential to take advantage of the strengths of both LCCs and VSCs in a hybrid network, for which there is an implemented case (McCalley and Zhang, 2020; Rao et al., 2021).

Technology decisions can affect the cost of interconnection points, as voltage-weak LCC nodes must be compensated; because interconnection point selection affects topology, technology decisions also influence topology. In addition, whereas LCC nodes may be located only at the terminals of point-to-point DC lines, VSC nodes may be located anywhere along a line, increasing flexibility in interconnecting with resources and adding nodes, and thus potentially affecting topology.

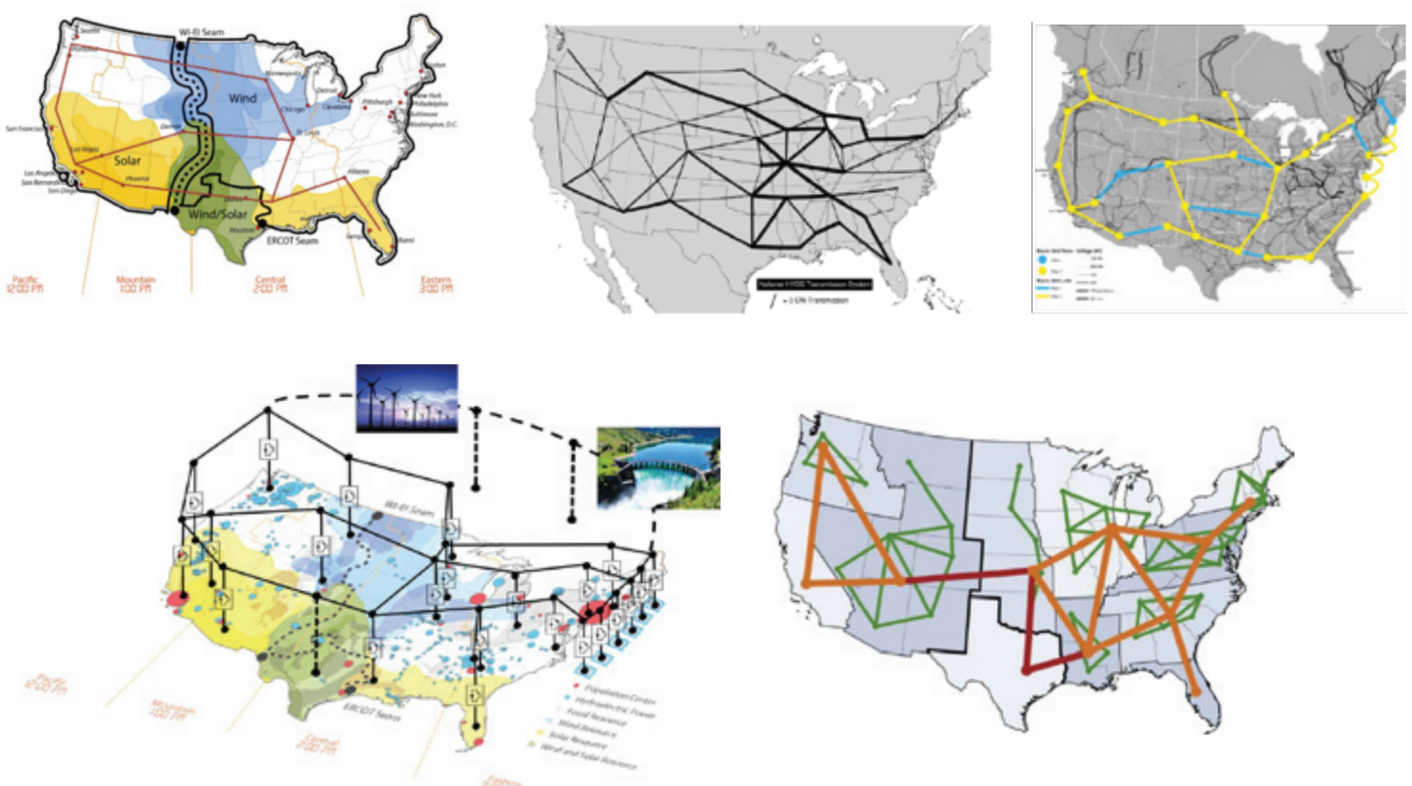
Although future studies should carefully consider the various technology options, we recommend and assume in what follows the adoption of a state-of-the-art, innovative option of a VSC-based multi-terminal HVDC network with grid-forming converters.

Step B: Macrogrid Topology

Macrogrid topology is developed in Step B. The objective of this step is to identify the number and location of macrogrid nodes together with the circuits that connect those nodes. The macrogrid topology explored in previous studies is shown in Figure 11.

Nodes should be located close to load centers or in areas where hydro, solar, and/or wind resources are expected to reach significant levels. There is a trade-off between macrogrid accessibility and cost. A large number of nodes increases macrogrid accessibility and may also reduce transmission spur cost from nodes to load and resource centers, but each node incurs the significant cost of an additional converter station. In addition, it may be useful to locate nodes to ensure balance between

FIGURE 11
Experience-Driven Macrogrid Topology Concepts



Several top-down designs have been proposed in recent research.

Sources, counter-clockwise from upper left: Figueroa-Acevedo et al. (2021); Clack (2021); Energy Systems Integration Group (2021); McCalley and Zhang (2020); Brown and Botterud (2020).

geographical regions, North American Electric Reliability Corporation (NERC) regions, RTO regions, and possibly states, as the decision to locate a node in an area may also influence that area's willingness to participate in macrogrid development, implementation, and operation. Consideration should be given to including terminals of existing or planned interregional transmission projects. A final consideration in identifying nodes is that there may be benefit to converting or extending existing AC substations, particularly those for which connected lines may use right-of-way that can be converted or adapted to DC line right-of-way.

Each pair of nodes may be connected by a circuit. With N nodes, there are N*(N-1)/2 possible circuits (e.g., 50 nodes results in 1,225 possible circuits). Yet only a small subset of the possible circuits are ultimately needed. Identifying those circuits should account for the impact of macrogrid outages on underlying AC system reliability, circuit cost, and usage within macrogrid operation, as described below.

- **Rule of three.** The rule of three is a guideline to ensure that circuit selection accounts for the impact of macrogrid outages on underlying AC system reliability. According to the rule of three, high-capacity interregional transmission can be built to be self-contingent and economically attractive if it is built using at least three parallel circuits. Self-contingent means that remaining macrogrid circuits are able to carry the additional loading for loss of one of the parallel circuits. Economically attractive means that, during normal operation, the circuit provides significant additional transmission capacity, with a low derating to satisfy N-1 contingency conditions. The rule of three is illustrated in the appendix.
- **Circuit cost.** Circuit cost should account for routing and related right-of-way cost, issues that are influenced by terrain, elevation, preserved land, lightning frequency, and availability of existing rights-of-way that could be used. Some work has been done on assessing right-of-way cost (Li and McCalley, 2015). Usage within macrogrid operation may be assessed through Step C, described next. The design process can be strengthened via iterations of Steps B and C, as Step C results can provide insight into use of nodes or circuits that were not originally considered.

Step C: Circuit Capacities

Circuit capacities are identified in Step C. This is accomplished through the use of a co-optimized expansion planning (CEP) application. CEP applications to

macrogrid design have been described in the literature (Bloom et al., 2021; Brown and Botterud, 2020; Figueroa-Acevedo et al., 2021; MacDonald et al., 2016). CEPs are computationally intensive; their application requires that industry-sized network and production cost datasets be reduced, a process described in the slide deck accompanying this report. These datasets should be selected so that they provide time-synchronized levels of demand, wind generation, and solar generation throughout the country. They should be based on projected loading and environmental conditions and not historical ones, since historical conditions may not well reflect future conditions due to increased electrification of other sectors and impacts of climate change.

A CEP determines those generation and transmission investments needed in a power system to achieve least cost (including investment and operational costs) subject to constraints and assumptions. A CEP is capable of determining investment timing as well. However, as described previously, the focus of this work should be on the end-point scenario (i.e., very high levels of clean electricity) rather than the transition years, and as such, it is reasonable to apply the CEP with a limited number of investment periods, e.g., one or two. Constraints include standard power flow constraints and requirements on ancillary services and annual planning reserves. Assumptions characterize the expected future conditions including, for example, demand growth, fuel prices, technology costs, environmental conditions, and policy directives. Costs associated with technologies not yet heavily used—e.g., HVDC breakers, demand control, and some kinds of storage—may require interaction with various manufacturers to obtain. AC transmission costs are typically available within RTO planning processes. For example, the Midcontinent Independent System Operator (MISO) has developed an excellent resource that includes both AC and DC costs (MISO, 2021). Such cost information should be integrated with methods of avoiding the use of new rights-of-way (e.g., using existing transmission, rail, or transportation right-of-way) and maximizing AC transmission power density in terms of MW of transmission capacity per unit of required right-of-way area (e.g., employing lines with double-circuit towers and high surge impedance loading designs).

It is typical to develop several scenarios, where each realizes a different set of assumptions. Multi-scenario assessment may be performed by repeating CEP analysis for each scenario. It is also possible to obtain "one-shot" optimizers that perform CEP under uncertainty (Hobbs et al., 2016; Maloney et al., 2021). In identifying scenarios, it is important to select a limited number that well represents the scenario space. In macrogrid design, recommended scenarios might include high and low growth in distributed energy resources; high and low technology maturation for VSCs, DC breakers, wind, and solar; and limited and aggressive implementation in CO_2 reduction policy. There are methods to select such scenarios based on scenario probability and proximity to other scenarios. A recent development also provides a simulation-based approach to test a CEP design against a large number of out-of-sample scenarios (Maloney, 2019).

Operating conditions modeled within the CEP should include those corresponding to different daily times for each of three seasons of the year together with the conditions corresponding to the annual peak for each U.S.

region. Transmission investments identified within the CEP solution include those associated with the macrogrid circuits identified in Step B as well as those associated with the underlying AC transmission system. When macrogrid circuits identified in Step B receive little or no investment following Step C CEP application (and thus have little or no capacity in the resulting macrogrid design), it is an indication that those circuits are not needed for transferring energy, services, or capacity between macrogrid nodes, and their elimination from the macrogrid topology should be considered.

CEP implementation of Step C should be performed twice, once with the macrogrid topology overlaid on the existing AC system (as assumed in the previous paragraph) and once without it, i.e., with only the reduced model of the AC power system. This second CEP implementation will establish a reference case that represents the targeted clean electricity level but without the macrogrid. Differences in the costs between the two cases (macrogrid and reference) can be used to assess the economic benefits of macrogrid development.

Step D: Performance of the Macrogrid Design

The performance of the macrogrid design is assessed in Step D, and the design is adjusted based on these results. Several of the performance assessments require a full unreduced model. This requires that the Step C macrogrid design, which includes generation and transmission investments represented at equivalent buses and lines, respectively, be translated to buses and lines in the full model. The translation function is described in the appendix of the attached slide deck and in the literature.

Following the development of the translated model, performance assessments are conducted, as described below. These assessments overlap with the discussion given in this report's section on reliability and resilience.

- **Production cost simulation (PS):** PS is necessary to check the benefits identified based on CEP results, since PS improves the quantification of operational costs. PS also enables characterization of how the markets and the system behave across daily, weekly, and seasonal periods in terms of flow variation in

each macrogrid circuit, congestion costs, and supply of energy, services, and capacity. PS modeling of such large systems (e.g., 100,000 to 120,000 buses is expected for modeling the entire United States) is a computationally formidable problem, yet recent advances in decomposed modeling make this problem tractable (Barrow et al., 2019).

The macrogrid provides an opportunity to improve the nation's ability to withstand and recover from extreme events. The potential for future extreme events motivates investment strategies that optimize performance during both normal and extreme conditions.

- **Resource adequacy (RA) evaluation:** RA is considered here as the ability to supply the entire system's demand during each hour of the year. Load diversity provides that different regions peak at different times of the year, and so, assuming each region's policy allows for interregional capacity-sharing, the macrogrid improves RA by enabling deliverability of that capacity. CEP modeling is capable of roughly capturing this (Figueroa-Acevedo et al., 2021), but RA evaluation via probabilistic modeling of demand, resources, and transmission provides the ability to capture the influence of macrogrid reliability, for each line and converter, resulting in system metrics familiar to the industry (for example, loss of load expectation). RA evaluation needs to account for the effects of wind and solar equipment failures and the effect of wind and solar variability (Ortega-Vazquez and Kirschen, 2009).
- **Steady-state (AC power flow) contingency analysis:** CEP modeling generally excludes contingency analysis to avoid its additional computational burden. But even if contingency analysis within CEP becomes tractable, it will be based on the simplified assumptions of the linearized (so-called "DC") power flow used within the CEP, which excludes effects of and impacts on voltage. Therefore, AC power flow–based contingency analysis is needed, including outage of AC generators and lines. Although CEP design should account for the "rule of three" guideline, it is necessary to use AC power flow–based contingency analysis to ensure that N-1 outage of a macrogrid line or converter does not adversely impact the underlying AC system.
- **Dynamic analysis including control design:** Dynamic analysis accounts for the impact of macrogrid line or converter outages, or AC transmission and generation outages, on transient (angular) stability, transient voltages, transient frequency, and oscillatory stability. These assessments should be done for macrogrid and AC transmission and generation outages per standard industry criteria (NERC, 2014). They should also be done for high-impact macrogrid outages, e.g., loss of two or more macrogrid lines and/or converter stations. Dynamic analysis should be done together, in an integrated way, with design of converter-based control that strengthens AC system response to macrogrid outages. Various other tools, e.g., PSCAD and eigenvalue analysis, may be needed in performing control design.
- **Resilience analysis:** The macrogrid provides an opportunity to improve the nation's ability to withstand and recover from extreme events such as Hurricanes Katrina and Rita on the Gulf Coast in 2005, Hurricane Sandy on the East Coast in 2012, the Midwestern derecho in 2020, and the Texas cold snap of 2021. The potential for future extreme events motivates investment strategies that optimize performance during both normal and extreme conditions. Such tools have been proposed but are research-grade (Newlun et al., 2019); additional development in this area is needed. Additionally, this analysis requires the development of datasets that include extreme weather conditions that represent current climate and future climate.

Reliability Analysis

Macrogrid Reliability Assessment

The reliability assessment portion of the macrogrid design studies is intended to demonstrate that a large-scale bulk power system with a macrogrid overlay can "work," that is, that it can meet established reliability performance requirements. At a minimum the reliability of the system must be maintained at a societally acceptable level.

To that end, the assessment must:

- Assess the reliability aspects of initial macrogrid overlay designs
- Explore how performance with initial macrogrid overlay designs compares against established metrics of reliability
- Identify in what respects, if any, a macrogrid could create greater vulnerability from reliability perspective
- Develop recommendations for mitigation of any negative impacts
- Identify opportunities for reliability enhancement from macrogrid overlay operation

Reliability evaluation, of the type grouped under "security" by NERC, focuses on how the grid responds to and tolerates disturbances. With the huge power ratings associated with macrogrid elements, the fundamental expectation is that the entire macrogrid would be self-redundant, with limited interactions with the underlying bulk AC transmission system. The study should examine how such an objective could be met in practice, and explore the limits beyond which substantial interaction might occur. The macrogrid could be leveraged to improve or enhance operation of the bulk AC grid, operating in coordination with underlying bulk AC system in ways that maximize reliability and economic benefits.

The behavior of the entire U.S. bulk power system will be impacted by the macrogrid, and these behaviors must be considered in the final design of a system. The system must tolerate a range of disturbances, some of which will be familiar and some of which may look radically different. 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. Macrogrid terminals offer large control opportunities valuable for grid management and security. A mixture of conventional and new technologies would be used during routine and high-consequence climate-induced and other severe events.

The macrogrid could be leveraged to improve or enhance operation of the bulk AC grid, operating in coordination with underlying bulk AC system in ways that maximize reliability and economic benefits.

The technology changes involved in the creation of a macrogrid are profound. 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. New concepts for appropriate mixes of

technologies will need to be considered, including line-commutated converter HVDC (LCC-HVDC), voltage source converter HVDC (VSC-HVDC), HVAC "collector lines," and AC grid reinforcement.

Thus, the intent of this effort is to provide quantitatively meaningful examples of the security performance of the bulk power system with a macrogrid overlay. The study should focus on how the macrogrid performs and how it interacts with the reinforced AC bulk power system. Particular attention should be given to looking for modes of failure, new and existing, that could present significant challenges. Each security challenge identified should have at least one, and hopefully an array of, mitigations applied.

Scope and Limitations of the Reliability Analysis

The reliability investigation is centered on considerations of security as per NERC practice. The reality is that most reliability determinations are extremely design- and detail-specific. This effort will focus on illustrating the security of a U.S. bulk power system with a macrogrid overlay, by carefully investigating all of the types of reliability concerns and opportunities that will arise.

The approach must be demonstrably complete in the depth of the analysis; that is, the details of the tests must cover all phenomena of interest. It need not be exhaustive in the geographic scope; there is no need to prove that every potential problem is resolved or that every potential benefit is quantified, rather, every potential type of benefit or problem needs to have been examined. Particular attention must be given to finding and mitigating failure modes associated with the macrogrid and its interaction with the bulk power system, and to finding ways in which the macrogrid may enhance the performance or value of the underlying bulk power system.

There are fundamental changes in the way the system will behave with a macrogrid that must be explored. The study will need to drill down in considerable detail at a few locations and explore every aspect of performance—especially stability. In many regards, this is new ground for the industry. The fact that VSCs are now available at 4800 MW, that the system will be looped with multiple terminals, not all of which are necessarily built at the same time, is revolutionary. This opens performance issues that are different and for which existing practice, based on point-to-point DC, is insufficient. Evaluation needs to be made under conditions that represent the future operation of a low-carbon system, with massive amounts of inverter-based generation, relatively low inertia, and the presence of a wide spectrum of active participants (such as active loads and distributed generation).

Stability Considerations

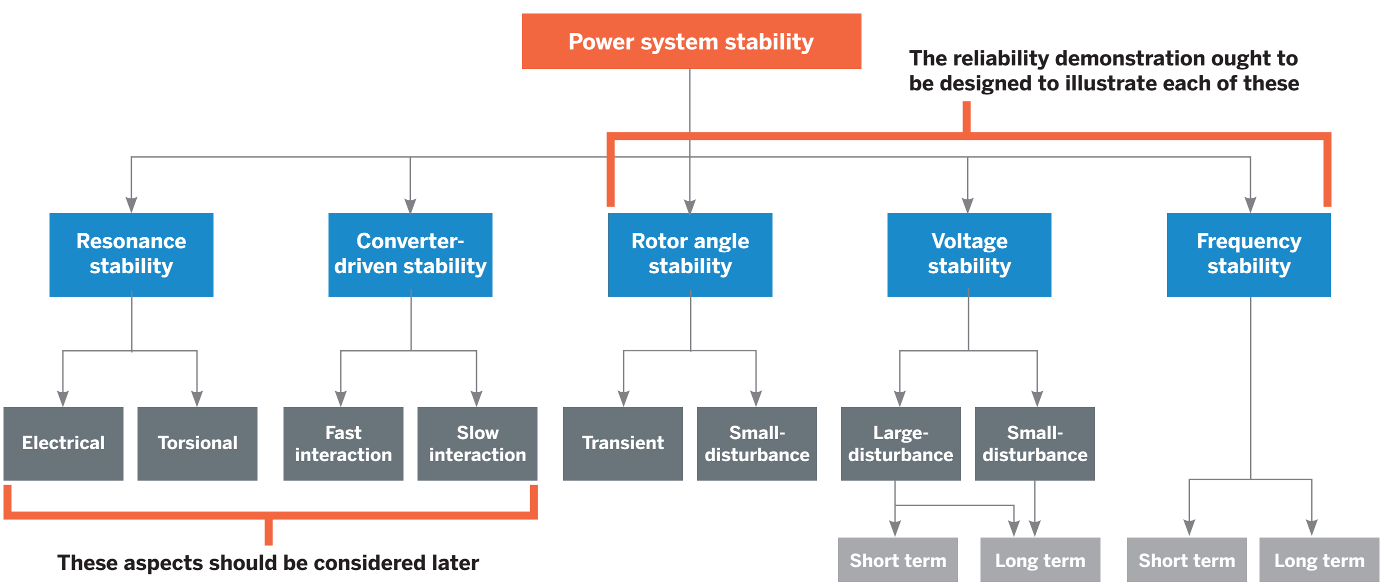
System stability is a necessary (but not sufficient) condition that must be met. The familiar IEEE stability framework covers a range of concerns, from those that are broadly systemic to those that drive very specific aspects of equipment and infrastructure design (Figure 12). The delineations are not sharp, but some aspects of system stability pose fundamental existential challenges for demonstration of the practicality of a macrogrid. This work needs to explore those stability concerns (rotor angle stability, voltage stability, and frequency stability) and existing (known) stability limitations, as well as probe for new risks in any of these three stability aspects. The other regimes (such as resonance and converter-driven stability) are important, but should be addressed downstream. There is little risk that these potential problems fundamentally alter the high-level findings of the work; rather, they are design-due-diligence elements for later.

Evaluating Reliability Improvements

The reliability work has as a minimum the objective of showing that a macrogrid overlay system "can work" with sensible engineering and available technologies. It must be reliable and stable, and use all of the infrastructure well. Beyond this, the investigations should endeavor to show that the macrogrid can make the existing grid work better. There is a lot of latitude for "better," which could include such benefits as increasing existing transfer limits or removing constraints (e.g., must-run generation, and allowing resources to be shared better), especially those essential reliability services that are needed for security. In short, we are looking for problems, solutions, and opportunities to do better than the status quo. 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 macrogrid.

A starting point should reflect minimum NERC reliability criteria. Because the bulk power system must be "fail-safe," the work should consider modifying criteria to reflect the macrogrid's potential for higher-consequence failures. The work may need to challenge criteria that

FIGURE 12
Spectrum of Phenomena for Stability Aspects of Reliability Investigation



Source: Adapted from Hatziargyriou et al. (2021). © 2022 IEEE.

have been traditionally enforced but yield poor efficacy (i.e., criteria that impose a high cost for poor return on reliability benefits). The study must be designed to test, challenge, and demonstrate reliability and to explore opportunities of the macrogrid to provide performance benefits (via control capabilities) not currently available.

This is one of the places where existing practice might reduce the benefits possible with the macrogrid. Present practice for N-1 basically says "no intervention that isn't automatic." With the envisioned self-sufficient macrogrid design, there will be capability to shift flows/loading in response to events on the AC grid as well. The study should motivate the opportunities of the macrogrid to provide control capabilities not currently available that would improve frequency stability, voltage stability, transient stability, and oscillatory stability of the existing grid.

In short, the work should incorporate a vision that calls for further technology development that can transform the grid operation and control.

Assessing Benefits for Local AC Systems

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—such as increasing path ratings or relieving reliability-must-run constraints. These will provide increased utilization, cost savings, and reduced need for more right-of-way for supporting AC circuits.

In some regards, the macrogrid will provide a solid "anchor" against which existing and new local/regional AC systems can lean.

The AC system around macrogrid nodes will be transformed in a number of ways. Some of it will be new "collector" systems, to bring power from wind and solar to the macrogrid nodes. Some of it will be parallel, with existing and possibly new paths competing with or augmenting the macrogrid's massive power flows. The macrogrid will substantively impact the performance of these local systems. Other constraints, such as voltage stability limits, may be favorably impacted. The demonstration must start with an aim of "do no harm," i.e., using established techniques to make sure that the AC system meets basic reliability criteria. Some advanced technologies may be needed: this isn't completely new ground, but the details will look different, and need to be approached carefully and systematically. Conventional number crunching will likely leave risks and opportunities underexposed.

Sharing Services: Frequency Response, Reserves, and Inertia

The macrogrid will tie regions together in ways that should facilitate better overall performance and the economic sharing of resources. However, security performance, particularly the response to events that unbalance the system—causing frequency and intertie violations—will be altered. Compared to transient and voltage stability, these issues will tend to be geographically broader or systemic.

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 (PFR), delivery of fast frequency response (FFR), and more economic compliance with frequency response obligations (FRO). Novel controls may be needed to fully realize some potential benefits.

This class of experiment is related to the transient and voltage stability, but needs to be examined somewhat differently. For example, today FRO is largely provided within each Balancing Authority. While there is limited possibility for adjacent Balancing Authorities to exchange frequency response, the existing grid (and practice) limits the implementation. A macrogrid, with suitable controls should be able to rapidly respond to regional upsets that today would stress frequency response resources. The potential to allow for less reserves, better response, and more economic operation are large, and will accrue to all the participants.

The investigation must include consideration of the types of events that currently guide reserves practices, as well as explore new risks that might accompany the overlay. This is coupled with the concept of the macrogrid being self-contingent.

Longer-term dynamic behavior may require some different experiments. For example, ramping events that occur over minutes to hours will stress the system differently. The macrogrid should allow for better response to these impacts. This spills over onto the operability task, but the investigation must recognize that some of the risks will manifest themselves as security failures and therefore will need to be evaluated in these reliability studies.

Assessment of Refinement or Addition of New Technologies

Grid security goes beyond the macrogrid, and encompasses the entire system—including the balance of the AC grid and the mix of resources, such as massive build-out of inverter-based resources, new energy storage resources, electrification of new sectors—each of which will be different. Reliability performance demonstrations should start with an assumption of best available and appropriate technology: for example, high-functionality inverter-based resources, best practice protection, high function reactive compensation, dynamic line rating, VSC HVDC, and others.

Studies must be designed to allow for the refinement and addition of new (but reasonably well established) technologies, as these can be used to mitigate problems or improve performance. The focus should be especially on those that are 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.

Technological advancement is a moving target to some extent. The reliability studies must recognize that the fundamentals—of generation, of load, of control—are advancing and will impact the efficacy and design of the macrogrid. At the same time, this is not a study of everything. The recommended approach is to take an

educated, moderately aggressive, guess at technology that is available or promises to be available in the near term, and which would reasonably be expected to provide performance benefits.

The evaluation of reliability/security issues should include specific sensitivities or demonstrations of how a variety of new technologies might result in better outcomes. Some care is needed to avoid this being a deep (and narrow) study of specific technologies (e.g., this is not a grid-forming inverter study, as such). One objective is to highlight what the advances in technology bring to reliability, with a view toward illuminating benefits of potential technology advances that may need some help (from the national labs, etc.) to get to the stage where they are available and practical for the need, and to quantify what those enabling technologies/features are "worth," from a reliability (and economy, resilience, etc.) perspective.

Basic technology questions may illuminate research needs in the reliability study phase. For example, is there sufficient institutional understanding of what happens when a DC line faults in a multi-terminal VSC grid? 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. Overall, this reliability study will need to identify and advise the industry and research affiliates of technology research gaps and needs.

Planning for Disturbances

The reliability investigation needs to consider a range of severity for disturbances. Up to some level of event severity (e.g., trip of a bi-pole) the macrogrid should be self-contingent. It is understood that other bi-poles pick up power. But will systems at nodes (nearby or otherwise) be affected? Will AC reactive support change? With VSC and big ratings, this is new ground. The study needs to consider normal disturbances, for which there should be no (or very limited) customer impact, and 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, also need to be considered.

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. This is complex, including classification of events and allowable response to those events; it should explore whether the existence of the macrogrid could enable new or different events.

Weather events will also need investigation. 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.

Investigation is also needed of interconnection-wide behaviors (as distinct from more localized stability concerns). Major frequency events, for example, a trip of two Palo Verde nuclear units, is a design basis event in the Western Interconnection. The Eastern Interconnection and Texas Reliability Entity have similar design basis events. This is basic, but very important. Design of experiments must consider the expectation of lower system inertia, and the potential for a wide range of resources to provide PFR, FFR, and other related frequency-response services.

Weather events will also need investigation. 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 blur the line between stability and operability in ways that are largely absent in thermal-dominant systems. Ramping reserves and sharing need to be demonstrated, and this spills over into the operability topic. Systemic response to (for example) ramping events must not push the system into conditions of security risk, even temporarily. Consequently, attention to stability risks is necessary as capacity and service expectations with the macrogrid are set.

Recommended Approach

The novelty, scope, and expanse of the proposed macrogrid obviously preclude a comprehensive reliability investigation for the continental United States. Instead,

the technical investigation should examine traditional events that pose risk for reliability, along with those that are particularly related to the presence of the macrogrid overlay and component technologies.

At a minimum, the investigation of transient and voltage stability issues should consider the classes of disturbances listed below. Each type includes some points of technical concern. This list is not exhaustive, but represents the minimum set of events that should be considered.

- **Fault, trip DC bi-pole:** The macrogrid should be self-contingent. In this case, other bi-poles should 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.
- **Fault, trip AC collector line:** This disturbance type will perturb other plants; DC will "see" disturbance. Depending on substation configuration, the existing grid may also see the disturbance. These are standard stability questions, but novel controls on the DC system might provide performance improvements that allow heavier loading/better use of this new AC infrastructure.
- **Fault, trip existing AC intertie:** The presence of DC will alter bulk power system behavior for critical (often-studied) faults, e.g., the stability of the Colstrip line has been critical for decades; flows on existing AC are limited by stability for faults like this. Again, DC will "see" the disturbance. But again, novel controls on the DC macrogrid might provide performance improvements that allow heavier loading/better use of this existing AC infrastructure.
- **AC fault in substation:** This is an extreme disturbance and would presumably result in the loss of "collected" plants. It must not be allowed to result in cascading failures. Loss of MW from trip of plants will make this both a transient stability and a frequency event. How will DC respond? Are strategies obvious, and are some better than others?
- **Clear node:** This is also an extreme disturbance, for which the macrogrid presumably is not self-contingent. Again, cascading failure is not allowed. What strategies result in the least bad outcomes?
- **Clear DC right-of-way:** This is extreme. Is it worse or better than clear node? Are strategies different? What does AC system see, during and after the DC fault?

The technical investigation should examine traditional events that pose risk for reliability, along with those that are particularly related to the presence of the macrogrid overlay and component technologies.

Further types of events that have consequence for frequency stability and sharing of ancillary services are also of importance:

- **Fault, trip largest units:** For example, a trip of two Palo Verde nuclear units is a design basis event. The Eastern Interconnection and Texas Reliability Entity 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 PFR, FFR, and other related frequency response services.
- **Loss of infeed events (new):** The macrogrid is expected to be self-contingent. As noted previously, 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.

- **Regulation sharing:** This is an intersection with stability constraints and the requirement for self-contingent management of the macrogrid. It applies to large discrete events as well as abrupt weather events mentioned in the section above.

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. The reliability study must deliberately seek tests, disturbance, and beyond, to stress various known reliability risks.

A test regime could proceed along the lines of the matrix shown in Table 1.

The investigation will need to distill and extract insights that can guide broader discussions, as well as identify topics that require further research. To that end, reliability investigation reporting must facilitate identification and mitigation of reliability challenges, and not just show success or failure of the specific system. Researchers should plan to parse results.

A potential approach for categorizing reliability events and issues considered in the investigation includes the following.

- 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
  - Macrogrid: pole trip, bi-pole trip, station trip
  - Severity of event
- What type of problem:
  - Per IEEE stability hierarchy

TABLE 1

Potential Matrix for Identification of System Events for Detailed Study in Reliability Investigation

Class of stability concern	Disturbances that might precipitate	What might be different with a 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				

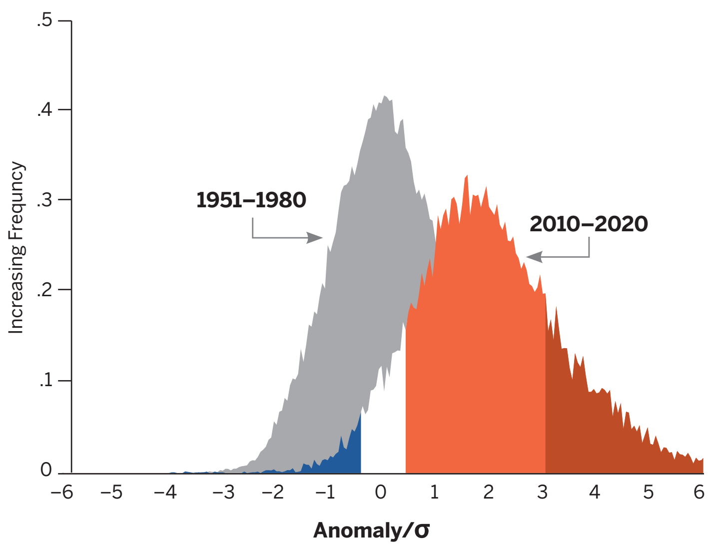
Source: Energy Systems Integration Group.

Resilience Analysis

Introduction

While power system reliability entails designing and operating the power system to maintain high standards of service under a variety of relatively routine and predictable conditions, system resilience is the challenge of how to prepare for and respond to high-impact grid-damaging events such as extreme weather and physical or cyber-attacks. There is clear evidence from both actual weather events—Figures 13, 14 (p. 34), and 15 (p. 35)—and scientific theory and modeling that extreme weather events of most kinds are becoming more frequent and more severe due to climate change, threatening our communities as well as the power system. Therefore, we will need to plan, design, and build the macrogrid to survive and operate through more extreme physical challenges and to enhance the power system's ability to quickly recover from such events.

FIGURE 13
Shifting Distributions of Temperature Anomalies in the Northern Hemisphere, June Through August



Source: Makiko Sato and James Hansen, Columbia University.

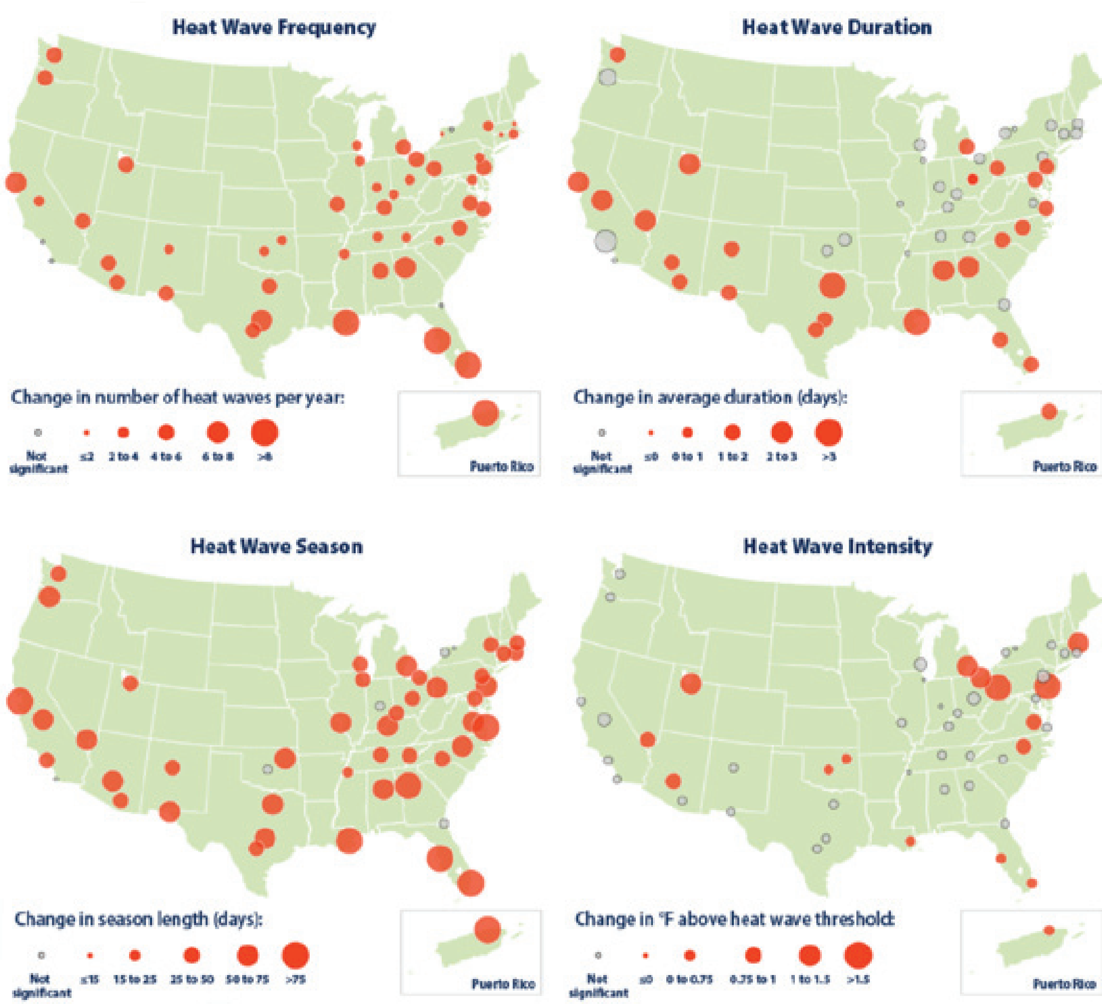
Resilience Metrics

Effective analysis of macrogrid options and alternatives will require rigorous qualitative and quantitative analysis of how the power system could be harmed by and recover from a variety of extreme threats and events. This analysis should compare different macrogrid options against business-as-usual (BAU) grid scenarios, assessing the performance of alternative system designs in the face of a consistent set of grid threat scenarios over time. This could include, for instance, multi-decade scenarios with more and hotter and drier heat waves and droughts, more hurricanes, more extreme precipitation and flooding, and more rapidly spreading and larger wildfires. These evaluations should look at the performance of each transmission system and power system portfolio scenario against a suite of resilience metrics that are closely related to reliability metrics:

- Loss of load expectation (LOLE)
- Number of customers affected by grid failure, duration of outages, and expected unserved energy
- The economic value of expected lost load
- Whether and how the macrogrid can expedite service restoration in an area hit by an extreme event (as with black-start recovery and energy imports)
- Other measures as appropriate

FIGURE 14

Worsening of Heat Waves in 50 Large U.S. Cities, 1961–2019



Orange dots show the magnitude of heat waves in U.S. cities between 1961 and 2019.

Source: Environmental Protection Agency (2022).

The above metrics and results should complement the reliability analysis and inform the economic analysis of macrogrid and BAU options.

Methodology for Evaluating the Resilience Contributions of the Macrogrid

Current thinking about how the macrogrid could improve power system resilience includes the following roles, which are informed by recent power system failures such as winter storm Uri, the Texas heat wave of August 2019, and the winter 2018 "bomb cyclone" cold weather event across the Northeast:

- The macrogrid will enhance the optionality, flexibility, and insurance value of transmission to the power system.
- The macrogrid will enhance and amplify the portfolio diversity of the power system overall.
- Particularly if the macrogrid is dominated by HVDC technology, it will offer additional operational tools that reduce system susceptibility to failure and enhance outage restoration capabilities and speed.

FIGURE 15

Acceleration of Coastal Flooding, 2011–2020 Versus 1950–1959

A comparison of the change in coastal flooding on U.S. coasts, 2011–2020 vs. 1950–1959.

Source: Environmental Protection Agency (2022).

The methodology for evaluating the resilience contributions of the macrogrid should include or be based on the following considerations:

- Geographic load diversity during extreme events
- Geographic supply diversity and deliverability during extreme events
- Imported energy capability (to make up for localized demand spikes and inability of in-region generation to perform due to storm impacts) with and without macrogrid
- The collected, credible set of high-impact medium-frequency extreme weather events. Forward datasets over 10-, 20-, and 30-year horizons should be developed with input from DOE, the Federal Energy Regulatory Commission (FERC), the National Oceanic and Atmospheric Administration (NOAA), and the Intergovernmental Panel on Climate Change (IPCC) on types, magnitude, frequency, and locations of extreme events for analysis here.
- Imported capacity (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

Electric power system resilience is a relatively new industry topic. Some recent analysis provides guidance on the approaches and metrics that can be used in the assessment needed here for the macrogrid:

- "February 2021 Cold Weather Grid Operations: Preliminary Findings and Recommendations" (FERC, 2021)
- *PJM's Evolving Resource Mix and System Reliability* (PJM, 2017)
- "Planning for Resilience in High Renewable Power Systems" (Miller, 2020)
- "Assessing Transmission Investments Under Uncertainty" (Hobbs et al., 2013)
- "Engineering-Economic Methods for Power Transmission Planning under Uncertainty and Renewable Resource Policies" (Muñoz Espinoza, 2014)

Economics and Feasibility

Objectives

- Use macrogrid design(s) to examine issues with line routing; find appropriate routing possibilities
- Estimate capital costs associated with macrogrid construction over a timeline
- Estimate ancillary economic benefits

Approach

Macrogrid and HVAC BAU analyses should use consistent economic analysis techniques to assess the costs, benefits, cost-effectiveness, and performance of a wide range of transmission system and power system scenarios, using a consistent set of metrics and assumptions. Every macrogrid option should be compared to the costs and feasibility of achieving the same clean energy goal without a macrogrid overlay, using only BAU technology, practices, and trends. The crux of macrogrid and BAU analysis should be to determine whether the macrogrid offers significant benefits that greatly exceed its cost, and whether it is possible to achieve the same level of decarbonized clean energy and power system reliability without a macrogrid.

Macrogrid and HVAC BAU analyses should use consistent economic analysis techniques to assess the costs, benefits, cost-effectiveness, and performance of a wide range of transmission system and power system scenarios, using a consistent set of metrics and assumptions.

One of the most important tasks of the economic analysis of macrogrid and BAU transmission options will be to estimate the total capital costs and investment period for each scenario that produces equivalent levels of clean energy and reliability. The analysis should document when and why a specific scenario proves incapable of delivering equivalent levels of decarbonization and reliability, and the cost consequences thereof if that is the case.

Quantification of the Benefits

Macrogrid and BAU analyses should consider and quantify a wide range of benefits over a national (or even continent-wide) scale, including:

- 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
- Resilience, and the value to consumers of transmission to protect against severe weather and other system stress conditions, including by delivering generation from one region to support its neighbor and its neighbor's neighbor
- Adequacy—capacity reduction to achieve the same level of resource adequacy by capturing load and

renewable diversity, and reducing planning and operating reserve needs (including ancillary services)

- Fossil fuel cost savings—through use of the most economic resources nation-wide and reduced energy consumption for fuel transportation, as opposed to the 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.

The economic analysis of every scenario should also consider broader societal benefits beyond the electricity system, including possible impacts on gross domestic product, tax payments, net employment, and public health from achieving a lower-emissions power system that is slowing the rate of adverse climate change impacts. Different policymakers and stakeholders will have different interests and jurisdiction to utilize these categories of benefits.

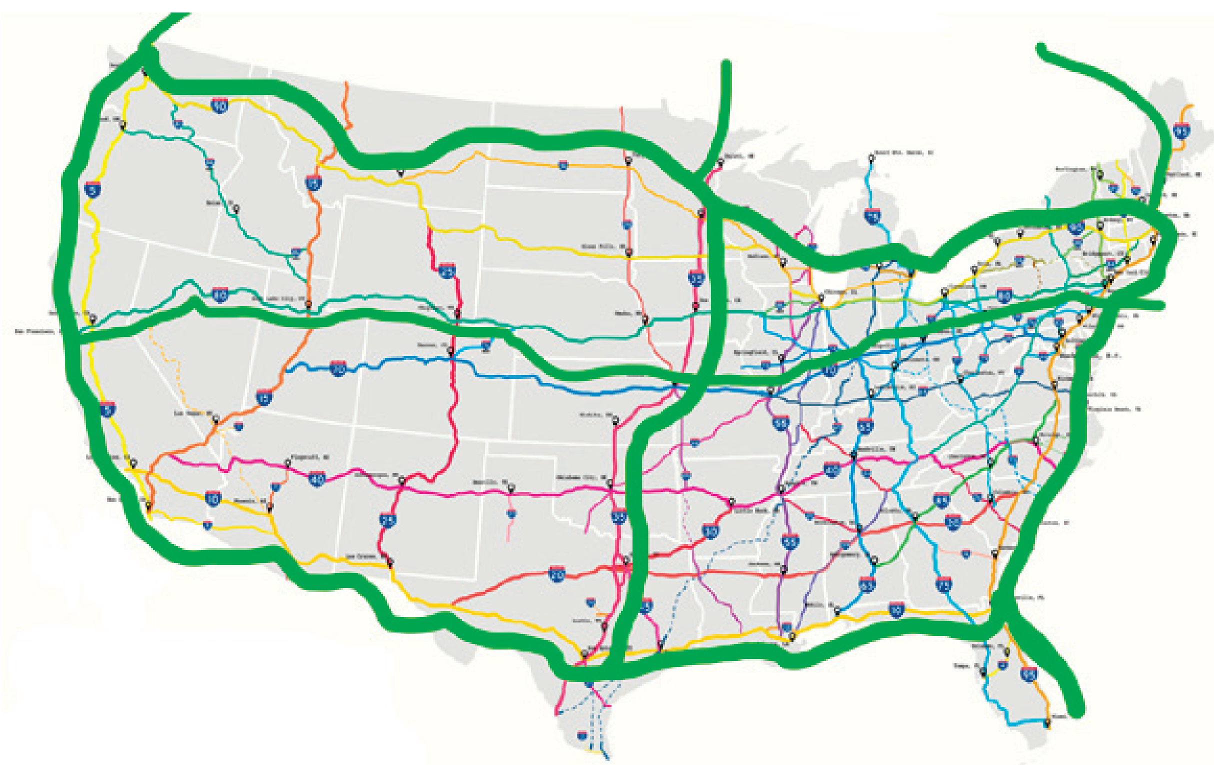
Options for Speeding Up Construction and Lowering Costs

A number of techniques and tools are available to speed the construction and lower the costs of new transmission, whether under a macrogrid or HVAC BAU option. Those options for routing and siting include using rights-of-way for existing transmission, highways, railroads, and pipelines (Figure 16); maximizing the size of initial builds (as with rights-of-way width and transmission structures) to facilitate later expansion; and building longer routes with higher land-owner payments to reduce land-owner and community opposition.

Relative to conventional EHVAC transmission lines, the transmission lines comprising the macrogrid will tend to be much longer (and higher capacity). The access points for the macrogrid—clean energy collection and delivery

FIGURE 16

Illustration of Potential Use of Interstate Highway Rights-of-Way for Macrogrid Transmission Circuit Routing



Source: Energy Systems Integration Group.

points—will have been identified in the earlier initial macrogrid design task. As part of this analysis, a detailed evaluation of how the macrogrid circuits can be routed to take advantage of the likely easier-to-secure right-of-way should be conducted.

Economic analyses of future transmission and macrogrid options should provide consistent presentation of all of the costs and benefits described above. Because these should study systems of transmission and generation rather than individual transmission lines, these analyses should calculate costs and benefits for large, integrated portfolios of lines and regional development, not for specific individual transmission or generation projects. These benefits and cost assessments should span entire regions and the nation as a whole, to help identify whether and where the benefits and costs of a macrogrid or BAU portfolio expand beyond the narrow footprint of specific transmission and generation developments.

Operations and Operability

Objectives

- Posit technical organizational structures and responsibilities for operation of macrogrid overlay
- Assess how operations could be coordinated with regional markets and entities
- Identify new tools and approaches that may be required to fulfill a national operational mission (i.e., simultaneous transport of energy with reliability constraints)

Discussion

A macrogrid could be leveraged to improve and enhance the operation of the existing bulk power grid, operating in coordination with existing and planned DC connections, as well as the underlying AC transmission system, in ways to maximize reliability and economic benefits to consumers. The behavior of the entire U.S. bulk power system would be impacted by the macrogrid in ways that make the existing grid work better, although it also would require a major paradigm shift to existing and

long-standing operating protocols and reliability practices that have been utilized by Balancing Authorities for decades. New architectures and methods for grid control would be needed. Although current control structures are based on cooperation with neighbors and within existing interconnections, new operational concepts and opportunities will extend across interconnections and to neighbors' neighbors and beyond.

The macrogrid's capabilities will be extremely valuable for grid management and security with very high levels of renewable resources to support decarbonization goals. The controls associated with HVDC equipment, and wide-area situational awareness enabled by new connectivity and technology, will tie regions together in ways that facilitate better and more efficient overall grid performance. A macrogrid can provide operational tools and capabilities that would not only reduce the bulk power system's susceptibility to failure, but can enhance outage restoration capabilities and speed, which can be critical during extreme operating scenarios.

The existing interconnections in the United States are managed through multi-party and multi-layer control structures that include embedded competitive wholesale energy markets. The macrogrid would add an overarching layer on this existing grid management structure, necessitating the coordination of national and regional energy flows, and would likely require the creation of an entity to ensure that the macrogrid is operated in such a way as to meet reliability and resilience needs and facilitate economic operation of the U.S. electricity infrastructure.

A Need for New Operational Mechanisms

With respect to operations and operability of the macrogrid, new mechanisms will be required to maintain bulk system security, provide essential reliability services, balance generation and load, manage congestion, and ensure necessary coordination between regional and national entities. Expected operational benefits associated with a high-capacity overlay network enabled by converter technologies and controls include the provision of dynamic voltage support for the AC system, thereby increasing transfer capability.

While the existing and planned operating protocols, practices, and metrics have served the bulk power system well for decades, they would need to evolve, in many cases substantially. The macrogrid creates an opportunity for bulk power system operators to rethink traditional operating requirements, including whether the provision of inertia from traditional resources remains necessary to provide system security. Advanced grid control and monitoring capabilities, combined with the attributes of grid-forming inverters on the bulk power transmission, as well as local distribution systems, provide an opportunity to dramatically improve system performance.

Better operating systems and tools would be required with a macrogrid with standardization to facilitate coordinated operations in the future. 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 levels of renewable resources. Better situational awareness and decisionmaking support tools will be needed to help operators evaluate and manage system security, and give operators guidance on the effectiveness of possible mitigating measures.

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:

- Sharing of energy, capacity, and services over the entire United States, thereby taking advantage of time zone diversity
- Sharing of contingency and other reserves, thereby reducing the total amount of reserves carried across the U.S. bulk system
- Providing dynamic voltage support to the AC system, thereby increasing its transfer capability
- Supplying voltage and frequency support
- Improving transient stability and reactive performance
- Providing AC system damping
- Serving as a "firewall" to limit the spread of system disturbances
- Decoupling 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
- Providing black-start capability to re-energize a 100% blacked-out portion of the network
- Mitigating weak grid issues that limit levels of inverter-based resources with grid-forming control of macrogrid nodes

The macrogrid 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.

Questions for Consideration

Many questions will need to be considered in addressing the operations and operability associated with the macrogrid. These extend beyond the effects on current operating parameters and requirements, including NERC standards. Researchers must collaborate with existing grid operators to address changes to existing practices, procedures, and tools to achieve the operational benefits of a macrogrid. A macrogrid would complement existing networks and markets, and not eliminate the need for regional markets and interregional planning within and across existing interconnections.

Some specific questions to be addressed include:

- How will the macrogrid affect current operating parameters and requirements?
- What is the value proposition of the macrogrid to consumers based on enhanced HVDC controls and capabilities to affect existing Balancing Area 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? If not, in what ways do they need to be expanded or modified?
- Is the macrogrid and its associated control system consistent with existing NERC standards? If not, what changes are needed?
- How could the macrogrid impact the provision and economics associated with essential reliability services for the bulk power system?
- How would the 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 can synchrophasor and other monitoring and analytics efforts be expanded to facilitate the needs of the macrogrid control system and mitigate impacts on the AC systems?
- How would the macrogrid and its associated capabilities impact existing joint operating agreements and coordination requirements between neighboring systems?

Assumptions

In the operating and operability assessment, a few core assumptions should be considered:

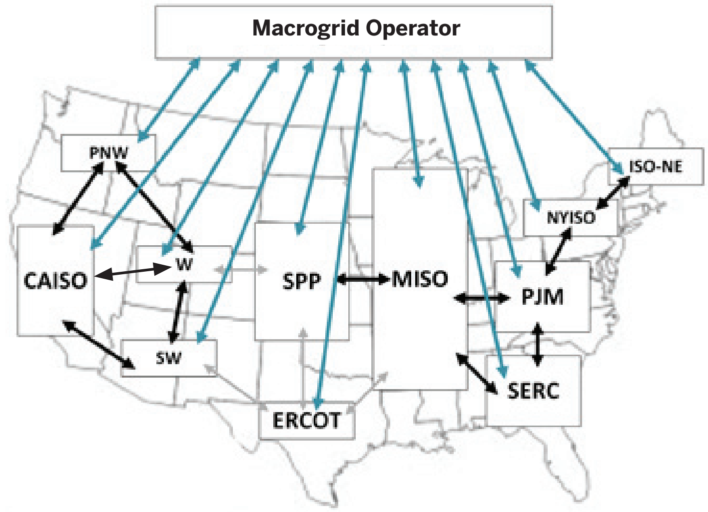
- A macrogrid will complement existing networks and markets, and not eliminate the need for regional markets and interregional planning within and across existing interconnections. It will introduce additional flexibility in the markets by increasing the number of trading options available.

- Although existing bulk power systems will integrate with a macrogrid, we will not need to redesign existing AC systems to handle a normal 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 because 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. From the perspective of power system operation and short-term operational planning, the macrogrid would require a new structure that would interact with all of the existing operating organizations for the U.S. bulk system (Figure 17). Current grid operations are affected by the actions of a relatively small number of entities (RTOs/ISOs, and other regional entities) that adhere to a common rulebook and have interactions with neighboring control entities. Macrogrid operations would necessarily have a national perspective, and seek to meet the energy, capacity, and services needs of all of the regional control entities in the most efficient manner.

The macrogrid 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.

FIGURE 17
Integration of Macrogrid Operations on Current Operational Structure for the U.S. Bulk System



From the perspective of power system operation and short-term operational planning, the macrogrid would require a new structure that would interact with all of the existing operating organizations for the U.S. bulk system.

Note: Arrows indicate information sharing and coordination of operations between entities, not necessarily power flow.

Source: Energy Systems Integration Group.

The dispatch and flow of energy on the macrogrid would be the responsibility of the macrogrid operator and effectuated by the real-time control of all macrogrid nodes (Figure 18). The diagrams are simplistic and short on detail, but very clearly illustrate the scope and complexity of this challenge. Control of HVDC systems at the core is relatively straightforward; with an expansive HVDC network and the large number of controllable device states and likely constraints, new control concepts will need to be developed.

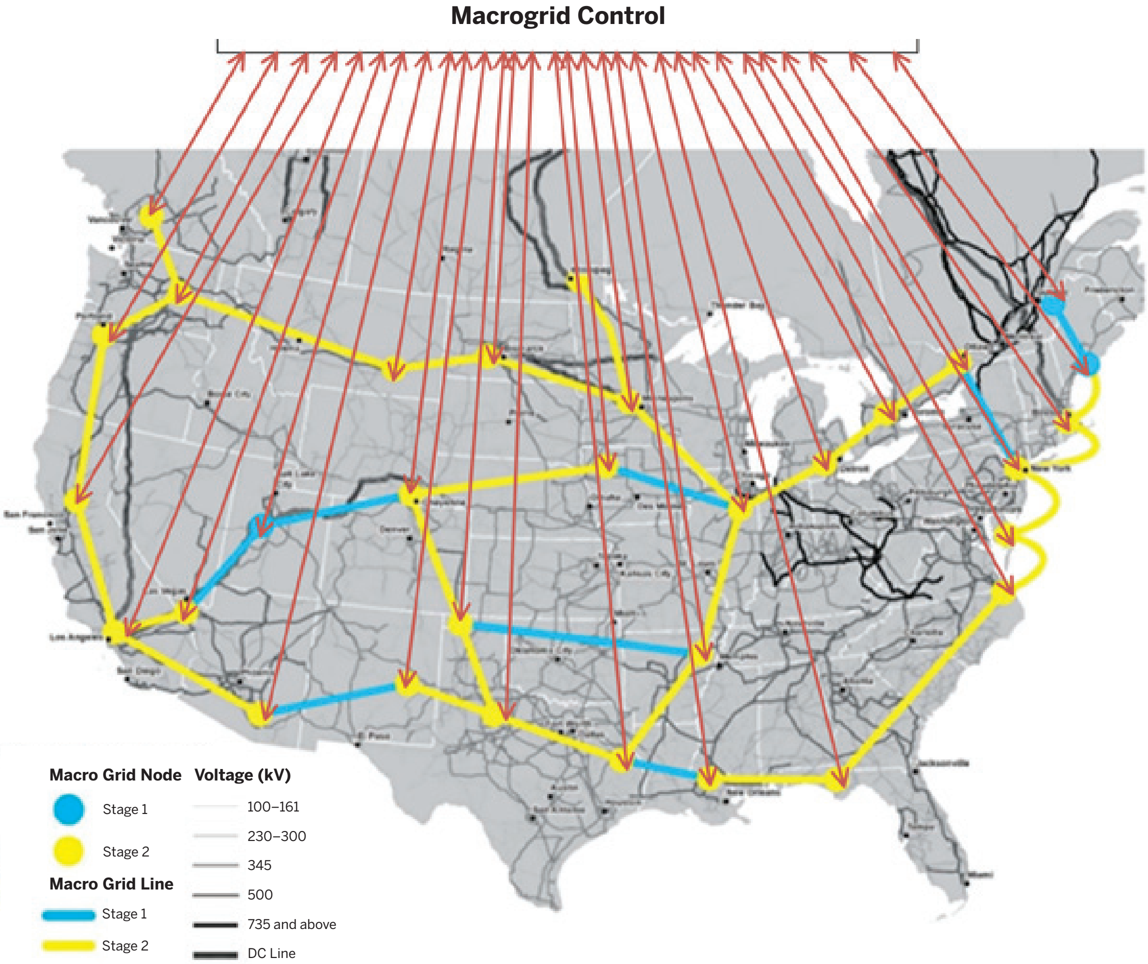
Recommended Approach

The intent of this study element is to take a deep dive into the many facets related to the operation of a controllable national HVDC overlay that supports very high levels of clean electricity. It should:

- Leverage DOE capabilities, resources, and leadership to identify and begin addressing operational issues and challenges that must be addressed to facilitate operation of a national macrogrid and capture its full

FIGURE 18

Macrogrid Operator Coordinates Control of All Nodes on Macrogrid in Response to Needs of Underlying Operating Areas



The dispatch and flow of energy on the macrogrid would be the responsibility of the macrogrid operator and effectuated by the real-time control of all macrogrid nodes.

Source: Energy Systems Integration Group.

benefits. The federal government possesses broad capabilities for studying and improving the power system through the DOE, national laboratories, power administrations, and FERC.

- 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 build-out and transition to a fully redundant, self-contingent macrogrid network.
- Identify and/or demonstrate new tools and capabilities to improve situational awareness, and operational support tools including coordination and communications needs in the real-time and operations planning horizons.

Summary

We recognize that what is proposed here represents a substantial departure from the current transmission expansion process. However, the notion of very high levels of clean electricity across the United States is itself radical, and justifies "out of the box" thinking about the infrastructure necessary to achieve such goals. Significant concerns remain over whether or not the massive transmission expansion required for very high levels of clean electricity can be achieved with conventional expansion of the bulk system. Scenarios developed in recent studies reveal that the volumes of required energy transfer and the transport distances may be too large to be accommodated by conventional expansion of the U.S. grid.

Technologies for advanced HVDC networks are nearing commercial readiness. In just six years since the National Renewable Energy Laboratory's Seam Study, the power ratings of VSC converters have increased to where they could replace the conventional HVDC assumed for that effort. An advanced HVDC network—the macrogrid—should be considered along with more conventional approaches in the DOE-led initiatives to explore clean electricity futures.

This report has explored the central tasks involved in working toward a viable macrogrid design and presented specific steps for addressing them.

- **Technical studies on reliability, resilience, economics, and operations.** A series of technical studies is proposed and described here to design and evaluate the macrogrid alternative for grid expansion. An initial design for the macrogrid would be based on clean electricity scenarios already under development in DOE initiatives. It is recommended that the initial macrogrid design be based on the end-point scenario, and not through a multi-step incremental expansion exercise.

  The initial macrogrid design for the selected clean electricity scenario would be subjected to further technical analysis. The general objective of these companion studies is to elicit further details on the range of ancillary benefits provided by the macrogrid infrastructure. The contributions to the reliability and resilience of the U.S. bulk power system could be very substantial, and would be unique to the macrogrid infrastructure compared to conventional alternatives for grid expansion.

- **Coordination and oversight of the physical infrastructure.** Physical operation of the macrogrid raises a number of technical challenges and questions. Currently, there is no operating entity that has the purview and national scope of the macrogrid infrastructure, or has the tightly coupled operating interactions with the number of entities that would be necessary here.

- **Cost comparisons.** The costs to build the macrogrid are obviously of major importance and would be compared to other alternatives for grid expansion to support the same clean electricity scenario. Against these costs, the full range of benefits—including those related to improved power system reliability and resilience—would be captured and quantified to develop a full picture of the macrogrid economics.

- **Use of rights-of-way.** Acquisition of rights-of-way for new transmission is a barrier to any form of grid expansion. Because of the architecture, the HVDC lines comprising the macrogrid would likely be much longer than new lines that are part of a more conventional grid expansion. Further, utilization in terms of power transfer of the rights-of-way would be much higher. As part of this evaluation, opportunities to use existing or more readily available line routes, such as interstate highways or railroads, would be explored in detail.

The convergence of the national push for very high levels of clean electricity and the advances in HVDC transmission technology of the last decade have created a unique opportunity for a detailed exploration of an alternative to the conventional transmission expansion process to address identified challenges for the U.S. electric power system.

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Appendix

The "Rule of Three" for Transmission Expansion

The "rule of three" is a guideline to ensure circuit selection accounts for the impact of macrogrid—or any new facility—outages on underlying or existing AC system reliability. It provides that high-capacity interregional transmission can be built to be self-contingent and economically attractive if it is built using at least three parallel circuits. "Self-contingent" means that remaining parallel circuits are able to carry the additional loading for loss of one of the parallel circuits. "Economically attractive" means that, during normal operation, the circuit provides significant additional transmission capacity, with a low derating to satisfy N-1 contingency conditions. The rule of three is developed and illustrated below.

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.

We require that the total max flow before macrogrid N-1 outage ≤ total capacity after macrogrid N-1 outage:

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

The above inequality can be manipulated to give:

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

which provides a lower bound for n; i.e., it provides the minimum number of new lines to ensure that remaining lines are not overloaded during loss of one macrogrid circuit. We provide two illustrations.

Case A: The Underlying System Has Capacity

In Case A, the underlying system has capacity:

C = 3,600 MW
(Capacity of one new line)

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

C_0 = 1,500 MW
(Capacity of existing underlying transmission system)

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

Case B: The Underlying System Has No Capacity

In Case B, the underlying system has no capacity, for example, when the new transmission connects two asynchronous grids:

C = 3,600 MW
(Capacity of one new line)

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

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

TABLE A-1

Comparison of Case A and Case B

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**
Case A: Underlying System Has Capacity			
1	0.37	3,600	1,323
2	0.73	7,200	5,276
3	0.88	10,800	9,549
4	0.97	14,440	13,925
Case B: Underlying System Has No Capacity			
1	0	3,600	0
2	0.62	7,200	4,500
3	0.83	10,800	9,000
4	0.94	14,440	13,500

Source: Energy Systems Integration Group.

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

We observe the derating factor for a two-line design (n=2) is p=73% for Case A and p=62% for Case B, implying we are only able to use, under normal conditions, 73% and 62% of the invested capacity in the two cases, respectively. But a three-line design (n=3) results in derating factors for Cases A and B of p=88% and p=83%, respectively, values that result in more economically attractive designs. The use of a four-line design is even better, but we may not need that much capacity.

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Design Study Requirements for a U.S. Macrogrid

A Path to Achieving the Nation's Energy System Transformation Goals

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The Energy Systems Integration Group is a nonprofit organization that marshals the expertise of the electricity industry's technical community to support grid transformation and energy systems integration and operation. More information is available at https://www.esig.energy.

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