Scope Development for Macrogrid Design Studies

Energy Systems Integration Group
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ESIG

Introduction

A number of recent, comprehensive studies point to the same conclusion: A 100 percent clean electricity future for the United States is dependent on massive development of the bulk transmission infrastructure.[1] Because of the national scope of this need and given the distance between vast amounts of clean electricity and the nation's load centers, the new transmission infrastructure must include a macrogrid that spans the country from east to west and north to south.

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:

- **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.[2]
- **Reliability.** Increased interconnectivity between regions of the United States can contribute to significant improvements in reliability. The technology comprising the macrogrid—extra-high and ultra-high voltage direct current (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.
- **Resilience.** Extreme weather events, an increased 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 go 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.
- **Operability and operations.** 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.

While the rationale and conceptual plans for this massive infrastructure have been laid out in recent studies, many facets of its design, construction, and operation have received only cursory or qualitative attention. A number of important questions must be researched and answered before a macrogrid can be built.

The Energy Systems Integration Group (ESIG) proposes that a cadre of studies be launched to develop the next level of quantitative detail about how a macrogrid could transform the operation of the electrical infrastructure in

1 P. R. Brown and A. Botterud, "The Value of Inter-Regional Coordination and Transmission in Decarbonizing the U.S. Electricity System," *Joule* 5, no. 1 (2020): 115-134, https://doi.org/10.1016/j.joule.2020.11.013; Vibrant Clean Energy, "ZeroByFifty," presentation at the Energy Systems Integration Group technical workshop (online), November 11, 2020, https://www.vibrantcleanenergy.com/wp-content/uploads/2020/11/ESIG_VCE_11112020.pdf; A. Bloom, J. Novacheck, G. Brinkman, J. McCalley, A. L. Figueroa-Acevedo, A. Jahanbani-Ardakani, H. Nosair, A. Venkatraman, J. Caspary, D. Osborn, and J. Lau, "The Value of Increased HVDC Capacity Between Eastern and Western U.S. Grids: The Interconnections Seam Study," Preprint, NREL/JA-6A20-76850 (Golden, CO: National Renewable Energy Laboratory, 2020); Midcontinent Independent System Operator, *Renewable Integration Impact Assessment* (Carmel, IN, 2017), https://www.misoenergy.org/planning/policy-studies/Renewable-integration-impact-assessment/#t=10&p=0&s=&sd=.

2 Vibrant Clean Energy, "ZeroByFifty."

the United States. The starting point for all of the studies would be based on the recent development of a conceptual view of the U.S. macrogrid so that all are focused on a common conceptual design. The studies would be conducted by qualified firms or collaborations having the requisite expertise in the specific area of interest, for example, power system dynamics, power system operations, and markets and economics.

ESIG recommends the launch of macrogrid studies as soon as possible. The immediate need is to define individual study scopes in sufficient detail to initiate requests for proposals, so that contractors can be secured as soon as study funding is available. The individual studies under this umbrella are all significant efforts, likely totaling upwards of $5 to 10 million or more.

Study scoping teams will need to have requisite knowledge in all study areas to extend the higher-level ideas above into detailed scopes of work that qualified contractors would execute. ESIG could serve in a project advisory role once studies have been initiated, which would include coordination among the study areas and periodic technical review.

Relevance of This Effort to a Prospective National Transmission Authority

Only the federal government has the scope and authority to effectuate a nationwide network of extra-high voltage and ultra-high voltage transmission that unites the country to achieve common clean energy policy goals. Because generation siting and development lies with state authorities while interstate transmission is a federal authority, a national transmission plan should be led by an organization with a national view that includes state authorities, and be based on the best available information on renewable resource potential and other clean energy options. An effective way to accomplish this would be to establish a National Transmission Authority, responsible for conducting national-level planning in coordination with regional planning authorities. This authority would establish an inclusive, ongoing planning process that utilizes a systems perspective of the entire country to develop detailed transmission plans and periodically update them over time. The National Transmission Authority would also play a role in supporting actual project development, siting and permitting, and cost allocation.

Because a National Transmission Authority requires congressional authorization, likely after a period of discussion and debate, it could be many months before meaningful progress is made toward the goal of dramatically expanding national transmission infrastructure. However, it is critical that this effort be initiated as quickly as possible. The successful completion of the macrogrid design studies described here would constitute a solid starting point for a National Transmission Authority, in effect giving it a "running start."

Purpose of This Document

The discussion below describes the general contours of the overall study effort and provides additional detail about the individual study elements. This additional detail is drawn from a wide range of sources and is intended to establish a clear starting point for the actual design and scoping of the individual studies.

Elements of the Macrogrid Design Effort

The four broad categories described above—economics, reliability, resilience, and operability and operations—suggest four separate but related study tracks. The common foundation for these studies is an initial macrogrid design upon which the various technical and economic analyses will be based. This initial design will build on recent studies and findings from the ESIG transmission workshops as well as include a number of considerations not incorporated fully into previous work.

Consequently, there is a sequence to the studies, with the initial macrogrid design comprising the first step and critical path. If time were no object, the other studies could proceed in sequence after this first step. However, since there is a need to complete the overall effort within a relatively short time frame—a one-year period is suggested here—parallel activities with potentially multiple study teams will be needed.

Initial Macrogrid Design

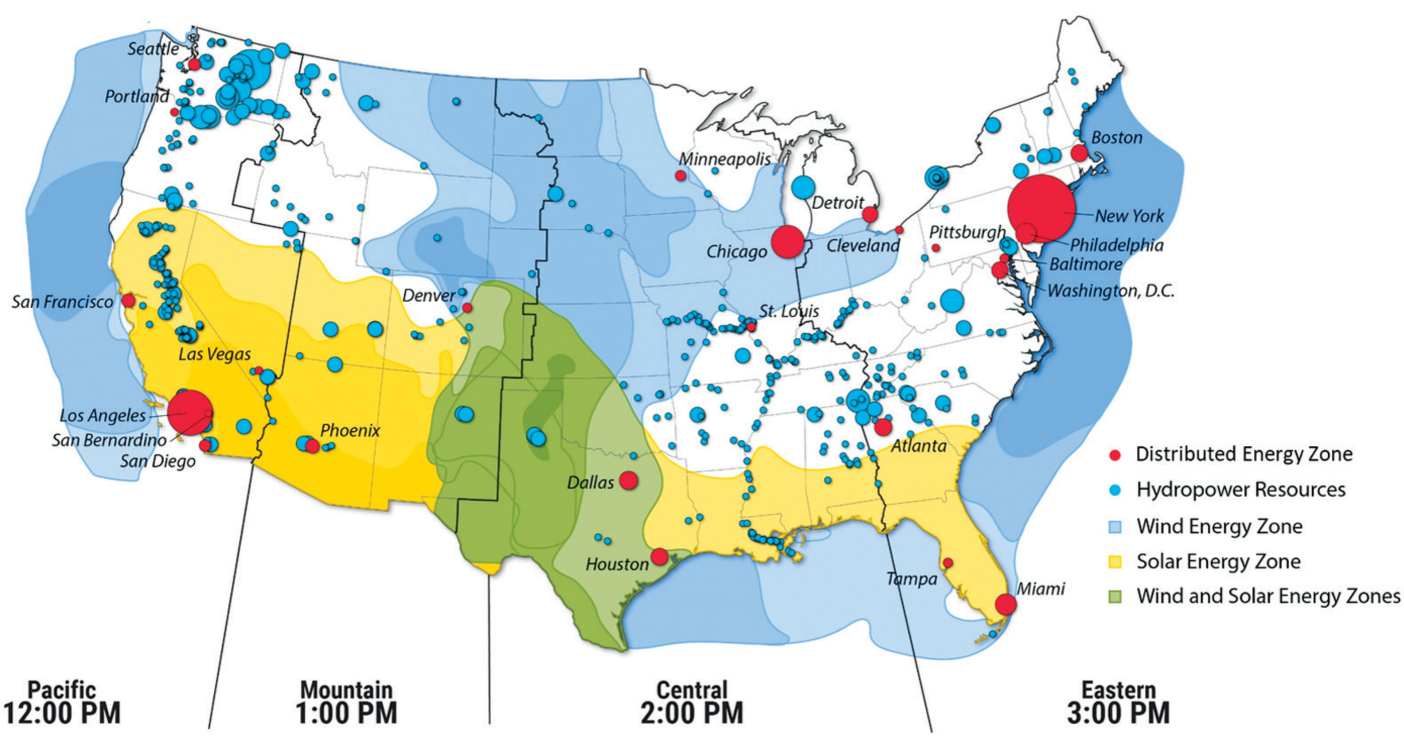
The studies described here focus on a fully developed macrogrid as it would exist at a future point in time. Effectively, the studies will examine the end point for 100 percent clean electricity in the 2035 to 2045 time frame (as opposed to addressing incremental developments from today's bulk grid to this desired end point). In this way the study results will be able to most accurately illustrate the broad range of benefits the macrogrid infrastructure would provide to the U.S. electricity supply.

Scenario-Based Methodology

The analytical approach would employ the now-standard scenario-based methodology used by regional transmission organizations for economic transmission expansion. As such, the first task would be to determine the relative locations of renewable generation and electricity demand in order to design a macrogrid able to support a 100 percent clean electricity future (see Figure 1 for the relative locations of load centers and areas of high-quality renewable resources).

Scenarios developed for previous study efforts must be leveraged to the fullest extent given the schedule constraints for this effort. In previous renewable integration studies, there has been emphasis on developing multiple future scenarios for the purpose of assessing sensitivities. It is recommended here that a single scenario be developed for the 100 percent clean electricity target, with perhaps some minor sensitivity analysis conducted to assess magnitude and locational differences with alternatives. In the end, however, only one scenario or future would become the object of the remainder of the analysis.

FIGURE 1
Potential Renewable Energy Zones That Would Be Connected with a Macrogrid



Source: Energy Systems Integration Group.

The conceptual macrogrid overlay (as shown in Figure 2) will be evaluated through chronological production simulations to determine the necessary long-distance transfer capabilities for initial sizing of the links between the suggested hubs. During this process, concepts and elements from present high-voltage alternating current (HVAC) and HVDC transmission proposals will be incorporated where available and as appropriate to leverage time and work efficiencies in already-completed design, routing, and land acquisition.

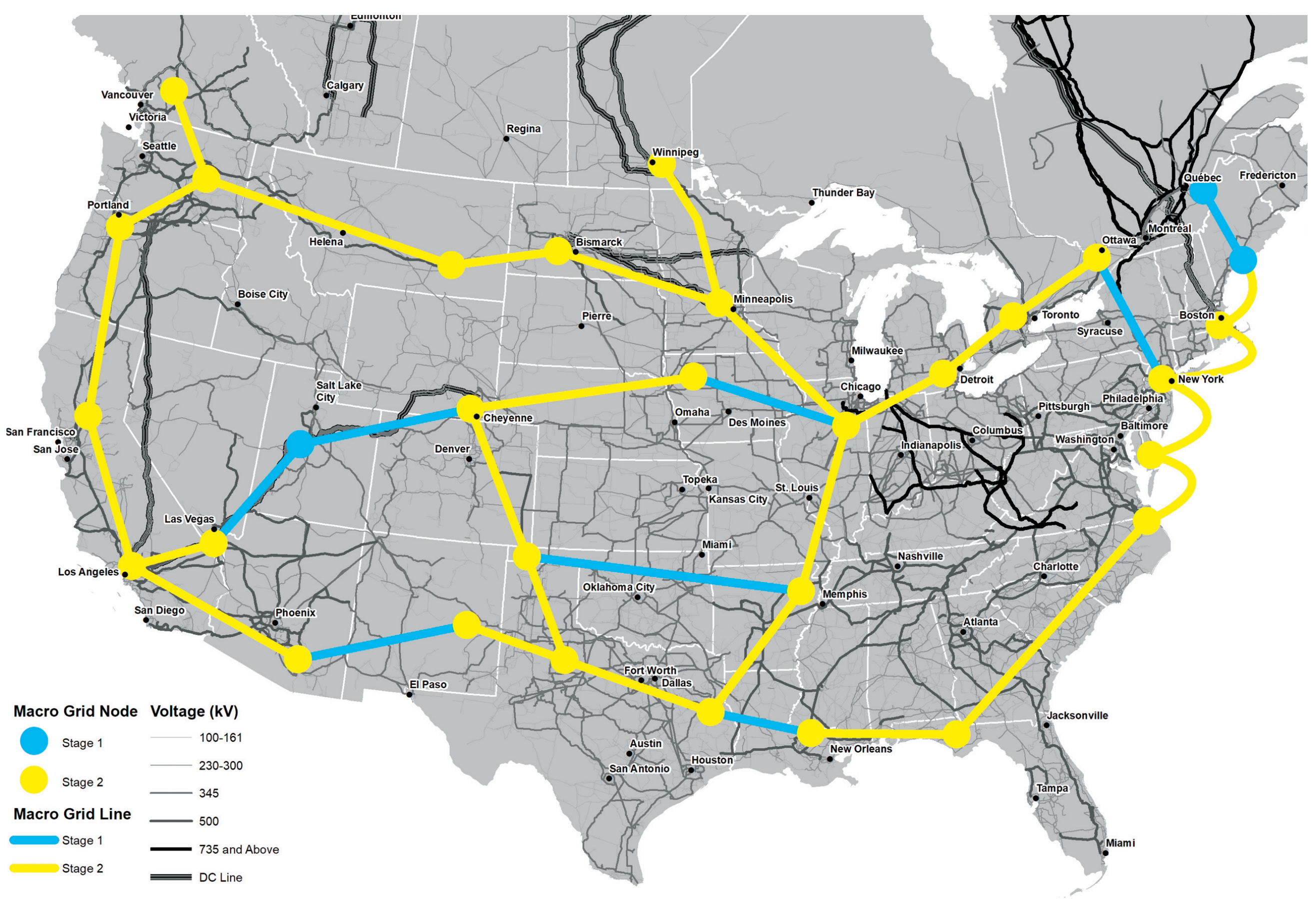
Development of New Engineering Principles to Move from Concept to Design

The process of moving from concept to preliminary design will involve more than sizing elements to transport energy. Because this effort is focused on the macrogrid as it would exist after years of development, there is an opportunity to develop some new engineering principles for the design of an advanced transmission infrastructure. These would include, but are not limited to, the following:

- Developing concepts for appropriate mixes of technologies: line commutated converter HVDC (LCC-HVDC), voltage source converter HVDC (VSC-HVDC), HVAC "collector lines," and AC grid reinforcement.
- Defining issues related to low- or zero-inertia power systems, the value of grid-forming technologies for VSC-HVDC terminals, and the utilization of multi-terminal HVDC concepts.
- Identifying engineering design considerations, such as design principles, modularity, ratings, circuit configurations, expandability, embedded VSC-HVDC considerations, and others.

FIGURE 2

A Conceptual Macrogrid Developed Through ESIG Workshops



Source: Energy Systems Integration Group.

- Assessing robustness and optionality in the face of significant uncertainty of future resource and load development paths due to: (1) evolving electricity supply and storage technology and cost options, (2) varying levels of electricity demand associated with energy efficiency, (3) demand response and electrification paths, and (4) policies and costs associated with distributed energy resources.

Feasibility Studies, Transmission Routing, and Determination of Costs and Benefits

Engineering and related feasibility studies will determine technology (AC vs. DC; line commutated converter (LCC) vs. voltage source converter (VSC)), configuration (single vs. double circuit, bipole vs. monopole), and voltage level and MVA rating of facilities (lines, converters, transformers, breakers, reactive power support, etc.). They will examine contingency considerations, power flow considerations (DC flows are controllable, whereas AC power flows are dictated by impedance of the network, and loop flow can cause unintended congestion in other regions), and considerations such as relaying, protection, and others.

Potential routing for transmission corridors will be determined and hub locations refined, given the size of the facilities and potential right-of-way options identified based on the rating/technology of the lines. Transfer capability will be maximized while minimizing cost and footprint based on hubs and facility size. Lastly, costs will be refined, and the production simulation modeling in the previous step will help determine system benefits, allowing for cost/benefit analyses and potentially indicating adjustments to plans as appropriate.

Reliability Analysis

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

- The degree to which a macrogrid allows for reductions in contingency reserves
- The benefits of geographical, technological, and fuel diversity for a power system that includes a macrogrid
- A macrogrid's benefits for system performance for a grid with high levels of renewables and very low inertia
- The role of grid-forming power electronic converters
- Ways in which a macrogrid changes or supports system response to major disturbances
- Opportunities brought by the existence of a macrogrid for new bulk grid control paradigms (e.g., with extensive and embedded controllable HVDC)

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

Resilience Assessment

Extreme weather events can affect large portions of the country and compromise both electricity supply and demand. The scope and scale of the macrogrid provides interconnectivity that spans the entire country, extending well beyond today's connections between mostly adjacent regions. While the reliability analysis study element above will address relatively conventional events and issues that could disrupt the grid, this resilience assessment will focus on high-impact, widespread events that occur much less frequently but have major disruptive potential. The February 2021 event in the Electric Reliability Council of Texas (ERCOT) system is a prime contemporary example, and there are many other plausible scenarios that would have similar consequences. These include:

- Catastrophic weather events
- Cyber attacks
- Weather patterns that cause widescale reductions in renewable generation
- Sudden jumps in electricity demand
- Sudden jumps in electricity demand caused by the same weather patterns that lead to reduced renewable generation

The expected approach for assessing resilience improvements with the macrogrid overlay would be based on chronological production simulations that illustrate changing energy flows to regional grids during major disruptions (such as the unavailability of large amounts of generation in ERCOT for an extended time period during the 2021 cold weather event).

Economic Analysis

The objective of the economic analysis will be to examine the initial macrogrid design from the perspective of overall benefits and costs—including issues related to permitting, siting and routing, and cost recovery—in order to quantify its ability to reduce the overall cost for a clean energy future.

The current methodologies employed by regional transmission organizations are thought by some to fall well short of capturing the widespread benefits of transmission infrastructure. Currently, a majority of approved transmission projects are for the purpose of reliability enhancement or local needs. Projects also tend to be evaluated on a singular basis rather than as part of a portfolio. And benefits of transmission are insufficiently captured when the focus is primarily on adjusted production cost savings rather than the full range of short- and long-term benefits.

Estimates of the economic impact of a macrogrid need to be framed by comparing three different economic scenarios:

- The economic costs and benefits of a clean, high-renewables grid with a macrogrid
- The economic costs and benefits of a clean, high-renewables grid without a macrogrid
- The economic and other costs to the nation of increasing climate change if achievement of a high-reliability, clean energy system is delayed by 10 or 20 years due to lack of adequate transmission

The objectives of this study element will be to apply a holistic view to the benefits of the initial macrogrid design and to capture the capital costs required to construct it. A recent, comprehensive commentary on the benefits of transmission and the shortcomings of current approaches for quantification can be found in an April 2021 presentation to the Federal Energy Regulatory Commission.[3]

Since the macrogrid design analyzed is considered an endpoint, rather than a series of investments over many years, assumptions will be required to quantify the investment timeline. Operating costs will be quantified by an assumed trajectory of levelized cost of energy (LCOE) for the 100 percent clean energy sources over the time period from the present to the assumed completion of the macrogrid. Benefits due to reliability and resilience enhancements will also need to be captured and may require inputs from other study elements. Job creation and other peripheral economic impacts should be quantified as well.

Operations and Operability Analysis

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 to this existing grid management scheme, which would require coordinating its operation with existing regional systems, markets, and organizations.

A national macrogrid would offer a degree of control over flows of energy from sources to loads that is orders of magnitude above that of today's power system. To leverage such control, new architectures for grid control may have to be developed. Currently, the structure is based on cooperation mostly between neighbors and within interconnections. With a macrogrid, operational concepts and opportunities would extend across interconnections and to neighbors' neighbors and beyond.

Coordination needs will include:

- Selecting or creating an entity tasked with ensuring that the macrogrid is operated in such a way as to meet reliability and resilience needs and to facilitate economic operation of the U.S. electrical infrastructure.

3 J. Pfeifenberger, "Transmission Planning and Benefit-Cost Analysis," prepared for Federal Energy Regulatory Commission staff, April 29, 2021, https://brattlefiles.blob.core.windows.net/files/22086_transmission_planning_and_benefit-cost_analyses.pdf.

- Determining appropriate mechanisms for technical control and operation of the macrogrid and underlying networks for:
    - Maintaining bulk system security
    - Balancing generation and load
    - Managing congestion
    - Coordinating between regional and national entities—i.e., system operations
    - Long-term resource assessments and planning
- Identifying appropriate options to manage economic and market transactions, including:
    - Renewable energy procurement nationally, both day-ahead and real-time
    - Coordination between regional and national entities regarding commitment and dispatch of all electricity sources, demand response and storage, and markets
    - Ancillary services management
    - Cost allocation of ancillary services and uplift costs

The study would likely be based on large-scale production simulations to illustrate both higher-level coordination concepts and more specific issues such as balancing and congestion management.

Macrogrid Study Logistics

Sequence of Studies and Schedule

The aggregate scope of the study elements described above represents a very ambitious effort, and the desire to expeditiously complete the studies establishes a significant constraint on all aspects—schedule, scope, and budget. With a tight time frame, the study elements will need to happen largely in parallel, although there will likely be some iteration between the study elements where results from one feed into others or have impacts on the final macrogrid design.

A conceptual staging for the study elements is shown in Figure 3 (p. 9). An outcome of the study scoping phase will be a refinement and enhancement of the timing, phasing, and relationships among the study elements.

Budget

Budget estimates for the individual study elements will be provided in the scoping phase. The budget estimate for the scoping phase is $150,000.

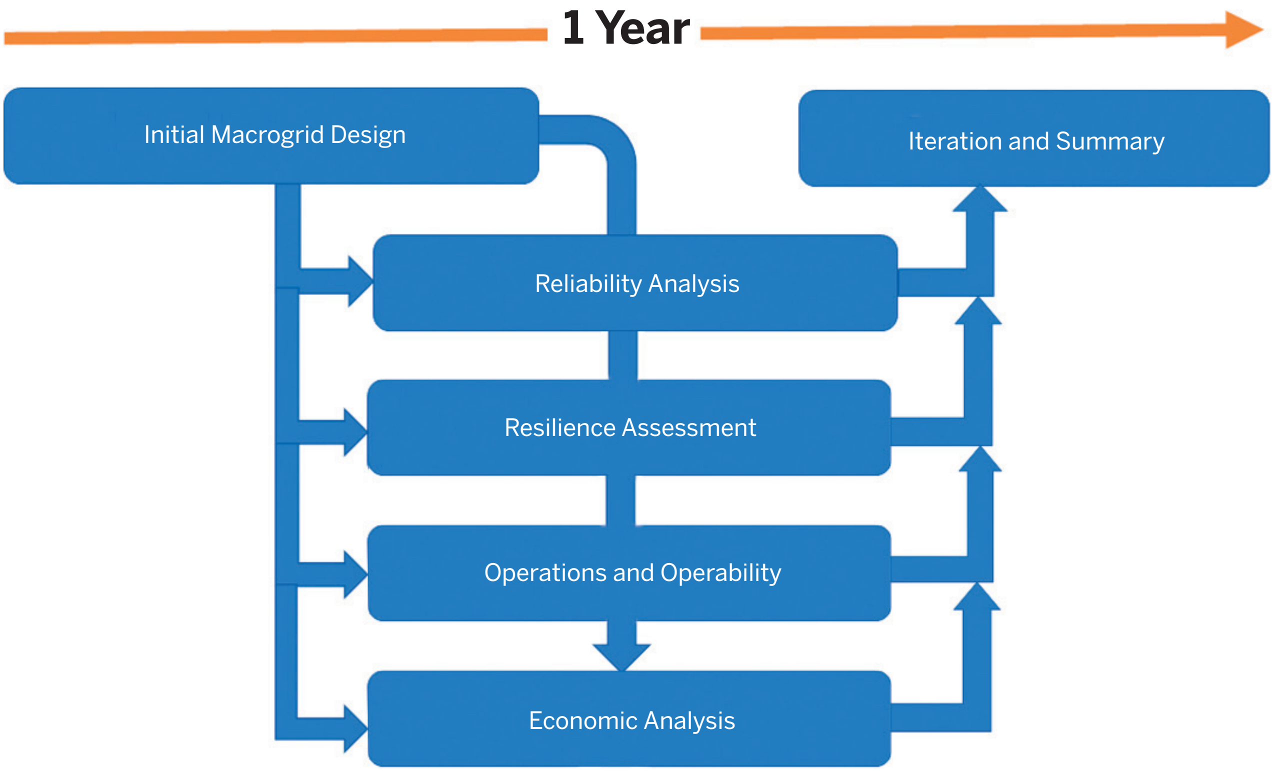
Project Oversight and Administration

ESIG is responsible for overall management of the scope development, and it will convene a Transmission Planning Task Force to provide technical oversight and guidance throughout the course of the activities. EnerNex will lead the task force and serve as project manager.

Study Project Team(s) Requirements

There are a number of important initial considerations. For example, one pillar in the initial macrogrid design and possibly in other study elements is the ability to run a national-scale production simulation at a minimum of hourly resolution for one or more annual periods. To build this model from scratch would be a very significant effort that could jeopardize the desired schedule. Through their involvement in previous studies, both the National Renewable Energy Laboratory and Vibrant Clean Energy possess excellent starting points for this effort in terms of the required national-scale model, renewable resource profiles, computing infrastructure, and software expertise. How best to make use of these existing capabilities along with outside contractors, and the impact on project budget and schedule, will need to be worked out.

FIGURE 3
Conceptual Staging of Study Elements and Relationships



Source: Energy Systems Integration Group.

Developing Detailed Scopes of Work for Individual Studies

The previous section provided general descriptions of the individual study elements that comprise the macrogrid design effort. The critical preliminary step will be to expand the detail for each of the study elements so that qualified contractors can prepare proposals for conducting the work.

To arrive at the full study work scopes, a team of expert ESIG members and advisors will develop individual work scopes to be used in requests for proposals soliciting qualified contractors who will perform the individual studies. This process will be aided by review and guidance from the ESIG Transmission Planning Task Force.

Schedule

Detailed work scopes will be ready within two months of initiating this effort.

Scope Development for Macrogrid Design Studies

This scoping document is available at https://www.esig.energy/reports-briefs.

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, particularly with respect to clean energy. More information is available at https://www.esig.energy or info@esig.energy.

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