Transmission Planning for **100% Clean Electricity**

A TECHNICAL BRIEF FROM ESIG

Achieving a Decarbonized Electricity System

To meet clean energy goals set by businesses and governments at the local, state, and federal levels, the country's generating capacity will need to double, with at least 1 terawatt of new wind and solar necessary to reach 100 percent clean electricity by 2035. A network of cross-country transmission is critical to minimizing cost and maximizing flexibility. Transmission provides a variety of benefits at a relatively low cost—enabling deliverability of resources to load, providing resource and load diversity to help balance the system and contribute to resource adequacy, providing access to reliability services such as frequency response, supporting both steady state and dynamic stability of the grid, and reducing overall system costs by connecting regions of high demand with high supply and reducing congestion.

ESIG synthesized key research studies investigating energy sector decarbonization and developed a conceptual design for reaching the United States' clean energy goals using proactive transmission planning and development. This technical brief outlines ESIG's recommendations and summarizes engineering analyses that will be needed to refine the design and support the construction of the U.S. macro grid. The white paper, "Transmission Planning for 100% Clean Electricity," can be found at https://www.esig.energy/transmission-planning-for-100-clean-electricity/.

ESIG's Recommendations for Moving Toward a National Macro Grid

The first component of ESIG's recommendations is the creation of a national transmission planning authority. It will develop the initial set of conceptual and engineering power system analyses in consultation with a broad suite of stakeholders and experts, and will work with regional authorities and others to facilitate the construction of successive stages of the macro grid. The second component is the identification of renewable energy zones that can support major levels of wind or solar development concentrated in favorable locations for which transmission can be proactively planned.

The third component is the design and construction of the macro grid. The initial design will require detailed engineering studies and an ongoing process to annually or biennially review system performance and generation interconnection queues, assess and adjust for significant technology changes, and make course corrections.

Stage 1 is the completion of approval and construction of individual high-voltage direct current (HVDC) transmission between most of the stage 1 transmission hubs (yellow dots in the figure). Several proposed transmission lines also offer promising routes and technologies for the macro grid (in blue). Stage 2 expands the bulk electricity transmission system, with regional collector systems uniting the stage 1 lines and being developed offshore in the Atlantic, in the southern United States, and in the central United States wind belt. Additional paths and expansion could follow.

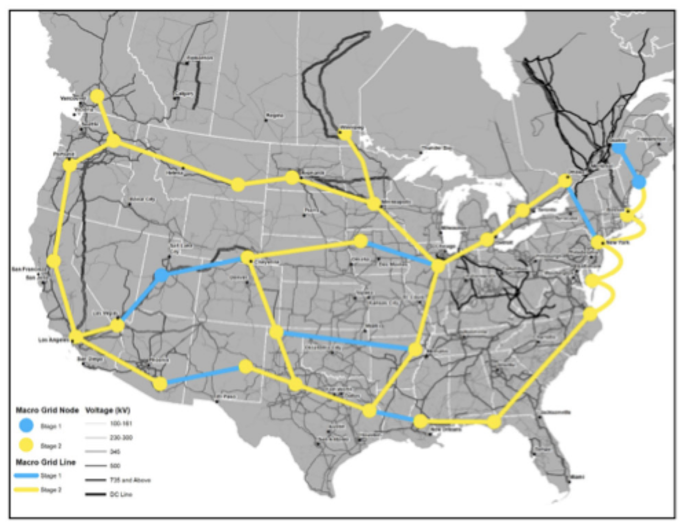

***Figure:** ESIG's conceptual design for a U.S. macro grid laid over the existing electricity transmission system.*

Engineering Studies Needed for the Development of the Macro Grid

High-level Resource and Transmission Planning

Capacity expansion modeling, which outputs size and location of generation/storage resources and transfer capabilities, will be needed for each stage of the macro grid's planning and construction to determine least-cost resource and transmission plans. Hub locations may be adjusted, and very long high-voltage alternating current (HVAC) transfers may be changed to HVDC for economic reasons. The plans will be tested for operability with nodal, five-minute interval production simulation analysis with load flows to ensure both that load is met and essential reliability services are provided.

Resource adequacy modeling will be used to examine loss of load risk, ensure that the system can meet long-term reliability metrics, and assess extreme weather risks. Given the climatic changes underway, models should use as many weather years as possible and incorporate changes in weather patterns due to climate change.

Feasibility Studies

Following the identification of the hubs' locations, the path ratings of new or expanded lines, and the locations of new resources likely to be developed, the integration of the macro grid hubs into AC systems should leverage capabilities of those networks; it should not impose burdens or require significant AC system expansion to support contingencies on parallel HVDC elements as that network is built out. Grid-enhancing technologies will need to be leveraged to manage flows and congestion on the underlying AC systems during the macro grid build-out.

Engineering and related feasibility studies will determine technology (AC vs. DC; line commutated converter vs. voltage source converter (LCC vs. 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 also 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 others (relaying, protection, etc.).

Potential routing for transmission corridors will be identified and hub locations refined given the size of the facilities and potential right-of-way options given 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.

Equipment Specifications

Once facilities and their locations and ratings have been identified and the cost/benefit ratio determined to be favorable, design specifications for the facilities are needed. This will include the necessary services and capabilities (e.g., frequency control, black start), transmission cable and towers, substation gear, and protection systems.

Stability Studies

In addition to the operability analysis, steady state and dynamic stability will need to be evaluated for normal operation and for disturbances. For frequency stability, stressed conditions to be studied include periods of low inertia or low levels of resources that provide frequency response. For transient stability, this includes high flows on key paths. Commitment and dispatch results from production simulations, including the retirement of large synchronous generators, will be screened to identify these stressed conditions for testing in stability modeling.
To evaluate the dynamic stability of this system with high levels of inverter-based resources, positive sequence tools (e.g., PSLF, PSSE) may be used under some conditions, and electromagnetic transient (EMT) analysis will be needed to assess stability in weak grids, control interactions, and other phenomena.

- Traditional power flow analysis will be needed to check the performance of the system in steady state in meeting thermal and voltage criteria for up to N-x contingencies. This step is conducted first and remediation performed before examining dynamic stability.
- Transient stability analysis will check the first swing stability of the system if there is a disturbance. In this expanded grid, many new disturbances will need to be examined. The system must meet all stability, transient damping, and dynamic voltage sag criteria for up to N-x contingencies.
- Small signal (eigenvalue) analysis will check the system for adequate damping of oscillations that may be triggered by a disturbance.
- EMT modeling will evaluate fast control stability, a potential issue due to interactions of fast regulators of renewable converters.
- Given that some fraction of the new inverter-based resources on the grid will provide fast frequency response or primary frequency response to assist with recovery from large contingency events, analysis of frequency response will include deliverability of frequency response services.

A key input to this set of studies will be assumptions regarding grid-forming inverter technology. While this technology will likely be widely commercially available in the future, it is not yet clear how the inverters will be designed. These studies will need to be done in concert with manufacturers in order to have the best inverter models for the simulations.

Finally, operational planning studies will be critically important to manage reliability and security during the macro grid build-out to ensure that reliability standards are met over the planning horizon with a focus on near-term needs. These studies should capitalize on grid-enhancing technologies to minimize curtailments and improve grid deliveries as well as utilization rates without degrading system security.

This technical brief is available at https://www.esig.energy/reports-briefs/.

The Energy Systems Integration Group is a non-profit 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.