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# Macro Grids in the Mainstream: An International Survey of Plans and Progress

Sponsored by Americans for a Clean  
Energy Grid as part of the Macro Grid  
Initiative



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# About Us.

## Americans for a Clean Energy Grid

Americans for a Clean Energy Grid (ACEG) is the only non-profit broadbased public interest advocacy coalition focused on the need to expand, integrate, and modernize the North American high voltage grid.

Expanded high voltage transmission will make America's electric grid more affordable, reliable, and sustainable and allow America to tap all economic energy resources, overcome system management challenges, and create thousands of well-compensated jobs. But an insular, outdated and often short-sighted regional transmission planning and permitting system stands in the way of achieving those goals.

ACEG brings together the diverse support for an expanded and modernized grid from business, labor, consumer and environmental groups, and other transmission supporters to educate policymakers and key opinion leaders to support policy which recognizes the benefits of a robust transmission grid.

## Macro Grid Initiative

The Macro Grid Initiative is a joint effort of the American Council on Renewable Energy and Americans for a Clean Energy Grid to promote investment in a 21st century transmission infrastructure that enhances reliability, improves efficiency and delivers more low-cost clean energy. The Initiative works closely with the American Wind Energy Association, the Solar Energy Industries Association, the Advanced Power Alliance and the Clean Grid Alliance to advance our shared goals.

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# Executive Summary

This report addresses interregional transmission and Macro Grids, to illuminate the value of developing transmission systems of this kind in the US. By interregional transmission, we mean transmission between two or more distinct geographical regions that are otherwise planned and operated separately, or between two or more distinct geographical regions that are separated by significant distance. By Macro Grids, we mean a network of interregional transmission lines, generally expansive in geographical scope. People have also used supergrids as an alternative to Macro Grids, both of which are used interchangeably throughout this report. The interest in interregional transmission and Macro Grids has grown worldwide, on every continent, because there is strong perception the benefits it provides are of high economic value and significantly outweigh the costs of providing it. The fact that interregional transmission and Macro Grids are of worldwide interest leads to the purpose of this report, which is to inform the US energy policy and engineering communities of answers to the following four questions:

(i) **Worldwide summary:** To what extent are the various regions of the world studying, planning, and building interregional transmission and Macro Grids?

(ii) **Benefits, costs, and characteristics for successful implementation:** What is the perception of interregional transmission and Macro Grids around the globe in terms of perceived benefits, costs, and characteristics for successful implementation?

(iii) **Engineering design:** What basic steps are necessary in order to motivate and perform an engineering design of interregional transmission or a Macro Grid?

(iv) **Consolidating and coordinating mechanism:** What potential consolidating and coordinating mechanisms are

necessary to accomplish an interregional transmission project in the U.S.?

In the US, the power industry evolved with hundreds of utilities that were vertical siloes of local generation serving local load. Regional institutions have only been added in this century and have barely begun to pursue interregional transmission between them. Interregional transmission was a job that was never clearly assigned to FERC, DOE, or any other entity. It is time for the change.

The following are some key messages resulting from this report:

- Macro Grids and high-voltage interregional transmission connections are either already in place, under development or being considered almost everywhere in the world.
- China has recently completed five times more high-voltage interregional transmission than Europe, and over 80 times more than the U.S.
- The European Union is planning and building high-voltage transmission to support the development of offshore wind in the northern seas.
- The U.S. should review its policies to address current challenges to interregional transmission and Macro Grid development.
- The same physics and economics generally apply everywhere, so Macro Grid development is a natural and unsurprising next stage of electric industry evolution. Reserve sharing and diversity has always been a feature of power systems but it is becoming much more pronounced given weather-driven (wind/solar) resource reliance.

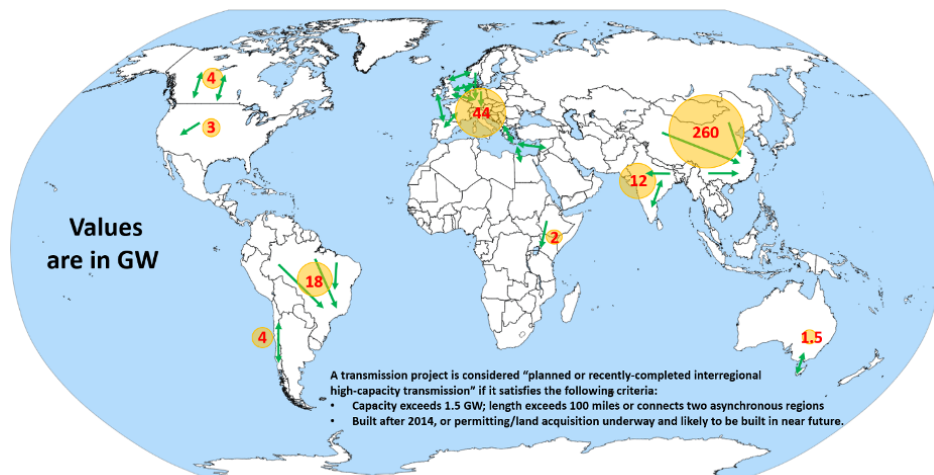
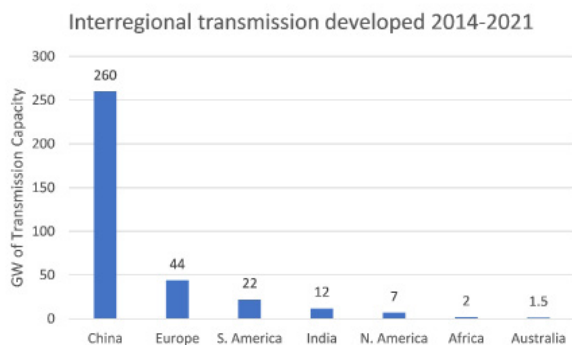


Figure 1: Total capacity of planned or recently-completed interregional transmission projects

## Worldwide Summary

The worldwide interest is indicated in Figure 1, which shows for each area of the world the amount of interregional transmission capacity that has been built since 2014 or is likely to be built in the near future based on the extent to which permitting and land acquisition is underway. These numbers are also visualized in the bar chart below. As Figure 1 demonstrates, significant interregional lines are planned or under development in Asia and Europe, which are expected to result in significant economic growth, job creation, and carbon emission reductions. In contrast, North America lags behind all other regions, with the exception of Australia and Africa, in developing interregional lines to integrate the lowest cost clear energy resources.



Several groups in the US have recently conducted studies to explore the benefits of interregional transmission and Macro Grids. Of these, the US Interconnections Seam Study, led by the National Renewable Energy Laboratory, has generated significant interest by proposing a Macro Grid that spans most of the US, but if extended into Canada and Mexico would be continental. Groups around the globe have conducted

continental studies for other areas. Figure 2 illustrates an aggregation of the topologies resulting from many of these studies. Most of these studies represent visions rather than projects in advanced stages of development.

Salient features of some of the worldwide designs are summarized in what follows.

## North America

Of the four nations comprising North America, the US stands out because of its geographical centrality and size, its high electricity consumption, the benefits likely to accrue from interregional transmission development, and the fact that it has both north-south and east-west opportunities that appear attractive. In regard to the characteristics necessary for successful development of interregional transmission, there is both precedent and existing features that suggest they are largely in place. The seven RTOs of today provide a regional force having no profit motivation, trusted for their knowledge and experience, providing a familiar and collaborative environment within which entities may engage and negotiate. The Federal Energy Regulatory Commission (FERC) and the Department of Energy (DOE), represent federal capability that could have significant influence on developing interregional transmission should federal policy swing in that direction. Indeed, FERC Order 1000 [8] already requires RTOs to consider interregional transmission, and the DOE has a track record which includes establishing successful collaborative mechanisms.

## Europe

Europe has an ambitious goal of achieving climate neutrality by 2050. The integration of offshore wind resources - especially in the Northern Seas (North Sea, Irish Sea, Baltic Sea,

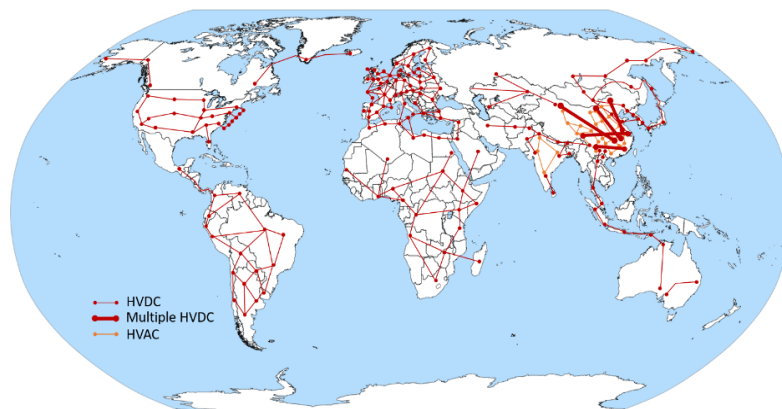


Figure 2: Global aggregation of Macro Grid designs

English Channel, and neighboring waters) - and the solar resource in southern Europe will rely on the development of a more interconnected European power system via high voltage transmission. A supergrid enabled by multi-terminal offshore hubs or potential energy islands in the North Sea is of particular interest. Cross-border interconnections have also been proposed for better sharing of resource and capacities. Major examples include the interconnectors between UK and Norway, UK and Denmark, UK and Continental Europe, and those between Spain and France. Important intra-state transmissions include the north-south HVDC links in Germany. Ultimately, these separated HVDC links and the regional supergrid such as that proposed for the North Sea region could be integrated into a European supergrid interconnecting the whole of Europe and neighboring countries. Yet, Europe faces unique challenges. For example, resistance due to weak historical relationships between some nations hinders the development of cross-border interconnections. Financial structures vary from one nation to another, and this increases uncertainty around cost allocation and cost recovery. Although the European Commission has some centralized power, it is limited in the extent to which it can facilitate development. Economic incentives are also weak for developing some lines, e.g., the German north-south transmission projects, due in part to the lack of a centralized market operator in much of Europe.

## China and Northeast Asia

China has made great progress in the development of ultra-high voltage (UHV) transmission. The developed UHV-DC interconnections generally follow north to south and west to east patterns, aiming to enable access to the low-cost, rich wind and solar resources of the remote areas to the major load centers. As a result, decarbonization cost is greatly reduced and environmental benefits are achieved with significant reduction in CO<sub>2</sub> emissions. The idea of an “Asian Super Grid,” if implemented, would allow the major load centers in northeast China, Korea, and Japan to access the massive amount of solar resource in the Gobi desert and the hydro resource in the Russian Far East.

## India and South Asia, Southeast Asia, and Australia

Development and integration of cost-effective renewable energy resources are driving interregional transmission development in South Asia, Southeast Asia and Australia. In India, two major existing and near-term planned UHV-DC corridors are the northwest to north central for integration of northwestern hydro resources, and the north-south corridor for sharing wind resources in the south. The interconnection between South and Central Asia is being strengthened, linking Pakistan with Central Asian countries Tajikistan, Kyrgyzstan, and Afghanistan for inter-seasonal resource sharing. For Southeast Asia, cross-border interconnectors are being developed in ASEAN countries (Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam) with an expected total capacity of 39 GW. Motivated by mitigating high pool prices and a desire to improve grid reliability, a trans-Australia HVDC line was proposed between Queensland and South Australia. One major ongoing project is the Marinus link which would be the second interconnection between Tasmania and mainland Australia, improving the grid reliability. An “ASEAN-Australia Supergrid” has received great interest, which would allow ASEAN countries to benefit from the low-cost solar resources in the northern part of Australia.

## Russia

Russia has not been active in planning and developing new interregional transmission lines because the current network is overbuilt, which was planned and mostly constructed in the Soviet times under a very optimistic economic forecast. With the economic collapse of the 1990’s and the “digitalization” of society, electricity demand has been increasing very slowly and does not justify the development of additional transmission. However, studies have been performed to evaluate the potential opportunities to interconnect Russia with Eastern Europe and northeast Asia for large scale sharing of renewable resources.

Yet, these studies are still at a conceptual stage.

## Africa

Although currently in a position with unreliable power supply and a generation mix dominated by the expensive oil-fired or diesel generation, Africa has huge potential for the development of renewable resources, for example, the huge solar potential in the Sahara desert of North Africa and a massive hydro resource along the Congo River in central Africa. Interregional high capacity transmission would be vital to facilitate the integration of these large scale renewable resources and reduce the cost of energy. A 100% renewable scenario has been shown to be technically and economically feasible for sub-Saharan Africa with the design of a continental HVDC overlay.

## Central and South America

Central American countries are interconnected via a 230kV AC system, whereas the countries in South America are currently operated with very few transnational interconnections. Central and South America have abundant renewable resources. For example, the Atacama Desert in Chile is rich in solar, and the northern coasts of Colombia and Venezuela are rich in wind. Other regions such as the Orinoco, Caroni, and Caura river basins in Venezuela and northern Brazil enjoy abundant hydro resources. Brazil has been actively developing interregional transmission within the country for hydropower integration, and more recently, for wind integration from the northeast. Chile also has near-term proposals to develop more interregional transmission within the country to harness the huge solar potential in the north.

## Benefits and Costs

Benefits associated with interregional transmission and Macro Grids include cost reduction via sharing; economic development; improved reliability; enhanced resilience and adaptability; increased renewable levels; and lowered cost of reducing emissions. Of these, the first and second represent direct economic benefits. The first benefit, cost reduction via sharing, results from the ability to share energy, flexibility services (i.e., reserves related to regulation, contingency, and ramping), and peaking capacity between regions.

The second benefit, economic development, occurs because cost reductions are reflected in savings ultimately passed on to electricity consumers raising the competitiveness of the commercial and industrial sectors while enabling increased household spending. In addition, interregional transmission stimulates infrastructure development in the form of new

supply resources. This infrastructure development provides lease payments to landowners, increases property tax revenues, and creates jobs, all of which are significant for both local and national economies. Economic development of this nature is will be increasingly important as nations around the globe grapple with ways to offset the economic impacts of the COVID-19 pandemic.

The third and fourth benefits, improved reliability, resilience, and adaptability, enhance the grid's ability to continue performing well under conditions where the power system is exposed to unexpected conditions. The fifth benefit results in the ability to integrate increased levels of renewable resources. The last benefit, lowered cost of reducing emissions, applies to the so-called criteria pollutants (carbon monoxide, lead, ground-level ozone, particular matter, nitrogen dioxide, and sulfur dioxide) and carbon dioxide (CO<sub>2</sub>).

The main costs associated with developing interregional transmission and Macro Grids are transmission line costs (including public outreach, regulatory approval, and permitting) and substation costs (including the cost of converter stations for HVDC). Of these costs, it is typical for interregional transmission to incur more line costs per GW-mile for public outreach, regulatory approval, and land owner negotiations. In the US, the amount of time required to plan and build interregional transmission is long, ranging from 7.5 years to as much as 13 years, and the overall process is complex, with many uncertainties that create high risk of increased project cost and of premature termination. This increased risk creates disincentives for organizations to initiate interregional transmission projects; such risk can be reduced by simplifying and shortening these processes.

## Characteristics for Successful Implementation

There are three overriding characteristics that facilitate the successful development interregional transmission: (1) consensus to develop; (2) approach to fund; and (3) public support.

A consensus to develop requires establishing a consensus strategy while defining the strategic values of the project to each participant and identifying those who will likely support the project and those likely to oppose it. There are at least five ways to fund interregional transmission projects: a merchant-driven investment; utility-group approach; a government initiative; a multiregional coordination; and a hybrid approach. The third characteristic for successful implementation is public support, which requires intentional and dedicated outreach to

stakeholders using various communication and engagement methods to facilitate two-way participatory dialogue about the need for and impacts of a proposed transmission project.

## Engineering Design

An interregional transmission design should take advantage of the strengths of both AC and DC technologies, combining AC in doing what AC does best with DC in doing what DC does best. AC excels in local collection of resources because it provides what might be called “on-ramps” within an AC transmission network at relatively low cost via AC substations. DC transmission is capable of moving power very long distances with low losses, making it economically attractive to move energy, ancillary services, and capacity from a region where it is low-priced to other regions where they are high-priced. Ultimately, technology choices for interregional transmission focus on four main issues: (1) whether the line needs to be underground or underwater; (2) the transmission distance; (3) the effect of losses; and (4) whether the transmission will span two or more asynchronous grids. There are four central steps to take in designing interregional transmission or Macro Grids: techno-economic design; resource adequacy evaluation; contingency analysis and control design; and resilience and adaptability evaluation. Although additional steps are necessary before construction, these four steps enable quantification of a project’s benefits.

## A 21st Century Vision

We provide a hypothetical vision of a potential option; this vision has not been studied and is offered to provide a sense of what a Macro Grid network might look like for the US. Further study is needed.

We imagine an HVDC Macro Grid spanning the continental US from the Atlantic seaboard to the Pacific coast, and from

Florida, the Gulf coast, and Southern California northwards to Canadian border, with the easternmost north-south link in the Atlantic serving the region’s offshore wind. Figure 3 illustrates this vision.

The overall HVDC grid could offer an attractive benefit-to-cost ratio for an eventual integration of over large amount of renewable capacity. Much of the benefit is driven by annual load diversity which allows shared capacity and significantly reduces what individual regions would have to build otherwise. CO2 emissions in the power sector are a small fraction of their 2020 levels. Retail electricity prices will drop by several percent throughout the country.

In our hypothetical scenario, the Macro Grid was designed by a multiregional collaborative stakeholder group comprised mainly of experts from the RTOs with vendors and consultants hired where appropriate; a sister organization consisted of representatives from each state’s regulatory body. Development and construction of this system was funded by merchants, utilities, state governments, and the Federal government.

Merchant and utility developers were incentivized to build consistent with design and competed for links based on long-term planning auctions. Federal government supported what merchant developers would not build while intimately coordinating with local government and industry. Routes utilized existing rail, highway, and transmission line rights-of-way as much as possible, but where siting issues arose, underground designs were used.

The HVDC national grid operator controls the HVDC network. RTOs retain regional control of the AC network. Power generally flows west-to-east and south-to-north during daytime hours and reverses these directions during nighttime hours. The system is self-contingent, i.e., its operational rules provide flow limits in each link which enable operating within all limits while safely withstanding loss of any one link.

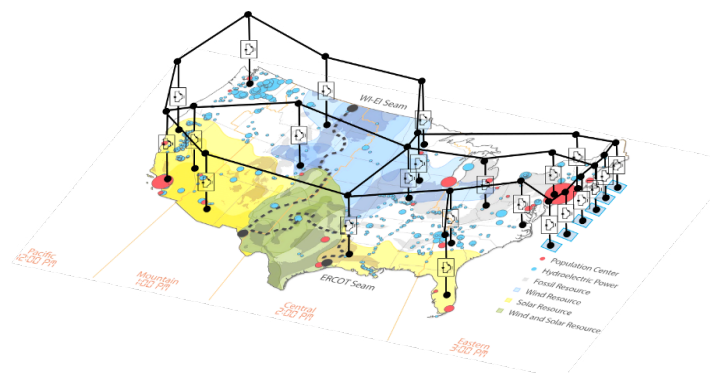
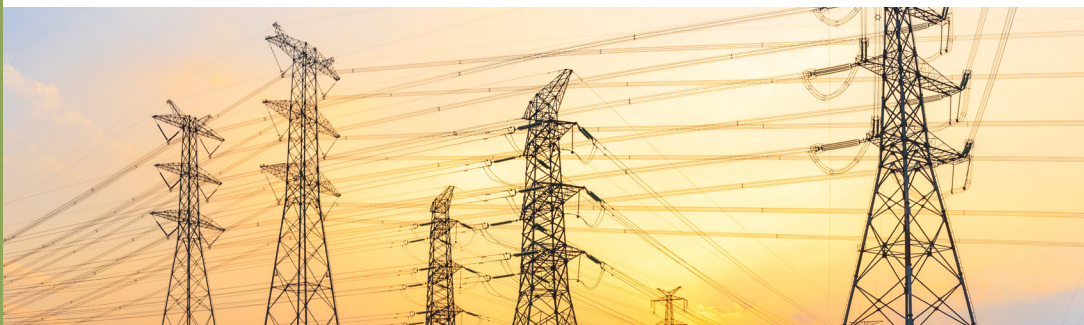


Figure 3: A 21st century vision (underlying US map adapted from [1])



# 01



## Introduction

The electric transmission system in the US has grown over the last century to over 600,000 circuit-miles at voltage levels from 69kV-765kV, comprising three interconnections: Eastern Interconnection (EI), Western Interconnection (WI), and the Electric Reliability Council of Texas (ERCOT). This transmission system is owned by hundreds of private, public, cooperative, and federal entities. The United States has a more diverse ownership of transmission than other countries. There is no federal coordination or approval associated with transmission siting, which is regulated by the states using a variety of approaches. There is no uniform nor clear path forward in the development of interregional transmission between the states. Interregional transmission beyond the borders of the United States requires treaties well beyond the rights and authorities of any State or private entity. Yet, interregional transmission can play a critically important role in delivering least-cost energy, maintaining reliability, and responding to natural disasters.

The need for interregional transmission has only deepened over the past 20 years as wind and solar penetrations have grown, much of which has been located distant from both load centers and existing thermal power plants, motivating the need for additional transmission capacity to move these resources to load. This need has converged with observations that interregional transmission brings benefits associated with energy and reserve sharing, together with reliability, resilience, and adaptability, resulting in a number of US-centric studies that have highlighted these various benefits.

For example, an early study, called the Eastern Wind Integration and Transmission Study (EWITS) assessed the value of high capacity, long-distance transmission connecting the Midwestern US to the East Coast, resulting in the following conclusions [2]:

- “Transmission helps reduce the impacts of the variability of the wind, which reduces wind integration costs, increases reliability of the electrical grid, and helps make more efficient use of the available generation resources. Although costs for aggressive expansions of the existing grid are significant, they make up a relatively small portion of the total annualized costs in any of the scenarios studied.” This point was illustrated in [2] via Figure 4, where the transmission portion of the total system annualized cost is the third segment down in each bar, where each bar corresponds to a particular interregional transmission design between the Midwestern US and the East Coast.
- “The study results show that long-distance (and high-capacity) transmission can assist smaller balancing areas with wind integration, allowing penetration levels that would

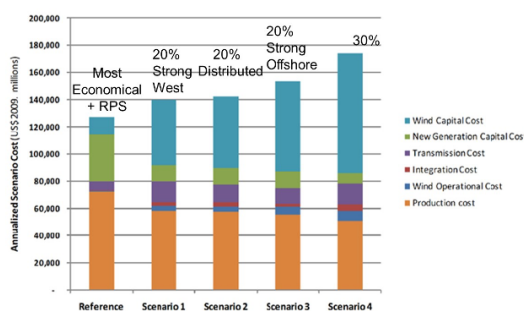


Figure 4: Comparison of annualized cost breakdown across five transmission design scenarios [2]

not otherwise be feasible. Long-distance transmission, along with assumed modifications to market and system operations, contributes substantially to integrating large amounts of wind

that local systems would have difficulty managing. In addition, long-distance transmission has other value in terms of system robustness that was not completely evaluated in EWITS.”

- “This and other recent studies ... reinforce the concept that large operating areas—in terms of load, generating units, and geography—combined with adequate transmission, are the most effective measures for managing wind generation.”
- “Wind generation can contribute to system adequacy, and additional transmission can enhance that contribution.”

A number of other US studies have been made since EWITS, all resulting in similar conclusions; a subset of those studies include [3, 4, 5, 6]. Of particular significance, the MidContinent Independent System Operator (MISO) reported on a nationwide HVDC network design in their MISO Transmission Expansion Plan (MTEP) of 2014, concluding that the HVDC network captures a number of benefits, including load, wind, and solar diversity, frequency response, reserve pooling, and energy arbitrage [7].

## 1.1 Terminology

It is useful to clarify terminology. The EWITS study used the term “long-distance transmission,” sometimes modified by the term “high capacity.” The above statement of purpose for this report uses the term “interregional transmission,” also used by FERC Order 1000 [8], a term we prefer and will use heavily throughout the report, to mean, similar to the EWITS study, transmission between two or more distinct geographical regions that are otherwise planned and operated separately, or between two or more distinct geographical regions that are separated by significant distance. We generally think of “significant distance” as hundreds of miles, or more. This definition is also similar to that used by the California Independent System Operator [9], which is “...a proposed new transmission project that would directly interconnect electronically<sup>1</sup> to existing or planned transmission facilities in two or more Planning Regions.”

We also address “Macro Grids” in this report, which we define as a network of interregional transmission lines. We observe that transmission circuits may satisfy the definition of interregional transmission but not that of a Macro Grid. The terms “overlay” and “supergrid” have also been used to denote networks of interregional transmission, although the difference is slight and generally only one of scale with “supergrid” suggesting a network that is geographically more expansive, possibly intercontinental.

<sup>1</sup> It is likely that this word “electronically” should be “electrically.”

Finally, we need to distinguish geopolitical entities as they exist in the electric power industry, since interregional transmission is a geopolitical issue. From the smallest to the largest the geopolitical entities are cities, counties, major utility service territories, Native American tribes, public utility commissions, state agencies, multi-state governmental associations, system operators, reliability coordinators, regional planning entities, Interconnections, Nations, and International Areas. For purposes of this report, we have divided the world into seven areas: North America; Europe; China and Northeast Asia; India and South Asia, Southeast Asia, and Australia; Russia; Africa; and Central and South America. Each of these areas are comprised of multiple regions between which interregional transmission may exist. Interregional transmission may also exist between areas, but such would generally tend to appear as an inter-continental supergrid.

## 1.2 Purpose of Report

The fact that wind and solar growth is a worldwide phenomenon leads to the purpose of this report, which is to inform the US foreign and domestic energy policy as well as the engineering communities of our response to the following four questions:

- (i) Worldwide summary: To what extent are the various regions of the world studying, planning, and building interregional transmission and Macro Grids?
- (ii) Benefits, costs, and characteristics for successful implementation: What is the perception of interregional transmission and Macro Grids around the globe in terms of perceived benefits, costs, and characteristics for successful implementation?
- (iii) Engineering design: What basic steps are necessary in order to motivate and perform an engineering design of interregional transmission or a Macro Grid?
- (iv) Consolidating and coordinating mechanism: What potential consolidating and coordinating mechanisms are necessary to accomplish an interregional transmission project in the U.S.?

## 1.3 Approach Used in Developing this Report

We have followed a three-step process in developing this report. In step 1, we gathered information from personal knowledge and experience, review of publicly available resources,

and particularly for areas outside of North America, e-mail correspondences and internet interviews with individuals known to have high levels of expertise in each area of interest. These correspondences and interviews were highly informative in regard to characterizing each of the various areas of the world. In step 2, we developed an initial draft of the report. In step 3, we obtained reviews from specific individuals experts in the area addressed by the portion of the report they reviewed. With their permission, these individuals are identified in this section together with the portion of the report that they reviewed.

## 1.4 Acknowledgement

We first and foremost acknowledge the financial support of the Americans for a Clean Energy Grid for making this report possible and particularly its Executive Director Rob Gramlich whose vision initiated this work and whose guidance significantly enhanced its substance and quality. Likewise, James Hewitt of David Gardiner and Associates, and Jay Caspary of Grid Strategies, LLC, both provided extremely

helpful comments on the work. We also acknowledge the reviewers of various sections as listed in Table 1 below. These comments were extensive and provided expanded perspective to the work described herein.

We also acknowledge a number of people who were instrumental in providing initial information and/or connecting us with individuals who could serve as effective reviewers.

## 1.5 Organization of Report

The report is organized as follows. Section 1 outlines the content of the report. Section 2 describes benefits and costs of interregional transmission. Section 3 identifies the characteristics of an area that are essential for successful development of interregional transmission. Section 4 summarizes studies, plans, and developments of interregional transmission for seven areas of the world. Section 5 overviews technologies and engineering design methods for interregional transmission. Section 6 provides conclusions

**Table 1: Summary of Report Reviewers**

Section Number	Section Title	Reviewer Name and Affiliation
Executive summary and 1-6	Entire report	Rob Gramlich, Grid Strategies LLC Jay Caspary, Grid Strategies LLC James Hewett, David Gardiner & Associates
1	Introduction	Robert Schulte, Schulte Associates LLC
2	Cost and benefits	Fred Fletcher, Power from the Prairie LLC
3	Characteristics for successful development	Will Kaul, Retired, formerly of Great River Energy, WI
5	Interregional transmission design	Marcelo Elizondo, Pacific Northwest National Laboratory Larry Pearce, Governors Wind and Solar Coalition Dale Osborn, Retired, formerly of MISO
4.1.1	United States	Josh Novacheck, National Renewable Energy Laboratory
4.1.2	Canada and Greenland	Anonymous*
4.1.3	Mexico	Abner Ramirez, Center for Research and Advanced Studies of Mexico

Table 1: Summary of Report Reviewers

4.2	Europe	Mike Hogan, The Regulatory Assistance Project Antje Orths, Energinet, Denmark Anonymous*
4.3	China & Northeast Asia	Anonymous*
4.4.1	India and South Asia	Ranjit Deshmukh, Lawrence Berkeley National Lab
4.4.2	Southeast Asia	Saad Mekhilef, Tofael Ahmed, Chittagong University of Engineering & Technology, Bangladesh
4.4.3	Australia	Zhaoyang Dong, University of New South Wales, Sydney
4.5	Russia	Andrey Churkin, Skolkovo Institute of Science and Technology, Moscow, Russia.
4.6	Africa	Christian Breyer, Lappeenranta University of Technology, Lahti, Finland
4.7	Central and South America	Lizbeth Gonzalez Marciaga, National Dispatch Center, Panama Albert Melo, Center for Energy Research (Cepel) and Rio de Janeiro State University (UERJ), Brazil Esteban Gil, Universidad Técnica Federico Santa María, Chile Santiago Lemos-Cano, Celsia, Medellin, Colombia

\* "Anonymous" indicates the reviewer provided review comments for the indicated section but did not want their name revealed in the report.

# 02

## Benefits and Costs of Interregional Transmission

As captured in Sections 2.1.1-2.1.6, there are six main benefits that motivate interregional transmission: cost-reduction via sharing; economic development; improved reliability; enhanced resilience and adaptability; higher renewable levels; and lowered cost of reducing emissions. There are three main types of costs associated with interregional transmission, as described in Section 2.2. The various benefits and costs are illustrated in Figure 5.

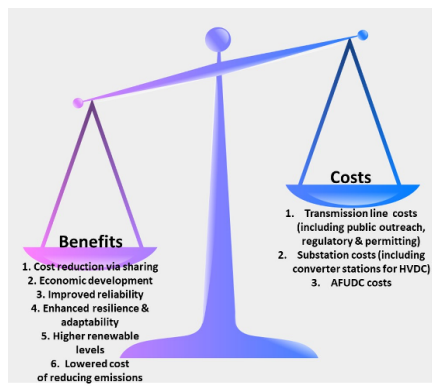


Figure 5: Benefits and Costs of Interregional Transmission and Macro Grids

### 2.1 Benefits

#### 2.1.1 Benefit 1: Electric Services Cost Reduction via Sharing

Interregional transmission enables sharing of resources between the connected regions. Such sharing results in attractive economies made possible by diversity in what,

where, and when resources are utilized. These economies are available under any resource mix but become especially prominent for portfolios having large renewable presence.

#### What: Resource Diversity

Resource diversity motivates interregional transmission to obtain preferred (less expensive and/or environmentally cleaner) energy, flexibility reserves (i.e., ancillary services), and contingency reserves. Doing so reduces costs and price volatility.

#### Energy swaps

Two regions may have differences in their energy-producing portfolios so that the strengths of one region's energy-producing resources complement the strengths of the other's. One region may have a rich nighttime-dominant wind resource whereas another region may have a rich solar resource; or one region may have an abundance of high-quality renewable resources, and another region may have very little. Swaps of diverse resources can address over-generation issues (where wind and/or solar generation do not match customer load patterns) while sharing the benefits of renewables investment between both regions. A region's ability to utilize another region's richest energy-producing resources may enable avoidance of using (and possibly building) more costly alternative intraregional resources by using (and possibly building) excess resources in the other region. Two good examples of this include the Midwestern US, with its rich wind resource, and the Southwestern US, with its rich solar resource; and the North Sea, with its rich wind resource, and Northern Africa, Italy, and Spain, with its rich solar resource [10]. Examples of when interregional transmission enables a region to have access to resources not otherwise accessible

is a UK-to-Iceland connection that would enable UK to benefit from Icelandic geothermal; or a Midwest US to Southeast US connection that would enable the Southeast US to benefit from Midwestern wind.

#### *Sharing of flexibility and contingency reserves*

The need for flexibility (regulation and ramping) reserves generally grows with increased wind and solar penetrations. Contingency reserves are usually set to be sufficient for loss of the largest unit in the system. These needs are met by paying resources to reserve such capabilities; typically, such resources are intraregional, considered prudent if the deliverability of resources is uncertain due to frequent congestion in existing interregional interconnections. Additional interregional transmission typically relieves congestion and so offers increased ability to share such resources.

This provides attractive economies by enabling use of the least-cost resources across both regions and deferring or avoiding new investments in resource-deficient regions. The ability to relieve congestion and increase competition via HVDC interconnections has been a strong motivator in considering a European supergrid [159]. Increased competition and cross-border trades lead to lower energy prices [11]. In addition, the need for reserves can be reduced, leading to reduced costs and emissions. For example, the European Climate Foundation Roadmap 2050 report found that increased interconnection could limit the utilization rate of back-up plants to 5% in an 80% renewable energy scenario, and reduce the total reserve requirements by 35-40%. E3G estimated that this could save €34.3 billion in backup generation across Europe [12].

#### **Where: Weather (Geographical) Diversity**

Variability of wind and solar resources, as a percentage of their installed capacity, decreases with increasing geographical diversity of the wind and solar. This is because wind and solar resources that are widely distributed experience different weather regimes such that power increases in one location can offset power decreases in another location. By increasing geographical diversity, interregional transmission decreases the cost of flexibility reserves per unit of wind and solar capacity and increases the effective capacity value of renewables, reducing installed capacity reserve needs.

#### **When: Time Diversity**

Time diversity has two different influences that may motivate interregional transmission: diversity in the timing of diurnal peaks, and diversity in the timing of annual peaks.

#### *Diurnal time diversity*

Interregional transmission that interconnects regions of different time zones can benefit from diurnal peaking differences, where the daily peaks of the two regions occur at different times, enabling a peaking region to benefit from unused capacity in the other region if that unused capacity is less costly than what would otherwise be used in the peaking region. This benefit is most salient for interregional transmission that spans a significant east-west distance.

#### *Annual time diversity*

It is typical that a region requires that installed capacity exceed annual peak load by some chosen margin, e.g., 10-15% is common. This ensures that, even with typical outages, the region will have capacity sufficient for supplying its annual peak. Without interregional transmission, if demand is growing, a region must periodically invest in additional capacity to satisfy this requirement. With interregional transmission, the requirement can be also satisfied via unused capacity from another region. For example, the study in [13] analyzed the multiannual complementarities of wind generation and hydropower to meet the energy demand in Brazil through renewable and sustainable resources. The possibility that another region will have significant unused capacity depends on the date of the other region's annual peak. If both regions have similar peaking dates, then the additional unused capacity will be small. If peaking dates are very different, e.g., if one region peaks in the summer and the other in the winter, then it is likely that the unused capacity will be significant. One example of such is the seasonal capacity sharing agreement between Hydro-Quebec and Ontario [14]. Sharing of planning reserves has potential to create significant cost savings by avoiding or deferring new capacity investment. This benefit tends to be most salient for interregional transmission that spans a significant north-south distance. A first-order indicator of benefit from annual time diversity can be obtained from a building climate zone map as contained in [15].

An important caveat in regard to annual time diversity is that there is a very strong institutional bias in the electric utility industry of many nations, and especially in that of the US, for local provision of resource adequacy. In the US, this bias is rooted at the state level [16]. In some regions, it has tended towards being more of an RTO responsibility [17], but even in such regions (e.g., PJM), there is evidence that, for the market through which resource adequacy is maintained, there is not yet consensus on how to treat capacity delivered by transmission from other regions [18]. Maintaining this bias and/or lack of attention to appropriately adjusting capacity market mechanisms inhibits a region from enjoying the substantial economic benefits associated with annual time diversity.

## 2.1.2 Benefit 2: Economic Development

Interregional transmission provides economic development in two ways. First, there is infrastructure development in the form of new supply resources built as a result of the transmission. This infrastructure development provides lease payments to landowners, increases property tax revenues, and creates jobs, all of which are significant for both local and national economies. For example, land-lease payments typically range up to \$10,000 per turbine per year; in 2018, rural landowners in the US received \$289M in these payments [19]. Property tax revenues increase revenue streams for local governments for funding schools, roads, and other community infrastructure and average about \$7000 per MW of installed capacity [19]. In regard to job development, the studies in [20] and [21] conclude that approximately 4 jobs can be directly created per MW of wind or solar power installations. These mainly include manufacturing of key components, power plant construction, and operation and maintenance (O&M). In the Interconnections Seam Study, one Macro Grid scenario modeled \$40B of transmission investment and \$500B of generation investment. An economic development study of this scenario [22] identified that on average, 389,000 jobs per year would result over a 15-year period. To provide context, this is about 17% of the annual average annual US job growth between the years 2009 and 2017.

The second way in which interregional transmission development provides economic development is that the cost reductions described in Section 2.1.1 are reflected in savings ultimately passed on to electricity consumers raising the competitiveness of the commercial and industrial sectors while enabling increased household spending. This is especially important in areas where electric energy costs are high. For example, with an average US price of 10.53 ¢/kWh, states such as California (16.58¢/kWh), Rhode Island (18.1¢/kWh), New Hampshire (17.01¢/kWh), Vermont (15.13¢/kWh), New York (14.83¢/kWh), and New Jersey (13.01¢/kWh) [23] can benefit a great deal by building transmission to bring energy from remote, low-cost renewables into their state. This is especially true in terms of energy-intensive manufacturing such as, for example, data centers, aluminum production and processing, pulp and paper mills, lime and gypsum production, iron and steel mills, basic chemical manufacturing, and foundries [24]. For such firms, electricity prices have a powerful influence on location and relocation decisions; low electricity prices go a long way towards retaining existing firms and attracting new ones, not only within the US, from one state to another, but also from abroad, i.e., from other countries to the US.

If a population cannot see economic benefits coming from interregional transmission sited in their region, then the public support for that “flyover” transmission, is going to be hard to

obtain. Designing transmission to avoid flyover pathways may be essential.

Economic development is attractive at any time. However, a final comment in this section must be made in the context of the times in which we are now living. At the time of the publication of this report, most of the world is in an economic recession caused by the COVID-19 pandemic. Given the expectation that the pandemic will weaken with time, each nation will look for ways to stimulate its economy. Building interregional transmission together with the renewable resources that it motivates may become increasingly attractive over the next few years as nations around the globe grapple with ways to offset the economic impacts of the COVID-19 pandemic.

## 2.1.3 Benefit 3: Improved Reliability

As indicated in Section 2.1.1, interregional interconnections can help to ensure security of power supply by sharing contingency and planning reserves to satisfy demand during peak conditions and/or conditions of power plant failures [129]. This is a form of improved reliability.

In addition, interregional transmission improves grid performance in terms of post-contingency steady-state voltage and loading and dynamic security (transient, oscillatory, voltage, and frequency stability) [25]. If the interregional transmission is AC, then grid performance is improved by reducing congestion, by lowering the impedance of the path between the terminating buses of the interregional transmission, and by decreasing reactive power consumption (by reducing reactive line losses and increasing reactive line charging). If DC interregional transmission is deployed within a single synchronized grid, it also improves grid performance by reducing congestion, but if it is deployed between two asynchronous grids, then it may not reduce congestion and indeed could increase it via the additional MW injection or withdrawal that it imposes on the system at the point of interconnection, an influence addressed through the provision of AC transmission reinforcements.

If the interregional transmission is DC using voltage source converters (VSC), then reliability can be further improved based on control capability associated with the VSC, particularly for voltage, frequency, transient stability [26, 27], and oscillatory stability [28, 29, 30, 31, 32] performance; some of these influences are illustrated in the design of HVDC links between North Africa and Europe [33]. A particularly interesting benefit of both thyristor- and VSC-based HVDC is their ability to improve frequency response, both inertial and primary, by enabling one grid to assist in the frequency recovery of another asynchronous grid, as illustrated in [34, 35].

Finally, an important way that interregional transmission can

contribute to reliability is by facilitating black starts to energize the network following large-scale outages. If a region loses its black start plants, then HVDC interregional transmission could facilitate restoration and recovery via access to the energized units or black start plants in other regions. Although VSC-based HVDC capability for black-start provision has been well established [36, 37, 38], LCC-based HVDC may also have this capability if appropriate auxiliary equipment is added to standard LCC configurations [39].

### 2.1.4 Benefit 4: Enhanced Resilience and Adaptability

Situations have occurred in the past and will occur in the future where resources in a given region become temporarily or permanently unavailable; these situations become particularly stressful when the amount of unavailable resource is large. We refer to such events as high-consequence events and characterize the ability to respond to them, temporary or permanent, as resilience and adaptability, respectively. Causes of temporary (and therefore resilience-related) high-consequence events include extended and extreme low or high temperatures, hurricanes, earthquakes, floods, derechos, wildfires, geomagnetic disturbances, and cascading [40]. It is typical that such events are relatively rare. The Katrina/Rita Hurricanes of 2005 is a good example; although power was mostly restored within weeks, it took over six months to re-establish the Gulf natural gas supply during which time electricity prices throughout the US remained elevated [41]. Another more recent example is that the absence of reliable interregional transmission made it more difficult to restore power in Puerto Rico after Hurricane Maria in 2017 [42]. Causes of permanent (and therefore adaptability-related<sup>2</sup>) high-consequence events are generally policy-related, such as the 2011 Fukushima tsunami that resulted in permanent reduction of most of the Japanese nuclear power fleet. It is possible that future policy changes will require permanent reduction in the use of some fossil-fueled technologies, resulting in a permanent change in availability of such technologies. Interregional transmission reduces the cost of responding to these two types of events by enabling low-cost sharing of another region's resources, thus enhancing the resilience and adaptability of a power system.

### 2.1.5 Benefit 5: Achieving High Levels of Renewables

Many utilities in the U.S., and several states, have announced goals for very high levels of renewable energy generation up to

100% of their customer load. Yet, their local renewable energy resources alone are not geographically diversified enough to achieve that. For example, the state of Iowa has excellent wind resources, but wind generation valleys occur frequently. Even if the region is expanded to include the entire MISO market in which Iowa is located, the east-to-west boundaries are relatively narrow, and because weather fronts generally move along east-west paths, the MISO geographical diversity is limited. To achieve higher levels of renewables, interregional connections to geographically diversified resources are necessary.

Swapping of time-diversified renewables over interregional transmission can act like long duration energy storage. One region can send its surplus renewable over-generation away on transmission and get another region's surplus renewable energy back sometime later on the same transmission. Physical storage may not have happened. But it looks like it to both regions. This is called "virtual storage" [43]. For example, the California ISO has recently recognized the need to diversify the renewable energy resources and promote long duration energy storage [44].

### 2.1.6 Benefit 6: Lowered Cost of Reducing Emissions

Emissions from electric energy production include the so-called criteria pollutants and carbon dioxide (CO<sub>2</sub>). There are six criteria pollutants (as required by the US Clean Air Act [45]), including carbon monoxide, lead, ground-level ozone, particular matter, nitrogen dioxide, and sulfur dioxide. Interregional transmission does not in itself reduce the emissions caused by electricity generation; that is provided by replacing emitting electricity supply technologies with non-emitting supply technologies. But because interregional transmission facilitates cost reduction via sharing enabled by resource diversity, geographical diversity, and time diversity (as described above in Sections 0-0), and because high renewable penetrations increase sharing opportunities and value, interregional transmission leads to significant decrease in the cost per unit of emissions reduction. For example, results in reference [46] indicate, over a 15-year period, annual US CO<sub>2</sub> emissions are reduced by 1.4 Billion Mtons/year from deploying 600 GW of new wind, solar, and gas-fueled generation; the presence of a US Macro Grid saves \$18.87B dollars over the 15-year period, equivalent to a savings of \$13.48 per reduced Mton CO<sub>2</sub> relative to the same conditions but without the Macro Grid.<sup>3</sup>

<sup>2</sup> Adaptability as used here refers to the ability to respond to events which impose permanent and high consequences. A closely related notion is that of optionality, the value of additional optional investments, relative to taking no action at all, independent of whether the consequence of no action is large or not. Interregional transmission provides this kind of benefit as well.

<sup>3</sup> A consequence of lowered cost of reducing emissions may well be that more emissions are reduced. Though this benefit is hard to quantify, it exists and may be very large.



## 2.2 Costs of Interregional Transmission

Cost of interregional transmission is composed of operating costs and capital costs. Operating costs are those costs associated with the operation of the line, the most significant of which are the losses and, for AC transmission, the reactive support.

Capital costs are further divided into capital costs for transmission, capital costs for substations, and funding required for project development licensing and construction. The capital cost components for developing and building interregional transmission are similar to the capital cost components for developing and building any kind of transmission, though the distribution among these components can be different. The Midwest Independent System Operator (MISO) [47] and the Western Electricity Coordinating Council (WECC) [48, 49, 50] both identify several components including transmission line cost, substation costs, and allowance for funds used during construction (AFUDC – to account for the cost of debt and equity through the project’s construction period).

The bulk of the capital costs reside in the first two categories: transmission line capital costs and substation capital costs. Transmission line capital cost includes land and right-of-way acquisition, structures and foundations, conductors and shield/communication wires, and professional services and overhead. Land and right-of-way acquisition includes routing analysis, public outreach, regulatory approval and permitting process, property tracts and mapping, land owner negotiations, and land acquisition and condemnation fees. Substation capital costs include land and site work, equipment and foundations, protection and control, and professional services and overhead.

Of these costs, it is typical for interregional transmission to incur more costs per MW-mile for public outreach, regulatory approval and government permitting, and right-of-way acquisition (including land owner negotiations), because interregional transmission projects usually span longer distances, cross more state lines and/or national borders, and involve a larger and more diverse number of stakeholders.<sup>4</sup>

These costs (outreach, approval/permitting, and acquisition) can vary greatly with many uncertainties that create high risk of

increased project cost and of premature termination. We refer to this risk as project development risk, a term adapted from [ 51].

Project development risk may be reduced by utilizing existing facilities and rights-of-way to the fullest extent, including use of underground if economically feasible. Nonetheless, project development risk creates strong disincentives for organizations to initiate a transmission project even when the project’s benefit-to-cost ratio is high.

The perception that project development risk can be significant is highlighted by Figure 6 (adapted from [52]), which characterizes project development processes in the US: initiation, transmission planning, cost allocation, approvals, and siting. The central takeaway from this figure is that the amount of time required to plan and build transmission is long, ranging from 7 to 13 years, and the overall process is exceedingly complex. Other important aspects of this process, as highlighted by Figure 6, are as follows:

- **Project initiation:** To initiate development of an interregional transmission project, there necessarily must be an interregional entity or coalition that identifies that the interregional transmission project may be of strategic value. This step is critical because nothing moves forward without it; this step is difficult because it requires experience and understanding on how to evaluate the benefits of interregional transmission together with the ability to bring together organizations interested in obtaining those benefits and able to provide funding towards pursuing them. The identified strategic value motivates a business plan to financially justify and guide the project.
- **Transmission planning (Block 1):** This process, typically requiring 1-2 years, needs the attention from experienced planners to design the transmission project and its technical features, consider alternatives, assess risks, ensure that the plan meets reliability requirements, and quantify costs and benefits and return on investment.
- **Cost allocation/FERC rate approval (Block 2):** FERC requires that the project be part of a fair and open planning process, that it be assessed within the planning processes of affected RTOs, and that it satisfy the RTO’s cost allocation principles. FERC also has authority to adjust cost recovery based on “added incentives” [53].<sup>5</sup> This step typically requires 6-12 months.

<sup>4</sup> The relationship between these costs and distance is a generalization and varies from project to project depending on several factors, particularly population density and outreach histories associated with previous projects.

<sup>5</sup> In 2006, FERC built into its processes (based on a section 219 Congress added to the Federal Power Act) the ability to add incentives for transmission projects proposed by a member of an RTO that ensure reliability or reduce cost of delivered power by reducing congestion, particularly for projects that present special risks or challenges. As described in [53], such incentives focus on risk and include higher return on equity; recovery of incurred costs if a project is abandoned for reasons outside the applicant’s control; inclusion in rate base of 100% costs for construction work in progress; use of hypothetical capital structures; accelerated depreciation for rate recovery; and recovery of pre-commercial operations costs as an expense or through a regulatory asset. FERC recently issued a Notice of Proposed Rulemaking to extend and refine their approach for evaluating

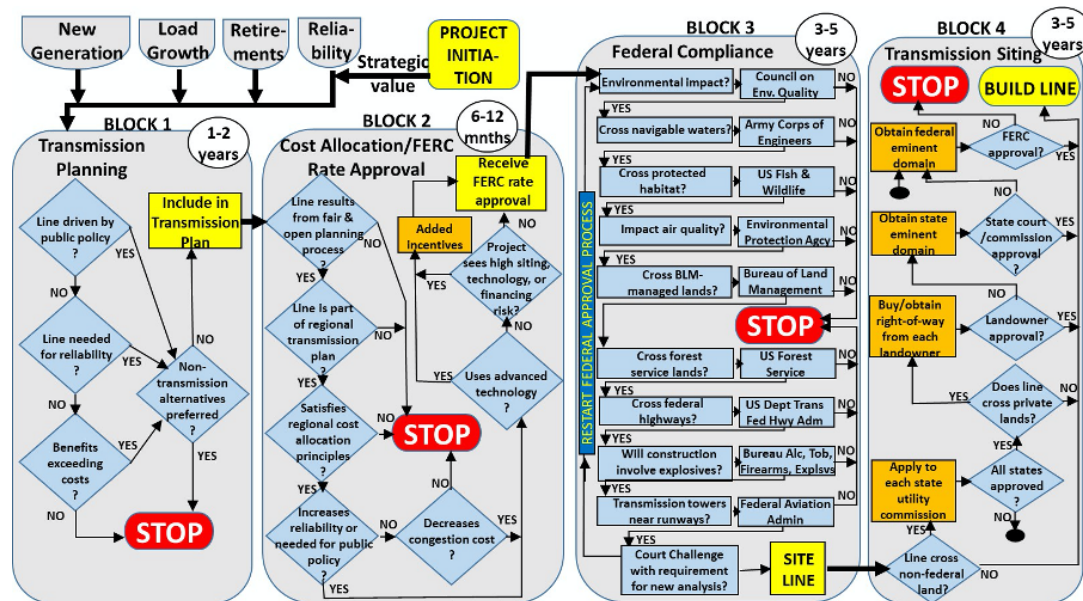


Figure 6: Transmission planning, cost allocation, approval, siting process in the US (adapted from [52])

• Federal compliance (Block 3): There are a variety of Federal permits that may need to be obtained. In theory, any of the various Federal agencies granting these permits can effectively stop the project, but in practice, it is the process of compliance rather than approval. Some of the compliance actions indicated in Block 3 are required of all projects, e.g., an environmental impact statement. Other compliance actions may not be needed, depending on the nature of the project. For example, an Army Corps of Engineers permit is required only if the project attaches to Corps facilities. Other requirements must be satisfied for crossing waterways and freeways and siting near airports or military bases. The compliance process of Block 3 may require 3-5 years. Effort has been made to reduce the required Block 3 time by granting the US Department of Energy “lead agency” status [54, 55], thereby coordinating and streamlining some of the processes. However, this rule does not apply to paths designated as national interest corridors according to the Energy Policy Act of 2005, a designation required in order for FERC to have influence on the siting processes (see next bullet describing the transmission siting issue).

• Transmission siting (Block 4): The most significant uncertainties occur during efforts to obtain transmission siting. Block 4 uncertainties occur largely because, unlike natural gas transmission, states are primary decision-makers for siting interstate electric transmission. There have been strong arguments made that, in order to obtain the very significant benefits of interregional transmission, FERC will need more siting authority [56], while state authorization and review processes are simplified [57].

Additional perspective on the last bullet, transmission siting, is appropriate here, as this issue has continued to increase in complexity over the past two decades. Indeed, the Energy Policy Act of 2005 (EPA 2005) was enacted to address this challenge by providing the US DOE with authority to designate National Interest Electric Transmission Corridors (NIETC) as congested corridors which, if relieved, would promote the nation’s energy independence, national security, and economic growth. (DOE has conducted three related studies [58, 59, 60] and recently released a fourth for comments [61], but only the first two of these actually identified NIETC; the other two had the purpose to update, review, and assess “...information on current transmission constraints and congestion and effects on transmission investment....”).

Even more, EPA 2005 in its Section 1221 empowered the FERC with new backstop authority to site transmission lines in a NIETC if a state delays or imposes conditions which undermine the project’s benefits [62]. In the words of [56], the EPA 2005 process “...was designed to facilitate a partnership between DOE and FERC in deciding when preemption of state siting laws is appropriate....” This legislation was met with vigorous resistance from the states and other organizations, with the main concern being the transfer of siting and eminent domain authority to the federal government; this resistance ultimately resulted in two federal circuit court decisions, one in 2009 and another in 2011, providing interpretations to the relevant sections of EPA 2005 that significantly weakened it. As a result, FERC has never attempted to exercise its Section 1221 backstop siting authority for electric transmission lines.

In 2016, DOE signed a Participation Agreement based on use

incentive requests – see Section 3.2 below).

of the subsequent section 1222 of EPOA to facilitate siting needs of the 4GW Clean Line Energy Project called “Plains and Eastern Clean Line” from Oklahoma through Arkansas to Tennessee. Section 1222 allows two federal power agencies (Western Area Power Authority, WAPA, and Southwest Power Authority, SWPA) to partner with other entities to design, construct, or operate transmission projects [56]. In 2018, DOE and Clean Line Energy terminated their Participation Agreement as well as DOE’s participation in the project, with NextEra Energy Resources acquiring Clean Line Energy [63], actions that resulted from increasing local resistance to the line in Arkansas [64]. It is unclear at the time of this writing whether further federal siting efforts stemming from EPOA 2005 will be attempted. The implication is the project development risk stemming from siting needs (Block 4 of Figure 6) likely remains an impediment for most US interregional transmission projects.

# 03



## Characteristics for Successful Development of Interregional Transmission

There has been a great deal of interest worldwide in studying the benefits of implementing interregional transmission for a particular area. As indicated in Figure 1 (which shows transmission with capacity greater than 1.5GW built after 2014 or likely to be built in the near future), many regions of the world have been very successful in recent efforts to develop it, e.g., China with 260GW, Europe with 44GW, Brazil with 18GW, and India with 12GW, in contrast to only 3GW in the US (corresponding to the 3GW TransWest Project).

In this section, we assess the reasons for that success or lack thereof, identifying characteristics that must be present to successfully develop interregional transmission. These characteristics are: (1) consensus to develop; (2) approach to fund; and (3) public support. We describe these characteristics in the following three subsections.

### 3.1 Characteristic 1: Consensus to Develop

Interregional transmission, by its nature, usually spans a large geographical distance, and as a result, tends to affect a large and diverse number of stakeholders. Achieving consensus can be difficult for any large and diverse group, and like any project requires a systematic sequence of consensus building.

Any interregional transmission must be represented by a lead entity. That entity has the sole authority to represent the project, bind the project, and act for the project. That entity

is responsible to secure the funding, approvals, financing, right-of-way, construction, compliance, monitoring, testing, acceptance for operations, and operations of the system. That entity must also have a clear strategy for the development of the project that was developed by experienced electric power planners, with written agreements from all partner organizations supporting the strategy. The lead entity should seek to include the following characteristics to ensure the successful development of interregional transmission:

- *Establish consensus strategy* based on a collaborative culture of the regions: Interregional collaborative cultures often arise through a history of collaborative activities, ranging from general interregional agreements in other areas (e.g., agreements for trade, health, education, or military) to collaborative organizations dedicated to electric transmission issues. Such cultures can be difficult to achieve if there exists very little collaborative history and especially if there exists history in past years, decades, or even centuries that has diminished the level of trust or even led to a culture of antagonism, a feature that may be more observable among some European nations and less observable within the US. Even when a collaborative culture exists, establishing a consensus strategy can be highly challenging if the number of decision-makers is large.<sup>6</sup>

- *Identify and clearly define* the strategic value of the project in terms of each Participant: The total benefit of the project across all affected regions and participants must clearly outweigh the expected costs (see Section 2 for benefits and costs). At least one RTO has required in the past some types of electric transmission projects (including interregional) to show benefit

<sup>6</sup> The current organizational balkanization between utilities and between wholesale markets in the US is as large a barrier as cultural trust issues. In the US, the electric power industry is influenced by a variety of decision-makers, including over 200 investor owned utilities, 10 federally power authorities, over 2000 publicly-owned utilities, about 900 rural electric cooperatives, seven RTOs, 48 state regulatory bodies (continental US), and many state and federal agencies.

to cost ratios [65] at the maximum FERC-allowable threshold [66] of 1.25. In addition, it is important that each individual region see an attractive benefit.

- *Identify support for the project* as well as opposition: There cannot exist one or more organizations within a region having blocking power and strong incentive to use it. Such organizations may include those owning a significant percentage of the region's electric infrastructure, regulatory bodies, or some branch of the local, state, or national government. Such an organization may block if it does not perceive a net positive benefit for itself, even if its region does. States perceiving themselves as “flyovers” where a transmission project serves few if any of the state's loads or resources, fall into such a category; there is recent evidence that ensuring benefits (e.g., serving load, providing other services such as broadband communication) for such states can be effective [67].

- *Preferred alternatives*: A region may perceive alternatives to interregional transmission that they prefer. The common alternative for a region positioned to receive electric energy, flexibility, or capacity from another region is to maintain or develop local resources instead. A region may prefer to do so even if it results in more expensive energy locally and less net benefit for all participating regions, simply because it results in local economic development, i.e., it adds jobs to the local economy. This has been called “resource parochialism” [68] or “state parochialism” [69]. For example, some argue that distributed energy resources (DER) is a preferred alternative to transmission [70]; others take a similar view of energy storage [71]. Still others view transmission as a substitute for storage, a “virtual storage” [43]. Both storage and transmission provide multiple benefits; which one is the holistic cost-effective choice may ultimately require co-optimized modeling accounting for all costs and benefits, in order to allow them to compete head-to-head.

## 3.2 Characteristic 2: Funding Approach

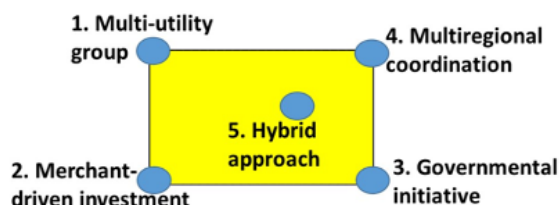


Figure 7: Funding approach

Even if several regions reach consensus to develop interregional transmission, they must have or develop an approach to fund it. There are four possibilities, as illustrated in Figure 7.

1. *Multi-utility group*: Two or more investor-owned utilities, public utilities, and/or rural electric cooperatives may form a group to build an interregional transmission project. For example, 10 such entities formed such a group to construct almost 800 miles of transmission lines and 22 substations from 2004-2017, consisting of four 345 kV transmission lines and one 230 kV line, strengthening the east-west flow between eastern South Dakota across Minnesota into western Wisconsin [72].

2. *Merchant-driven investment*: In this approach, one or more entities gather financing from the open market to build a line, with return identified by negotiations with willing customers who would obtain firm capacity from the line. Merchant-driven investment benefits if there are price signals to indicate the value of the line in enabling trading of energy, flexibility services, and/or resource adequacy-driven capacity. Such price signals should reflect sustained price differences for these various services, suggesting that interregional sharing of these services will be economically attractive. In addition, the development cycle for transmission should be short enough to attract investors, or else, payments for use should be allowed early in the development cycle [73].

3. *Government initiative*: National and/or local governments in the participating regions may elect to fund the project, perceiving the infrastructure to be a public good and therefore having costs appropriate to pass to taxpayers. The US has done this before with the interstate highway system, where the Federal government paid 90% of the cost (via a gasoline tax) and states paid 10% and managed the efforts associated with location, design, right-of-way acquisition, construction, and operation and maintenance [74]. The US has also done this before with electric transmission (see Section 4.1.5).

4. *Multiregional coordination*: Multiregional stakeholder groups consisting of multiple organizations from the electric utility industry, and possibly local governments and advocacy groups as well, develop consensus, initiate the project, coordinate and fund its design and construction, and oversee its operation. This approach is particularly advantageous with respect to ensuring that “internal” (to a particular region) transmission reinforcements, to accommodate the interregional transmission, are made and considered in the cost allocation mechanism. In the US, there is no formalized mechanism for coordinating between members of multiple RTOs, although we may point to the Eastern Interconnection Planning Collaborative (EIPC) and the Eastern Interconnection States Planning Council (EISPC), active from 2010-2014, as an example where such coordination was initiated and explored [75]. In addition, there have been

some pairwise movements among RTOs to establish so-called “seam” coordination, including activities between SPP and MISO [57, 76, 77] and between MISO and PJM [57, 78]. These activities provide precedents and a structural basis in establishing multiregional coordination mechanisms. FERC’s recent interest in extending incentives for transmission projects offering high benefit to cost ratios (see its NOPR on transmission incentives [53, 79]) provides a basis for attracting interest in these mechanisms and, perhaps, opportunities for negotiating with entities that might otherwise be less inclined to support interregional transmission projects.

*5. Hybrid:* A hybrid approach utilizes some features from two or three of the above approaches. For example, it may be designed using a multiregional collaborative stakeholder group where impasses are addressed by government-appointed arbiters. Compensation strategies are considered in the arbitration. Merchant developers are incentivized to build consistent with design. Federal government supports what merchant developers will not or cannot build, while intimately coordinating with local government and industry.

In the US, FERC has emphasized a cost allocation approach based on identification of who obtains the benefits, stating in FERC Order 1000 [8] that “the costs of transmission facilities must be allocated to those that benefit in a manner at least roughly commensurate with the estimated benefits received.” Although precision in identifying beneficiaries and corresponding quantification of benefits is difficult to achieve, it is probably not necessary either: a reasonable level of accuracy is sufficient.<sup>7</sup> as long as it is possible to operate the interregional system to supply the benefits to paying entities and to limit the benefits to non-paying entities, i.e., to prevent so-called “free riders.”

### 3.3 Characteristic 3: Public Support

Obtaining public support, overcoming NIMBYism, requires intentional and dedicated outreach to stakeholders using various communication and engagement methods to facilitate two-way participatory dialogue about the need for and

impacts of a proposed transmission project. We do not here address these methods of public outreach; it is a discipline in its own right [80, 81, 82, 83], and transmission developers employ professional experts trained and experienced in that discipline [84].

Ultimately, there are always at least two basic areas of public concern: benefits and undesired impacts. The public needs to know that a project provides benefits that they value, and that the undesired impacts will be minimal. Communicating benefits (see Section 2) in publicly understood and recognized ways is essential, and all involved regions must be able to see them. Decreased energy cost is usually an essential public positive and one that occurs when transmission connects regions having an oversupply of low-cost energy to regions which otherwise have access to only high-cost energy.<sup>8</sup> When involved resources are mainly renewables, the public may also value the associated environmental benefits including reduced CO<sub>2</sub> and improved air quality.<sup>9</sup> However, the transmission itself, though necessary to realize these benefits, is often understood by the public more in terms of its undesired impacts than its ability to serve as an enabler of the benefits. Therefore, for transmission, it is important to minimize undesired impacts.

For interregional transmission connecting two or more points within the same synchronized grid, using AC transmission is an option. However, use of AC transmission is usually a significantly more expensive option if the spanned distance exceeds a breakover value, often in the range of 350-450 miles. And if the interregional transmission interconnects two asynchronous grids, use of AC transmission would require that those grids be operated synchronously, and analysis should be done to ensure that the associated stability requirements do not drive the need for capacity beyond the level that is economically desirable. And finally, if there are reasons to go underground or undersea, the economic benefits decrease with distance because charging (capacitive) effects decrease power transfer capacity. This effect increases with voltage so that, for example, a 345kV cable reaches zero transfer capacity at about 43 miles, and a 500kV cable does so at about 30 miles [85]. These values assume no use of inductive compensation; guidelines for undersea AC transmission indicate it is limited to between 60 and 90 miles if inductive compensation is deployed at both ends [86].

<sup>7</sup> Some, however, argue that the problem may be more to identify who does not benefit, a point underlying the comment made in [18] in reference to “extremely narrow ‘beneficiary pays’ formulations that, had they applied to interstate highways, the interstate highways system would never have been built”).

<sup>8</sup> Focusing only on energy prices (and not prices related to flexibility or capacity), then there can be cost increases in the sending region due to interregional transmission, since the additional sales will cause the market-clearing prices to move up the supply curve to a more expensive unit (but still at a price significantly below that of the receiving region). However, this effect will be insignificant as long the sending region is willing and able to develop additional low-cost resources to supply the other regions.

<sup>9</sup> But there are can be undesired impacts on the resource side as well. For example, wind can have bat and avian impacts, cause shadow flicker and noise, change the visual aesthetics of the land, and influence farming practices.

For these reasons, use of DC transmission is often favorably considered for interregional transmission. In addition, DC maximizes the line capacity per unit required right-of-way (ROW). For example, Figure 8 shows (on the left) a  $\pm 500$ kV HVDC line with power transfer capacity of 3100 MW in contrast to a 345kV AC transmission line having power transfer capacity of 300MW. Both have approximately the same ROW requirement ( $\sim 50$ m), so that the capacity per unit ROW of the DC line is an order of magnitude greater than that of the AC line, i.e., for the same ROW, this DC line gives  $\sim 10$  times the power transfer capacity of the adjacent 345 kV line. Use of 765 kV in this situation, instead of 345 kV, reduces this ratio from 10 to about 2 [87]; nonetheless, these examples show why DC can be so effective in minimizing ROW requirements in response to public concerns. Furthermore, right-of-way requirements can be less than 10 feet if the project can afford to be undergrounded (although at more than double the project cost), something that is possible with DC.

A final comment in regard to maximizing public support is, whenever possible, to make use of ROW that has already been obtained for some other purpose. This can be done by co-locating transmission on rail [88], highway, or pipeline ROW, although there are variations among states in regards to allowing it, and if so, under what conditions [57]. Another approach is to convert existing transmission lines from AC to DC [89, 90].

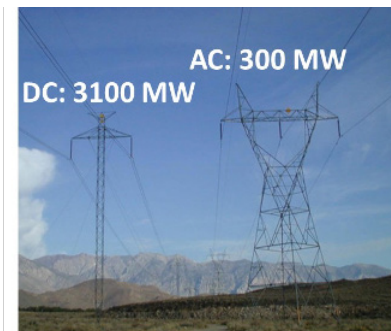


Figure 8: Comparison of Capacity-to-ROW requirement ratio

# 04



## Interregional Transmission and Macro Grids: Area Analysis

In this section, we summarize high capacity interregional transmission and Macro Grids around the world, including those completed, those planned for development in the near-term, and those that have been studied as promising conceptual designs. Identified designs are captured in summary form via Figure 1 and Figure 2 of the Executive Summary. In the below subsections, these interregional transmission and Macro Grid designs are presented for each of seven separate areas of the world: North America (Section 4.1); Europe (Section 4.2); China and Northeast Asia (Section 4.3); India and South Asia, Southeast Asia, and Australia (Section 4.4); Russia (Section 4.5); Africa (Section 4.6); and Central and South America (Section 4.7). We also summarize intercontinental supergrid designs (Section 4.8), which are characterized by multiple interregional connections among multiple regions.

### 4.1 North America

Considering the contiguous North American continent, there are two major grids, the Eastern Interconnection (EI) and the Western Interconnection (WI), and four smaller ones, the Electric Reliability Council of Texas (ERCOT), Quebec, Alaska, and Mexico. Interconnections exist between the US and both Canada and Mexico. As illustrated in Figure 9, as of 2017, total transmission capacity between the US and Canada is (a rough estimate) 11.8GW, with about 2.8GW in the WI and about 9GW in the EI (adapted from [91]; for links where capacity information was available, north-to-south capacities were used; otherwise, capacities were estimated based on the voltage level of the lines). Most of this transmission capacity was built to support import of Canadian hydro into the US.

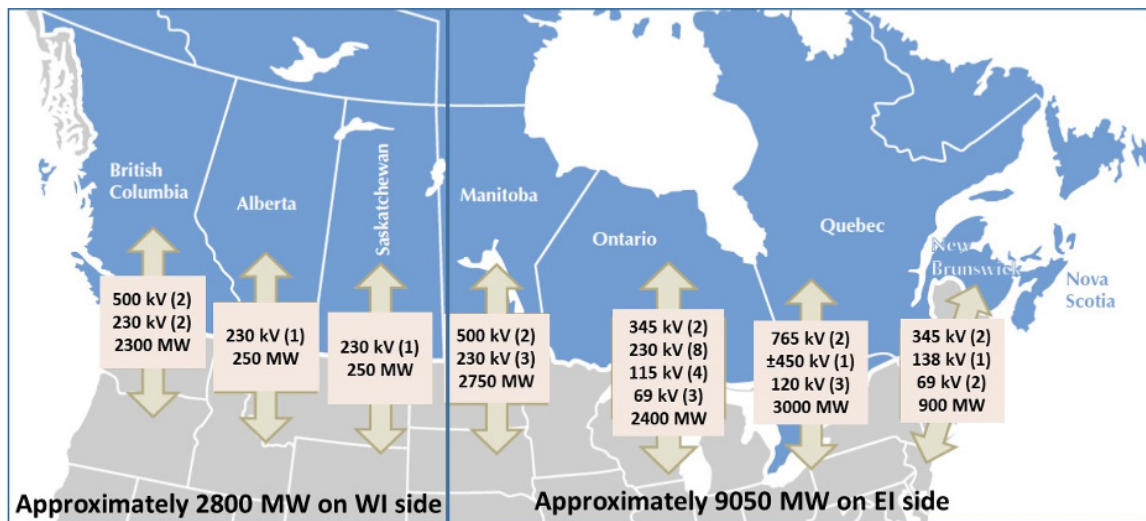


Figure 9: US-Canada interregional transmission corridors [adapted from 91]



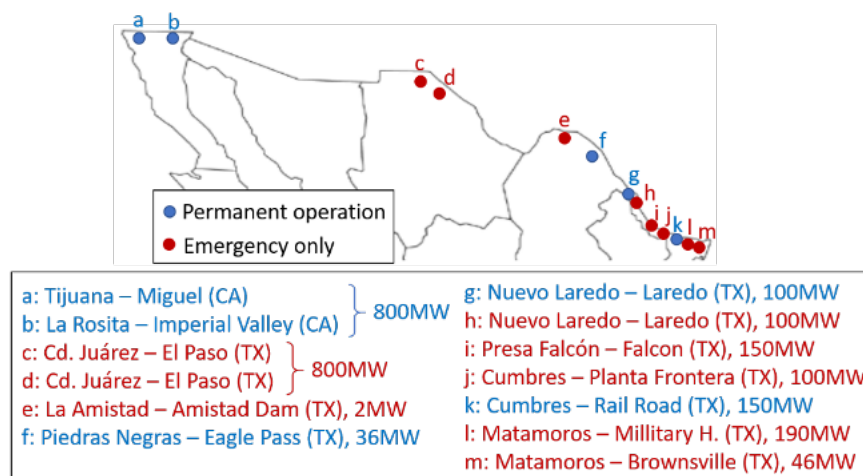


Figure 10: US-Mexico Electric Transmission Interconnections [adapted from 92]

Mexico is electrically connected to the US but with only a few interconnections totaling just under 1.9GW of capacity, as shown in Figure 10 [92]. Of this amount, about 1.1GW is for regular trade, with the rest being for emergency use only. On its southern border, Mexico is connected to Guatemala with a 400kV interconnection of 0.2GW capacity. Mexico and the US signed bilateral principles in 2017 promoting more interconnections between the two countries to ensure a more reliable integrated system and to achieve mutual economic benefits [93].

### 4.1.1 United States

Existing AC interregional transmission in the US

Interregional transmission has been developed in the US using both AC and DC transmission. We mention three AC examples. The first example is the Pacific AC Intertie (PACI) of the Western Interconnection, originally designed (together with the Pacific DC Intertie) to bring inexpensive hydro power from the Northwest dams of Canada, Washington State, and Oregon into the load centers of California. The PACI has been expanded since it went into service in 1970 and is now comprised of three 500 kV lines with a maximum north-to-south flow of 4800 MW across the California-Oregon border.

The second example is the 765 kV transmission system of Ohio, Indiana, Virginia, Kentucky, and West Virginia, the first line of which went into service in 1969. This voltage level is the highest used in the US today and results in lines having capacities exceeding 2GW. Although moving coal-fired and nuclear generation to load centers was certainly a motivation for building this system, it was also viewed to be "...just another step arising from the continuation of the basic philosophy that a strong transmission network, adequate at all times to

meet the most severe outage conditions, is indispensable to the successful operation of a fully integrated power system" [94]. The terms "strong transmission system" and "integrated power system" point to the observation that extra- high voltage AC transmission creates strength that facilitates reliability to planned contingencies, resilience to extreme events, and adaptation to permanent changes.

The third example is the transmission expansion built in Texas between 2009 and 2014 facilitated by the Texas competitive renewable energy zones (CREZ). As described in [57], this expansion consisted of 3600 miles of ROW for 72 mostly new single and double-circuit 345 kV lines to deliver over 18GW of wind capacity generated in the zones, mostly in northwest Texas, to the eastward load centers, at a total cost of \$6.9B. The organizations who developed these projects were competitively selected by the Public Utilities Commission of Texas (PUCT) and included both incumbents and new entrants. This has been cited as a model process for expanding transmission. However, although the transmission expansion was extensive and involved a large geographical region, permitting and approvals were required from only a single state. Translating the success of this expansion to other regions must include consideration of how to simplify the process when interregional transmission involves multiple states.

### Existing and Planned DC Interregional Transmission in the US

There are eight HVDC lines or cables in operation in the US. The main purpose of these existing HVDC projects are for interconnecting remote hydro or coal generation to load centers [95] or to supply a specific somewhat or fully isolated urban load via underwater cable. More recently, there have been a number of proposed high capacity HVDC projects, heavily motivated by renewable resource integration. These existing

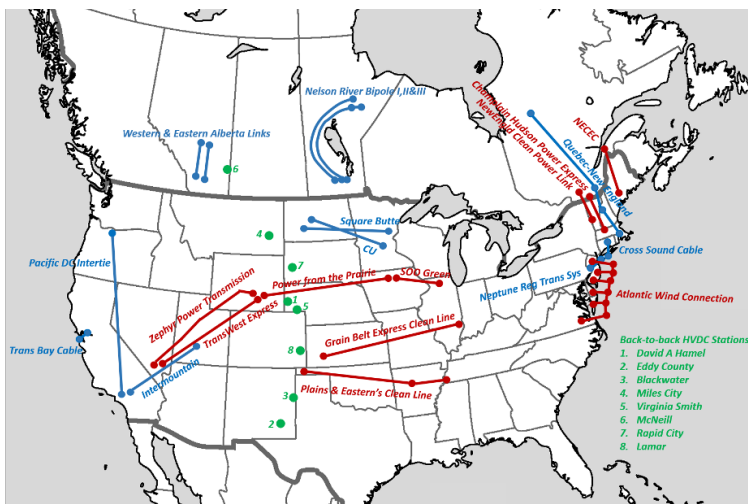


Figure 11: Existing and planned HVDC facilities in North America (blue: existing lines; red: planned or proposed lines; green: existing back-to-back converters)

and planned HVDC projects are shown in Figure 11 and summarized in Table 2; Canadian HVDC lines are also shown in the figure. Reference [96] provides additional perspective in regards to proposed and planned HVDC projects in the US.

In addition to HVDC lines and cables, the EI and WI are interconnected by eight back-to-back (B2B) HVDC facilities having a total transfer capability of 1.46GW (1.31GW resides in the US and 0.15GW in Canada). This amount is very low

relative to the installed capacity of these large interconnections (844GW in EI and 234GW in WI [97]). Several factors drive the need for developing more cross-seam transmission, among which is to facilitate the integration and utilization of renewable energy resources. Recent studies have shown that significant economic benefits can be achieved by developing additional cross-seam HVDC transmission between these asynchronous interconnections [3, 4, 6].

Table 2: Existing, Planned and Proposed HVDC projects in the US

Project Name (overhead or underground)	Year of Commission	Power Rating (MW)	Voltage Rating (kV)	Line Length (mile)	Original Application	Status
Pacific Intertie (overhead)	1970 (upgrades in 2020 planned)	3800 (Celilo), 3220 (Sylmar)	±500	845	Transport hydro generation	Existing
Square Butte (overhead)	1977	500	±250	449	Transport coal generation	Existing
CU (overhead)	1979 (upgrades in 2004, 2019)	1172	±400	427	Transport coal generation	Existing
Intermountain (overhead)	1986 (upgrades in 2010)	2400	±500	488	Transport coal generation	Existing
Quebec-New England (overhead)	1990 (upgrades in 2016)	2000	±450	920	Transport hydro generation	Existing
Cross Sound Cable (undersea)	2003	330	±150	24	Supply Long Island	Existing

Table 2: Existing, Planned and Proposed HVDC projects in the US

Neptune Reg Trans System [98] (undersea/grnd)	2007	660	±500	65	Supply Long Island	Existing
Trans Bay Cable (underwater)	2010	400	±200	53	Supply San Francisco	Existing
TransWest Express [99] (overhead)	2024 (expected)	3000	±600	730	Renewable Resource Integration	Planned
SOO Green [100] (undergrnd)	2024 (expected)	2100	±525	350	Transport wind generation	Proposed
NewEngld Clean Power Link [101] (underwater)	Unknown	1000	±300	150	Transport wind & hydro generation	Proposed
Power from the Prairie [102] (overhead)	Unknown	4000	Unknown	700	Transport wind/solar across seam	Proposed
Grain Belt Express Clean Line [103] (overhead)	Unknown	4000	±600	800	Transport wind generation	Proposed
Zephyr Power Transmission [104] (overhead)	Unknown	3000	±500	500-850	Transport wind generation	Proposed
Plains & Eastern's Clean Line [105] (overhead)	Unknown	4000	±600	700	Transport wind generation	Proposed
Atlantic Wind Connection [106] (undersea)	Unknown	7000	±800	560	Transport offshore wind generation	Proposed
ChamplainHu Power Express [107] (underwater/grnd)	Unknown	1000	Unknown	330	Transport hydro and wind	Proposed
David A Hamel, Eddy County, Blackwater, Miles City, Virginia Smith, McNeill, Rapid City, Lamar	1977, 1983, 1984, 1985, 1988, 1989, 2003, 2005	100, 200, 200, 200, 200, 150, 200, 150, 200, 210	50, 82, 60, 82, 50, 42, 13, 63.6	Back-to-back	Cross-seam interconnection	Existing

### Additional interregional transmission studies for the US

A joint effort from national labs, universities and industry partners performed the “Interconnections Seam Study” [108] to identify the value of increasing transmission capacity between WI and EI under 40-50% of renewable penetration (mainly composed of wind, solar, and hydro) in the future. The aim was to reduce the cost of developing and utilizing the nation’s renewable energy resources such as wind in the Midwest and solar in the southwest. Major economic benefits include access of load centers to richer renewable resources, interregional sharing of most economic energy resources on a diurnal basis, and interregional sharing of capacity to satisfy each region’s annual peak with consequential decrease in capacity investments.

Load diversity itself can contribute to 45% of the economic benefits [34]; Figure 12 illustrates the minimum bi-directional load diversity between US regions found over the years 2006 through 2012, offering a capacity savings of 32GW. The Interconnections Seam study also shows that one HVDC design, the so-called “Macro Grid,” yields a benefit-to-cost ratio between 1.15 and 2.5 depending on the scenario [108]. As a result, the Seam study concludes that a national HVDC overlay with renewables would be cost-effective. Another study [5] shows a national HVDC transmission overlay results in significant annual savings for US electric energy consumers. Recently, the Macro Grid Initiative [109] was launched by the American Council on Renewable Energy and the Americans for a Clean Energy Grid to promote the development of the Macro Grid in a cost-effective way.

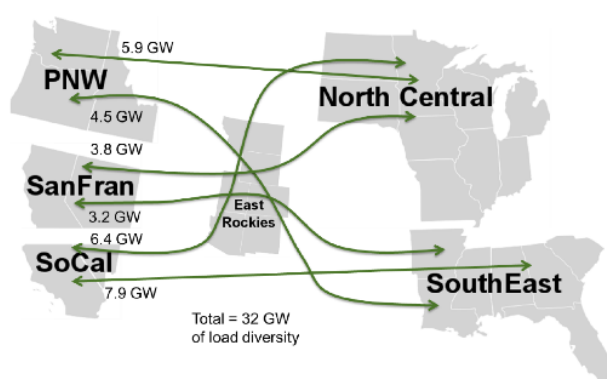


Figure 12: Load diversity between different regions of the US power grid [109] (used with permission)

Several HVDC transmission designs have been proposed to accommodate future high growth renewable scenarios in the US [108, 110], as shown in Figure 13. Design 1 is a reference

scenario without additional cross-seam transmission, but new generation and intraregional AC transmission are co-optimized to minimize system-wide costs. In Designs 2a and 2b, the capacity of the existing cross-seam B2B facilities are co-optimized along with other investments in AC transmission and generation. In addition, Design 2b also builds three cross-seam HVDC transmission lines, with terminal locations chosen to maximize cross-seam transmission value. Finally, in Design 3, a continental HVDC overlay, the so-called “Macro Grid” is built, co-optimized with other investments in AC transmission and generation. The four designs are studied under two different renewable penetration levels and policies – 50% renewables (by energy) with an escalating carbon emission price and 40% renewables without the carbon emission price.

In terms of converter technology, LCC is utilized for the HVDC lines in Design 2b. In Design 3, a mix of LCCs and VSCs is proposed. The LCC terminals are necessary to enable high capacity transfers between EI and WI during non-coincident peak times. The terminals are selected based on locations with highest annual load diversity as presented in [111]. The VSCs are also included in the design to facilitate ramping capability and dynamic/stability support, and are placed in locations with rich wind and solar resources.

Besides economic benefits, efforts have also been made to evaluate the potential reliability benefits of a North American HVDC overlay. In [34], an initial effort was reported on developing a 100,000 bus transient stability model for the Macro Grid interconnecting EI and WI (Design 3), under the assumption that all HVDC sections are LCC-HVDC links. It demonstrated reliability benefits to provide primary frequency support between the interconnections via HVDC upon outage of large generation. The study in [35] further shows the frequency support benefits with a Macro Grid composed of both LCC-HVDC and multi-terminal VSC-HVDC systems.

At the time of this writing, a study funded by the Power Systems Engineering Research Center ([www.pserc.org](http://www.pserc.org)) is evaluating the feasibility of synchronizing AC operations of the Eastern and Western US Interconnections. No results are yet available.

## 4.1.2 Canada

Canada is one of the top hydroelectricity producers in the world and has a low carbon generation mix. In 2017, about 79% of electricity was generated from non-emitting resources (mostly hydro and nuclear), out of which 60% is from hydro resources [112]. As a result, Canadian consumers enjoy some of the lowest electricity prices in the developed world. The Canadian

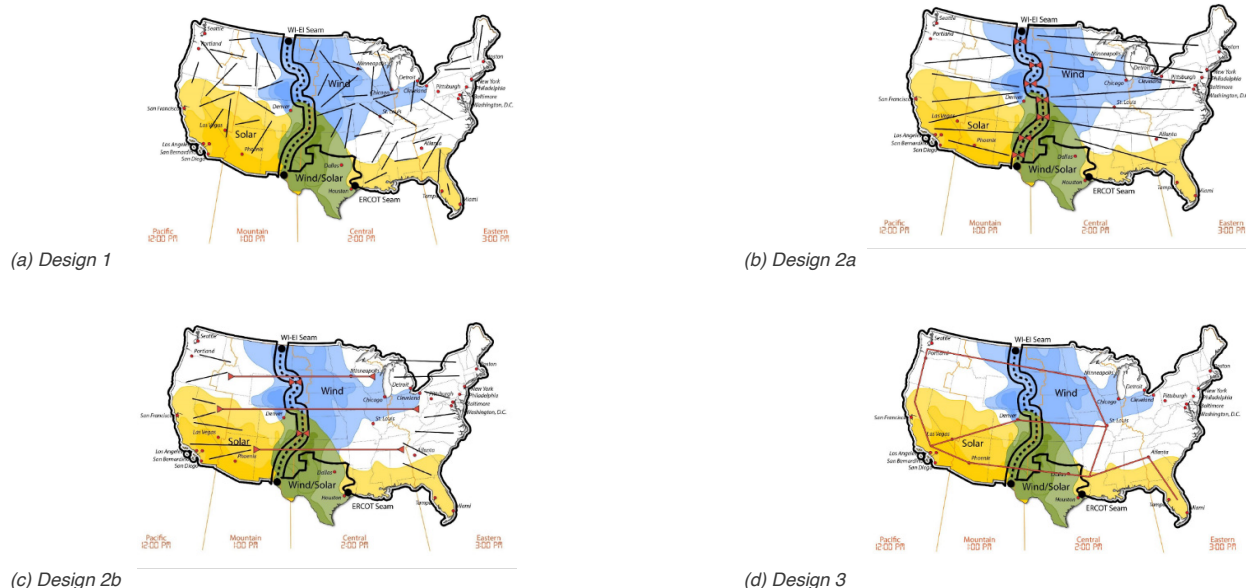


Figure 13: Conceptual transmission designs for continental US [adapted from 108]

transmission networks are closely connected with the US power grid, with over 35 major import/export interconnections<sup>10</sup> between the two countries [113] which are continuously expanding. Every Canadian province along the US border is electrically interconnected with a neighboring US state, forming a highly integrated grid with mutual benefits and robust trading opportunities. Some trading reflects the seasonal variations as electricity demand peaks during the winter in Canada and peaks during the summer in the United States. In recent years, Canada has been a net exporter of electricity to the US. About 10% of the total generated electricity is exported to the US, with a total revenue of \$2.9 billion in 2014 [114].

The transmission system in Canada is part of North American interconnected electricity system. Alberta and British Columbia are part of the WI, while the rest are part of the EI, with Quebec as a separate interconnection itself. The Canadian power network is characterized by north-south high voltage power lines and interconnections with the US, with far fewer east-west interties. This is largely due to uneven distribution of population, as well as the long distance between hydro-rich areas in the north and major urban areas in the south. The northeastern US is the largest market for Canadian electricity export, although North Dakota/Minnesota is also a major export destination [115].

Four major high capacity HVDC projects are in operation in Canada, as described below. These lines are also shown

in Figure 11.

1. Since the 1970's, the Nelson River double circuit HVDC (Bipole I and II) [116] has delivered power along the Nelson River from the Northern Manitoba to the load centers in the South. A third circuit (Bipole III) with completely separate physical structure was built in 2019 adding an additional 2GW of capacity [117] to the corridor on top of the existing 3.4GW from Bipole I and II. This new 860mile  $\pm 500$ kV HVDC transmission line mitigates the risk of weather related circuit outages and enhances the grid reliability for the Canadian province of Manitoba.

2. Another major HVDC project, which is a cross-border HVDC with the US, is the Quebec-New England HVDC between Radisson, Quebec in Canada and Ayers, Massachusetts in the US. The 920mile  $\pm 450$ kV line can transfer 2GW of hydroelectric power to Montreal and the Northeastern US [118]. In 2011, a similar HVDC project (Northern Pass initiative) connecting Quebec and New Hampshire was proposed, which would be able to carry 1200MW upon completion. However, in July 2019, the project was officially discontinued due to public resistance [119].

3. Two Alberta HVDC transmission lines with a total capacity of 2GW were built in 2015 linking Edmonton and Calgary: the 350km 500kV Western Alberta link and the 480km 500kV

<sup>10</sup> There are about 85 additional "border accommodations" lines crossing the US-Canadian border, but these are low voltage and not used for power import and export.

Eastern Alberta link [120]. These HVDC lines improve the reliability of Alberta's power system by relieving pressure off the existing underlying AC system. Moreover, when operating north-to-south, they move hydro, coal, and gas-fueled generation to the south, and when operating south-to-north, they move wind and solar in southeastern Alberta to the northern part of the province [121].

4. A  $\pm 320$  kV, 1200 MW, 145 mile HVDC line from Chaudière-Appalaches, Quebec, to Lewiston, Maine, the New England Clean Energy Connect (NECEC) project, is planned for completion in 2022, to bring hydro-generated electric energy into Maine [122].

### 4.1.3. Mexico

The generation fleet in Mexico is still largely based on fossil fuel resources, despite the large potential of solar resources in the northern part of the country. Only 20% of generated energy is from non-emitting resources in 2017, about half of which is from hydro resources [123]. Mexico has not invested in interregional transmission exceeding 1500MW of capacity for more than 10 years. Two interregional high capacity HVDC transmission lines were proposed recently but were both cancelled in January 2019 [124]: one was a 3GW HVDC line to interconnect Southern Mexico with the center of Mexico aiming to integrate the renewable generation from a huge wind park in the Istmo de Tehuantepec; the other was a 1.5GW HVDC line to interconnect the isolated Baja California with the rest of the country. Although the Mexican government has stated intentions to strengthen the energy sector, the investment in transmission infrastructure by companies is sluggish due to the high capital costs involved in developing these projects.

As renewable energy penetrations increase, the grid operator faced technical challenges due to its intermittency and overloading of existing transmission infrastructure during periods of large wind/solar energy contributions. A few 400kV AC transmission lines have been developed for renewable integration, including, for example, the Ixtepec Potencia-Juile double circuit line with 3000MW transfer capacity which was put in operation in 2007. The main goal of the line was to transfer wind energy from generation units in the Istmo de Tehuantepec in southern Mexico to the rest of the country. Another example is the Reynosa-Monterrey transmission network along the northeast border that, if developed, would help facilitate the integration of 1100MW of wind resources from the state of Tamaulipas. Building more interregional high capacity transmission not only improves grid reliability by sharing capacity and reserves to address intermittency, but would also encourage more wind and solar development to achieve decarbonization goals.

### 4.1.4 Greenland

Greenland's population density has been too low to justify an extensive interconnected grid, and as a result, Greenland's electricity infrastructure consists of 69 separate isolated systems, with only two towns connected by overhead lines [125]. Many of these systems are supplied by hydroelectric generation; between 60-70% of Greenland's energy supply is from hydro. Although wind energy may ultimately be useful in Greenland [126], today, the systems not supplied by hydro are almost entirely supplied by diesel. These fossil-fueled communities have motivated some interest in laying an HVDC cable along the southern coast of Greenland to provide them with hydropower access.

### 4.1.5 Summary for North America: Benefits and Characteristics

The North American area has potential to benefit from the three types of diversity (resource, weather, and time); reliability; resilience and adaptability; and economic development. North America is commonly thought to include four time zones, but if the eastern-most regions of Canada are included, there are five, and if Greenland is considered, there are six. Even at four time zones, the potential benefit from diurnal diversity is large, since typical urban peaks incur as much as three hour differences. Likewise, the area spans a latitudinal range of 68°, from 15° at the southern-most point of Mexico to 83° at the northern most point of Greenland, providing significant opportunities for annual time diversity benefit.

#### United States

Of the four nations comprising North America, the US stands out because of its geographical centrality and size, its high electricity consumption, the benefits likely to accrue from interregional transmission development, and the fact that it has both north-south and east-west opportunities that appear attractive. In regards to the characteristics necessary for successful development of interregional transmission, there is both precedent and existing features that suggest they are largely in place. For example, the ability to achieve consensus to develop can look back to the evolution of the California-Oregon Pacific AC and DC Interties, completed in 1970, following extensive interregional and international negotiations during the years 1958-1964 [127]; a unique US example in that it was funded through a combination of Federal appropriations, and investor and municipally-owned electric utility companies. The consortium developed by the utilities to represent them in these negotiations, called the California Power Pool, is a good example of other such consortia that have developed in the US, ultimately giving way to the seven RTOs of today; these organizations provide a regional force having no profit

motivation, trusted for their knowledge and experience, and providing a familiar and collaborative environment within which entities may engage and negotiate. The ability to design and operate markets means that price signals for building transmission can be communicated. Efforts of merchant transmission developers have not yet been successful, although there are several ongoing projects today that may soon change this [96], as indicated in Table 2. One of these, in particular, has seen no public resistance as a result of the fact that it is using underground HVDC on existing rail right-of-way, an optimistic sign that public resistance will not be a factor in developing interregional transmission if undesirable impacts are effectively eliminated. The three undersea and/or underground HVDC projects successfully developed in densely populated areas from 2003-2010 are further evidence of this (see Table 2). Finally, the Federal Energy Regulatory Commission (FERC) (which oversees the North American Reliability Corporation, NERC), and the Department of Energy (DOE), represent federal capability that could have significant influence on developing interregional transmission should federal policy swing in that direction. Indeed, FERC Order 1000 [8] already requires RTOs to consider interregional transmission, and the DOE has a track record which includes establishing successful collaborative mechanisms in 2010 via an Eastern US group for engineering (Eastern Interconnection Planning Collaborative, EIPC) and a sister organization for regulatory engagement (Eastern Interconnection States Planning Council, EISPC). Although activities of these organizations diminished after 2014 (EIPC still maintains some activities, see [75]), they showed that interregional collaboration can be effective.

### Mexico and Canada

Most of the existing high capacity interregional transmission lines in North America were built for remote generation connection in the US and Canada, especially for hydro resources. A few recent HVDC projects were built in Canada to mitigate the risk of weather-related circuit outages and alleviate the stress of the underlying AC network to improve grid reliability. Resource sharing between the hydro rich region in the north and wind & solar in the south is also achieved. The Canadian transmission network generally follows a north-south pattern, and is tightly integrated with the US power grid, enabling resource sharing and power trading between the two countries.

Although the interconnection between the US and Mexico is currently weak with only a handful of interconnections mostly for emergency purposes, the two countries have signed bilateral principles to promote more interconnections for improved reliability and mutual benefits. The geographical location of Mexico makes it a vital player in any potential intercontinental interconnections between North and South America.

## 4.2 Europe

To respond to the Intergovernmental Panel on Climate Change (IPCC) issued in October 2018, the European Union (EU) has set a goal to achieve net-zero greenhouse gas emissions by 2050. Of equal significance is the EU's Green Deal, which is driving about 450GW of zero-carbon capacity from offshore wind, most of which will be in the North Sea [128]. These developments have led to increasing deployment of renewable energy resources, mostly wind and solar energy. As the production of wind and solar increases, the need for transmission also increases to facilitate the integration of electricity generated from wind and solar resources into the energy markets across Europe. The EU council has set targets for all member nations to have electricity interconnections equivalent to at least 15% of their installed production capacity by 2030 [129]. Three specific thresholds are proposed by the European Commission to facilitate the realization of this 15% interconnection target, which also serve as indicators of the urgency of action needed reflecting the three headline goals of European energy policy: (1) to increase competitiveness through market integration; (2) to guarantee security of supply; and (3) to achieve climate targets through the utilization of renewable energy resources. To help minimize the wholesale market price differences, the first threshold sets a wholesale market price difference of 2€/MWh between Member States, which if exceeded additional interconnections should be prioritized. To ensure peak demand can be satisfied in all conditions with both domestic supplies and imports, the second threshold indicates that if the nominal transmission capacity of interconnectors falls below 30% of their peak load, additional interconnectors should be urgently investigated. To ensure the deployment of renewable energy is not limited by the export capacity, the third threshold states that if the nominal transmission capacity of interconnectors is below 30% of installed renewable generation capacity, further interconnectors should be urgently investigated. The "system-needs" study performed by the European Network of Transmission System Operators for Electricity (ENTSO-E) has identified an additional 93GW of cross-border capacity by 2040, in addition to the 35GW of reinforcements that are already well advanced, to be in place by 2025 [130].

A boundary is identified when a major barrier (e.g., lack of transmission line capacity) constrains power exchanges between markets in different countries. Figure 14 shows the boundaries identified in the 2018 10-year network development plan (TYNDP-2018). Five major factors drive the development of more interregional transmission across these boundaries [131].

1. Extensive increases in production from wind and solar resources and thus the increased need to transmit this energy.

2. Even higher integration of countries having high hydro resources, which could provide storage capacities for electrical energy if that energy can be transferred.

3. High price differences between countries indicating the inability to transfer and trade energy between these countries to reduce these differences (a less integrated market system leads to less efficient power transfer, which means that the power cannot flow from lower-cost areas to more expensive ones.)



Figure 14: Main boundaries identified in TYNDP-2018 [adapted from 131]

4. Increased local variations of power in-feeds cause higher European flows which require the stronger integration of power systems.

5. Ireland, Great Britain, and Baltic States are isolated and the Iberian Peninsula and Italy are weakly connected to the European network.

Another influence that is strongly encouraging cross-border electric energy trading is the “Clean Energy for All” package of legislation adopted in 2019, particularly Article 16.8 of Regulation 2019/943 [132] which sets a minimum of 70% of interconnector capacity that must be made available for cross-border trade, prohibiting the limiting of “interconnection capacity for use of solving congestion inside their own bidding zone or as a means of managing flows resulting from transactions internal to bidding zones.” Thus, no more than 30% of the interconnection capacity “can be used for the reliability margins, loop flows and internal flows....”

To increase the interconnectivity of the European power system

while addressing decarbonization goals, the main tool is the expansion of the existing AC grid, which includes a number of long DC lines crossing the European waters such as those in the Northern Seas interlinking four synchronous areas. In some countries, long onshore DC projects are already built or planned. Additionally, some interregional transmission grid models are proposed in Europe, which can be categorized into three main clusters: (1) the offshore supergrid in Northern Europe mainly to harness the wind from North Sea; (2) the HVDC grid to integrate concentrated solar power (CSP) and photovoltaic (PV) between North Africa, Middle East, and Southern Europe around the Mediterranean Sea; and (3) planning studies with a European continental-wide perspective, including the so called European Supergrid [133, 134]. We describe these three clusters in the following three subsections.

#### 4.2.1 Cluster 1 – North Sea Supergrid

Five major studies have been performed related to this cluster, including OffshoreGrid [135], North Seas Countries’ Offshore Grid Initiative (NSCOGI) [136], NORTHSEAGRID [137], North Sea Wind Power Hub (NSWPH) [138], and the PROMOTioN research project [139]. The OffshoreGrid project proposed two offshore grid designs, each having benefits that are about three times the investments and thus highly attractive from a social-economic perspective. The NSCOGI study is the results of a collaboration of 10 governments, the TSOs and regulators of these 10 countries, and the European Commission. Two offshore grid designs (radial and meshed) were proposed and compared in the planning horizon from 2020 to 2030 to maximize the economic use of offshore renewable resources and infrastructure investments. The meshed design performs slightly better economically with the assumed generation mix, although the complexity associated with operating such a meshed grid is considered to be a potential challenge. Possible advantages of the meshed design are identified to be greater resilience provided by the operational flexibility, and the reduced environmental impact with larger cable and fewer landing points.

The NORTHSEAGRID project is a techno-economic study which builds on the results of the OffshoreGrid project. It investigates practical financial and regulatory barriers to the development and construction of offshore grid interconnections and propose solutions accordingly. The NSWPH program proposed a Hub-and-Spoke concept, aiming to build one or more energy islands in the North Sea to facilitate the deployment of large-scale offshore wind with minimum environmental impact and at the lowest cost for society, while maintaining security of supply.

The recently completed PROMOTioN project [139] addressed the technical, legal, regulatory, market, and financial barriers to achieve a meshed offshore grid (MOG) in the Northern



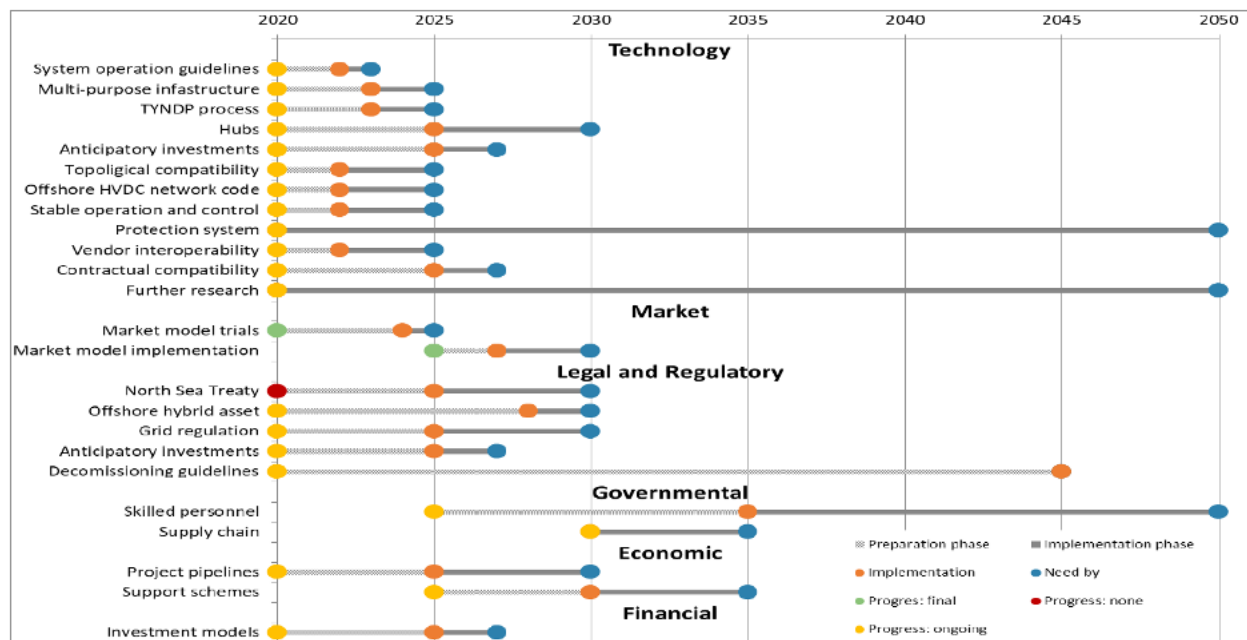


Figure 15: Roadmap to a meshed offshore grid proposed by PROMOTiON [140] (used with permission)

Seas from 2020 to 2050. The four-year project established an interdisciplinary platform with participation of 33 partners from 11 countries. The main objective of the project was to further develop and demonstrate four key technologies: multi-vendor HVDC grid projection, HVDC network control, long duration testing of HVDC gas insulated switchgear, and full power testing of HVDC circuit breakers. Regulatory and financial frameworks are also developed to coordinate the planning, construction, and operation of the offshore meshed grid. A roadmap to achieve a meshed offshore grid was proposed as shown in Figure 15 [140]. Four offshore grid expansion designs were analyzed under three different offshore wind deployment scenarios to produce 12 grid topologies from 2020 to 2050 in five-year time steps. The project shows that artificial islands with larger power concentration tend to be more cost-effective than individual HVDC platforms, and meshing the grids generally leads to lower curtailment and higher security of power supply. It also emphasized the need to develop a common offshore HVDC network code to ensure multi-vendor interoperability especially beyond 2030 as the deployment of offshore wind accelerates with more complex cross-border multi-terminal connections.

Another recent NSWPH study [141] focuses on the integration of ~180 GW of offshore wind and investigates different integration routes followed by cost benefit analysis. It suggests that the hybrid offshore transmission topology which combines offshore wind farm electricity grid connection with electricity market interconnection allows dual use of the assets, and thus it provides significant cost advantages as compared to

the conventional radial connection approach. In addition to the need of long distance HVDC corridors, bulk storage is identified as useful in providing time-shifting flexibility for integrating the large-scale offshore wind, where the concept of Power-to-Gas (P2G) would be the most cost efficient method to convert some parts of the produced electricity from the offshore wind into hydrogen for storage and transportation. Therefore, it concludes that integration routes that combine electricity and gas infrastructure would cost ~25% less than those routes via only electricity infrastructure in terms of annualized cost, mainly because of the fact that the local generated hydrogen via P2G by otherwise curtailed electricity is cheaper than importing hydrogen, and thus the total hydrogen needed is reduced as compared to the scenarios with integration via electricity infrastructure.

Congestion in the onshore transmission grid is identified to be a major barrier for offshore wind deployment after 2030; indeed, it's already a significant issue especially in Germany, an issue that needs near-term attention in order for EU to reach its decarbonization targets. The Power-to-Gas – Gas-to-Power route can mitigate the congestion, reducing the need for additional onshore electricity transmission, assuming existing gas transmission can be used for the transport of produced hydrogen. Therefore, it is concluded that integrated planning of electricity and gas is necessary for increased penetrations of large-scale renewable energies. The transmission grid capacity after optimization for a meshed DC grid is shown in Figure 16. These efforts are conveniently aligned with a recent proposal (from the German natural gas operator FNB

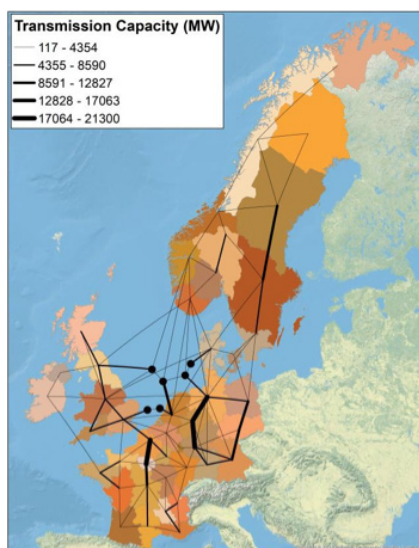


Figure 16: Transmission grid after optimizing with offshore grid illustrating hub-and-spoke concept [141] (used with permission)

Gas) to build a 1200km hydrogen transmission network by 2030, a 660 million euro project, which will be the largest hydrogen transmission network in the world upon completion [cxlii]. The integration of power-to-gas is also proposed in the Eurobar (European Offshore Busbar) concept, which proposes to use a single offshore platform along with onshore HVDC corridors to maximize the utilization of wind capacity from the North Sea [143].

#### 4.2.2 Cluster 2 – EUMENA Supergrid

Two major studies focusing on the EUMENA [European Union (EU) and the Middle East and North Africa (MENA)] region are Dii Desert Energy [144] and MedGrid [147]. Dii Desert Energy is an industry initiative focusing on market development and renewable integration in Southern Europe, North Africa, and West Asia. It was initially called the DESERTEC Industry Initiative and was first proposed by Gerhard Knies [145], aiming for a sustainable globe powering from the Sahara Desert. Concentrated solar power (CSP) would play a major role to take advantage of the massive solar resource in the region.

Figure 17 shows the initial conceptual proposal from DESERTEC of an HVDC overlay across EUMENA. In the Dii's report [144, 146], a pan-EUMENA HVDC overlay grid is proposed, and assessed from 2030 to 2050, to facilitate the integration of renewable resources and enable exchange of large amounts of electric energy across the EU and MENA electricity markets. It shows that all countries in the EUMENA region would benefit from an integrated power system based on 90% of renewable energy. Such an integrated system would enable Europe to achieve its CO2 reduction target of 95% in

the power sector more effectively and more economically by importing up to 20% of its electricity demand from the MENA region, at a savings of €33B per year. The developed desert power would not only supply the electric energy needs within the MENA region itself contributing to a 50% CO2 reduction in the power sector but would also benefit from exporting the surplus energy worth up to €63B per year. The marginal cost of CO2 emissions would be reduced by 40% to 113€/ton. The proposed 2050 HVDC overlay grid is shown in Figure 18. The report concludes that in order to achieve such an HVDC overlay by 2050, a total capacity of 628GW and 625GW across EUMENA countries are needed for internal lines and cross-border lines, respectively.



Figure 17: The DESERTEC concept [cxlix, cl] (used with permission)



Figure 18: Line capacities of EUMENA overlay grid by 2050 [144] (used with permission)

A similar project was the Medgrid Industrial Initiative which was formed in 2010 to support the design and promotion of a Mediterranean transmission network able to export 5GW of electricity from MENA to Southern Europe out of the 20GW of renewables to be built in MENA. The overall estimated cost of the combined project was between 38 and 46 billion € [147]. The MedGrid consortium ceased its operation in 2016 after

completion of several planning and pre-feasibility studies [148].

Although the DESERTEC and MedGrid studies created a great deal of interest, they are no longer considered viable, at least not in the sense of the original vision. This is because European nations are hesitant to accept significant energy dependence on North Africa, and because some North African countries have come to view the effort as reminiscent of the European colonialism of previous centuries [151, 152].

### 4.2.3 Cluster 3 – Continental European Supergrid

One of the earliest proposals for a European continent-wide supergrid was the 2010 Roadmap 2050 [153] and subsequent follow-on studies [154]. From a high level, a European Supergrid could be either composed of single DC links, or one meshed DC grid [134]. So far, single DC links have been deployed in the major implementations when building actual transmission projects, whereas most meshed DC grid proposals are at conceptual stages.

#### European Supergrid composed of single DC links

For a supergrid composed of single DC links, ENTSO-E's bi-annual TYNDP is the most comprehensive planning reference for the pan-European electricity transmission network. It presents and assesses all relevant pan-European projects at a specific time horizon under a set of various scenarios. It is also used as basis for the selection of projects of common interest (PCI), which are key infrastructure projects, especially cross-border projects that link energy systems of EU countries to achieve climate and energy objectives. PCIs are identified under the responsibility of the European commission based on cost benefit analysis, which can serve for EU-wide cost-allocation purposes. PCIs receive favorable regulatory treatment and can apply for financial support from the European commission. Figure 19 shows the high voltage electricity transmission PCIs captured from an interactive map [155].

The legal basis of the PCIs are settled in Regulation (EU) No 347/2013, among others describing the 12 corridors [156], which are nine priority corridors (4 electricity corridors, 4 gas corridors, 1 oil corridor) and 3 thematic corridors, such as smart grids deployment, cross-border CO<sub>2</sub> network and Electricity highways. The idea of the “Electricity highways” corridor is based on the EU research project with the same name called “e-highway 2050” [157]. The e-Highway 2050 project is a 40-month research project, carried out by a large consortium of TSOs, industrial associations, academics, consultants and one NGO, investigating transition paths to support the European Union in reaching a low carbon economy from 2030 to 2050. An invariant set of transmission requirements as shown in

Figure 20 were found regardless of the simulation scenarios, most of which lie in the major “North-South” corridors, whose benefits resulting from the optimal use of energy sources largely exceed their costs. They are good candidates for mid-term grid investments due to their robustness when facing large uncertainties. The total investment in the grid expansion

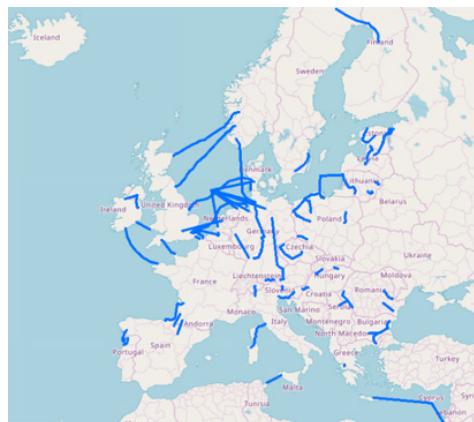


Figure 19: High voltage lines in Projects of Common Interest [adapted from 155]

lies between €100B to €400B, depending on the scenarios. However, the resulting benefits outweigh the investment cost in all cases: the renewable curtailments can be reduced by 500TWh, and 200 mega tons of CO<sub>2</sub> emissions can be eliminated. In one scenario, with 100% renewables, the grid investment is €20B per year but the savings from the grid reinforcement reaches €55B per year, yielding a benefit-to-cost ratio of 2.75. The parameters used to calculate savings include energy not supplied, fuel savings, and CO<sub>2</sub> reduction savings (assumed to be €270 per ton).

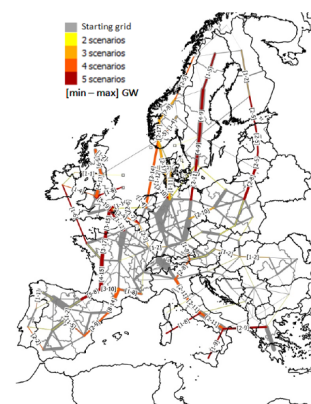


Figure 20: e-Highway 2050 major transmission corridors (widths indicate average reinforcement capacity; color represents the number of scenarios where the reinforcement is needed) [157] (used with permission)

Another older study called Greenpeace [158] focuses more on Central Europe network expansion without considering the integration of wind in the north and solar in the south. It compares three scenarios with different energy mix assumptions, and concludes that, in comparison to the TYNDP 2012 design, an optimized HVDC overlay would integrate two times more renewable energy (860GW of wind and PV in contrast to 400GW in TYNDP), using only 74% of the transmission expansion levels used in TYNDP. With a curtailment reduction of 2%, the saved curtailment cost could reach €60B which itself is comparable to the network expansion cost of €61B.

### European supergrid composed of one meshed DC grid

A continental European supergrid with a meshed DC grid was proposed by some older studies. These studies received significant attention between 2010-2013 but have been more recently superseded by other studies; they illustrated more of a vision rather than a plan, and aimed to feed a public/scientific debate. Two proposed designs are listed in this section.

The first study is a 40-node DC grid proposed by ABB. The 40-node HVDC grid with 30GW infeed of renewable power is shown in Figure 21. The main generation resources are the solar energy from the Sahara Desert in the south (19.2GW),

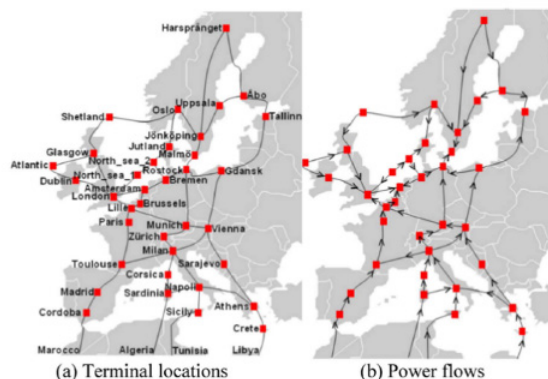


Figure 21: ABB 40 nodes overlay HVDC grid [clix] (used with permission)

hydropower in Northern Europe (2.2GW), and wind power from Western Europe (7.8GW). The terminals are all VSC in bipolar configuration with metallic return cables. Munich is used as the only DC slack bus to control the DC voltage, while all other VSCs are in power control mode. The results have shown that the very large DC grid is feasible in terms of load flow, but it is desired to have multiple converters participate in DC voltage control in case of power unbalance in the DC network, to share the burden of the only slack converter at Munich and also mitigate impact to the AC system connected to it.



Figure 22: Friends of the supergrid (FOSG): scenario 2050 [adapted from clix]

Another continental European supergrid topology was proposed by what was initially known as the Friends of the Supergrid (FOSG), currently known as “Friends of Sustainable Grid,” as shown in Figure 22. The motivation of the design was to integrate the offshore wind in the North Sea and solar resource in North Africa into continental Europe and surrounding countries.

### 4.2.4 Summary for Europe: Benefits and Characteristics

Europe has an ambitious goal of achieving climate neutrality by 2050. The integration of offshore wind resource especially in the Northern Seas and the solar resource in southern Europe will rely on the development of a more interconnected European power system via high voltage transmission. As more wind and solar resources are integrated into the system, the inertial reduction also requires a more integrated system for sharing of ancillary services to achieve a more reliable grid. It is shown in [161] that the cost of reserves could be reduced by up to 70% if the HVDCs are equipped with emergency power control schemes, leading to savings of 1.7-4.8 million euros per year in the Nordic system.

An offshore supergrid enabled by multi-terminal offshore hubs or potential energy islands in the North Sea with a “Hub-and-Spoke” concept is of particular interest. ENTSO-E has recently identified five pillars for a successful offshore development [162]: (1) holistic planning and timeliness; (2) a modular and stepwise approach based on consistent planning methods; (3) interoperability unlocking smarter integrated and secure system operations; (4) keeping energy bills and environmental footprint low through innovation; and (5) a future-proof regulatory framework. Significant progress has also been made in the Mediterranean Sea region as building

permits are issued for the EuroAsia and EuroAfrica projects [163, 237], linking Greece and Cyprus with Israel and Egypt. Cross-border interconnections have also been proposed for better sharing of resource and capacities. Major examples include the interconnectors between UK and Norway, UK and Denmark, UK and Continental Europe, and those between Spain and France. Important intra-state transmissions include the north-south HVDC links in Germany. Ultimately, these separated HVDC links and the regional supergrid such as that proposed for the North Sea region could be integrated into a European supergrid interconnecting the whole of Europe and neighboring countries. Although various conceptual designs have been proposed for such a meshed European supergrid, the development of such an integrated continental supergrid is still at an early stage.

In terms of actually building these proposed lines, Europe faces some unique challenges as compared to the US. For example, interstate resistance due to distrust between different nations could potentially hinder the development of cross-border interconnections. A significant problem faced by all European member states is public resistance mainly due to potential visual impact or fear from electromagnetic fields. In some cases, the allocation of costs and benefits raises discussions as citizens of one state do not want to pay for their neighbor's benefits. To address this cost and benefit allocation issue, the Regulation (EU) No 347/2013 foresees a cross border cost allocation mechanism, which is currently under review and is an important initiative as part of the European Green Deal [164]. Financial structures are different in the member states, which increases uncertainty around cost allocation and cost recovery when considering interregional transmission. Furthermore, the European Commission has some but not unlimited scope to push the development of these proposed lines. For example, the EC provided the regulation framework with Regulation (EU) 347/2013 for PCIs. Project promoters and national authorities have to do their utmost to follow related given timelines in project implementation. If one of the partners is too slow, then the EC can intervene and push the development. Finally, economic incentives are also missing for the development of some of these proposed lines, e.g., the north-south transmission projects in Germany, due largely to the lack of a centralized market operator in much of Europe. The Regulation (EU) No 347/2013 attempts to address the lack of economic incentives by giving access to financial support in case a project is beneficial for Europe and has a positive cost-benefit relation but one of the hosting member states is a net-payer.

## 4.3 China and Northeast Asia

### 4.3.1 China

In order to move the carbon emission peak to earlier than 2030, and achieve the goal of 2°C temperature rise according to the United Nations report (2014), the CO<sub>2</sub> emission intensity of the Chinese power sector needs to be reduced by 90% by the year 2050 [165]. The electricity sector emits more than 40% of China's CO<sub>2</sub> from fossil fuel combustion. Therefore, increasing the share of clean energy or renewables is vital. The fact that the load centers (in the south and east) are far away from the renewable energy resources (in the north and west) favors the development of ultra-high voltage (UHV) transmission due to its long distance bulk power transfer capability and high efficiency with low power losses.

Electricity planning in China is mainly guided by the five-year planning process at both the national and provincial levels, which enumerates policy directions and key investment projects nation-wide. Five major drivers for China's development of high capacity interregional transmission are as follows [173, 175, 166]:

1. Uneven distribution of generation resources and load; major loads in the east and south coasts are far from northwest resources (one HVDC line, from Qinghai to Henan, reduces CO<sub>2</sub> emissions by 7 million tons/year (equivalent to 2 million cars being taken off the road);
2. Rapid urbanization of society, especially in eastern & central China;
3. Government-led infrastructure development for economic growth;
4. Renewable integration goal in response to climate change;
5. Lack of natural gas/petroleum resources to provide flexibility;
6. Cascading risk in UHVDC-receiving regions (e.g., Shanghai); UHVAC near these regions are built to address this concern.

High generation cost and low transmission capacity are identified to be the two major barriers for renewable energy resource development. The study in [165] performs quantitative analysis to identify the most effective regional subsidy and interregional transmission capacity levels to facilitate integration of clean energy resources, including biomass, wind, hydro, solar and nuclear. The most effective subsidy is defined as the lowest subsidy among all scenarios to achieve a maximum generation capacity in all four decades of 2020, 2023, 2040 and 2050.

These subsidies ensure a smooth and steady increase in developing the clean energy resources. The study finds that

even with the most effective clean energy subsidies, the share of coal-fired plants is still over half of the generation capacity

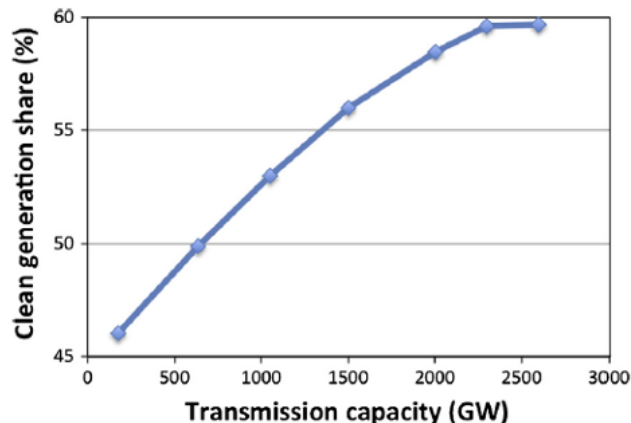


Figure 23: Clean energy capacity share and transmission capacity in 2050 [165] (used with permission)

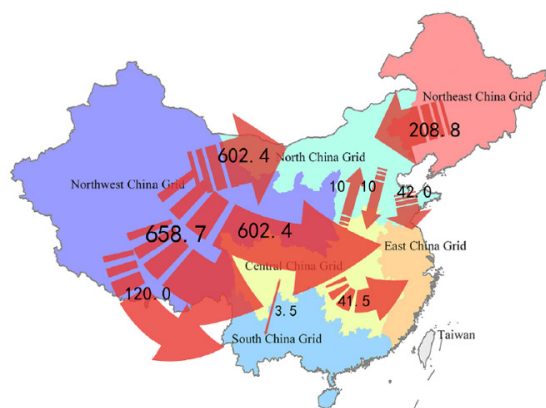


Figure 24: Six regional grids in China and the most effective interregional power transmission capacities (GW) in 2050 [165] (used with permission)

because of the insufficient transmission capacity. It concludes that there is strong inter-relationship between the interregional transmission capacity and the clean energy penetration levels, as shown in Figure 23. The study shows that given the most effective subsidies are provided, the most effective interregional transmission capacity is 2300GW (with a clean energy share of 59.6%), beyond which the clean energy share would not further increase. Figure 24 shows the most effective interregional power transmission capacities in 2050 [165].

China is heavily deploying UHV transmission. By October 2019, there were 9 UHVAC and 14 UHVDC transmission lines [167]. State Grid Corporation of China owns all nine UHVAC lines and 11 UHVDC lines; China Southern Power Grid owns the remaining three UHVDC lines. The 14 UHVDC lines form an

“eight-vertical six-horizontal” structure across China. The nine UHVAC lines are mainly located in North-Central and East China Grid, composed of three major structures: a “two-horizontal one-vertical” structure in the North Grid, a ring network in the East Grid with extension to Fujian in the south, and an interregional AC transmission line connecting the North Grid with the Central Grid. The world’s first 1000kV gas-insulated line (GIL) to transmit power under the Yantze River (part of the 1000kV Huannan-Nanjing-Shanghai UHVAC transmission project guided by China’s air pollution control action plan made in 2013), was put into service in 2019. It completes the UHVAC ring network in east China, improving power acceptance capability. It reduces the consumption of coal by 170 million tons annually and CO2 emissions by 310 million tons annually, improving environmental quality [168].

A total of more than 30,000 km of UHV lines have been built across China [169, 170], with the largest link being the Changji-to-Guquan 1100kV HVDC link from the west to the east [171]. However, for stability concerns, this link has carried less than one-quarter of its designed capacity of 12GW on average, which causes curtailment of abundant renewable energies in the west. Other UHV lines have a similar situation, which is worsened by the fact that eastern provinces do not have enough incentives to import the clean energies carried on these UHV lines. A practical solution to this issue is to increase the redundancy of these HVDC lines and to strengthen the receiving region with UHV AC lines to help distribute the imported electricity, although some experts argue unifying China’s grid would make it more vulnerable to cascading blackouts [169]. Figure 25 shows the existing and planned UHV lines in China by 2025.

Table 3 shows length and capacity of existing high voltage transmission built in China until 2019. Since the start of 2020, China has proposed to build 14 new UHV lines: seven UHVDC and seven UHVAC [172, 173], as listed in Table 4. The total cost of these UHV projects is estimated to be \$25.6 billion in 2020. Among these planned UHV lines, there has been significant progress for three UHVDC lines: the 1700km Yanzhong-Nanchang UHVDC line, the 1100km Shaanbei-Wuhan UHVDC line, and the 1500km Qinghai-Henan UHVDC line [174]. Each line has 8GW capacity. Once operational, the Qinghai-Henan project is estimated to reduce CO2 emissions by approximately 20 million tons per year, equivalent to over six million passenger cars being taken off the road [174]. Moreover, the Qinghai-Henan UHVDC project alone could drive more than \$28.2 billion investment and create 10,000 jobs in renewable energy development and associated industries [175]. In terms of UHVAC development, it is expected to form a “five-horizontal four-vertical” network in the east, and “two-vertical one-ring” network in the west by 2025 [178].

The Global Energy Interconnection Development and



Figure 25: Existing and planned (dashed) UHV lines by 2025 [179] (used with permission)

Table 3: High voltage transmission statistics in China [177]

		Transmission line length built (km)		Power transmission capacity (GW)	
		2019	2018	2019	2018
A	1000kV	11,709	10,396	162	147
	750kV	22,198	20,543	178	168
D C	±1100kV DC	608	608	18	6
	±800kV DC	21,954	21,954	178	178
	±660kV DC	2091	2091	19	19
	±550kV DC	15,428	15,428	134	134
Total		73,988	71,020	689	652

Table 4: Near term investments in UHV transmission projects in 2020 [172,179]

Technology	Transmission Line Name	Voltage (kV)	Timeline	Investment (\$bn)
UHVDC	Qinghai - Henan	±800	2020 partial COD	3.79
UHVDC	<u>Shanbei - Hubei</u>	±800	2020 partial COD	2.59
<u>UHVDC</u>	Longdong - Shandong	±800	2020 seek approval	NA
UHVDC	Hami - Chongqing	±800	NA	NA
<u>UHVDC</u>	Yazhong - Nanchang	±800	2021 COD	4.44
UHVDC	<u>Baihetan - Jiangsu</u>	±800	2020 seek approval	2.28
<u>UHVDC</u>	Baihetan - Zhejiang	±800	2020 seek approval	2.79
HVDC	<u>Yunnan - Guizhou</u>	±500	2020 COD	NA
<u>HVDC</u>	Fujian - Guangdong DC B2B	NA	2020 seek approval	NA
UHVAC	Zhangbei - Xiongan	1000	2020 COD	1.47
UHVAC	Nanyang - Jingmen - Changsha	1000	2020 seek approval	2.94
UHVAC	Zhumadian - Nanyang	1000	2020 COD	1.26
UHVAC	Zhumadian - Wuhan	1000	2020 seek approval	1.26
UHVAC	Jingmen - Wuhan	1000	2020 seek approval	0.63
UHVAC	Nanchang - Wuhan	1000	2020 seek approval	1.68
UHVAC	Nanchang - Changsha	1000	2020 seek approval	1.68
<b>Total Chinese investment in near term UHV transmission projects</b>				<b>25.6</b>



Cooperation Organization (GEIDCO) recently published two reports focusing on the energy transition and electricity planning in China, which serve as a valuable reference for the upcoming 14th five-year national plan (from 2021 to 2025) in 2021. The major message from these reports is to build a clean-energy-based low-carbon modern energy system with high security and high efficiency in China. The energy transition report [178] communicates several important strategic features of the recommended approach, as follows:

1. Coal-to-clean energy: Transition from coal dominant to clean-energy-based energy production, strictly control the total capacity of coal plants, and develop clean energy based resources.
2. Electrification: Transition from fossil fuel based to electricity-based energy consumption.
3. Build transmission: Transition from local balanced energy allocation to wide area interregional interconnection, build two

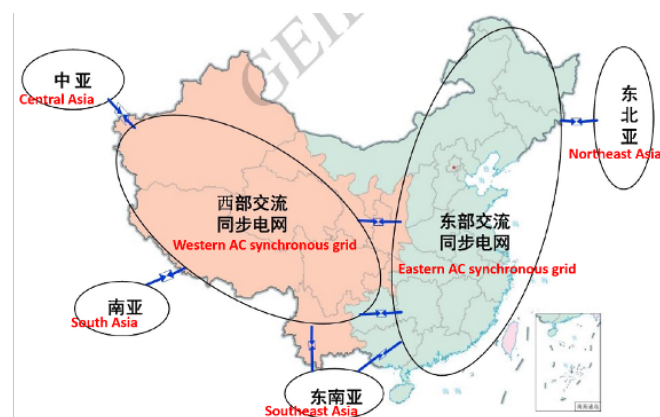


Figure 27: Interregional, interprovincial, and international 2025 power exchange capacities [adapted from 179]

large asynchronous interconnections in the east and west per Figure 26, strengthen UHV backbones, and form the pattern consisting of “Western electricity to the East,” “Northern electricity to the South,” and international Interconnections.

4. Technology: Expedite technology innovation in energy development, conversion, allocation, storage and applications.
5. Markets: Expedite the construction of a mature power system market for open and fair competitions.

The electricity planning report [179] predicts that the interregional and inter-provincial power transfer capacity will increase from 220GW in 2019 to 360GW, 550GW and

740GW in 2025, 2035 and 2050, respectively. The proposed interregional power exchange capacities for 2025 and 2050 are shown in Figure 27 and Figure 28, respectively.

The report also points out the necessity of building a synchronous grid with UHV AC backbones in the North, Central, and East China to improve grid resilience, which

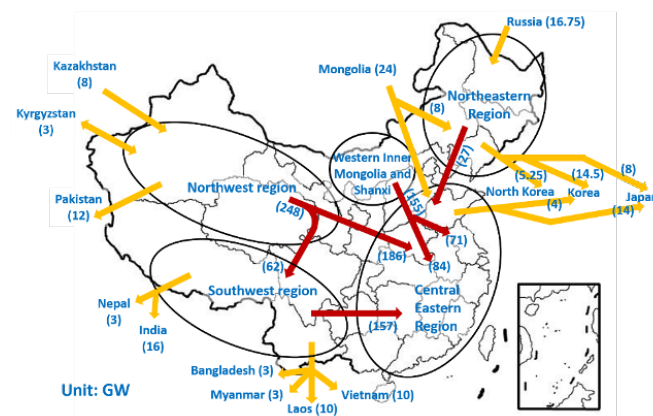
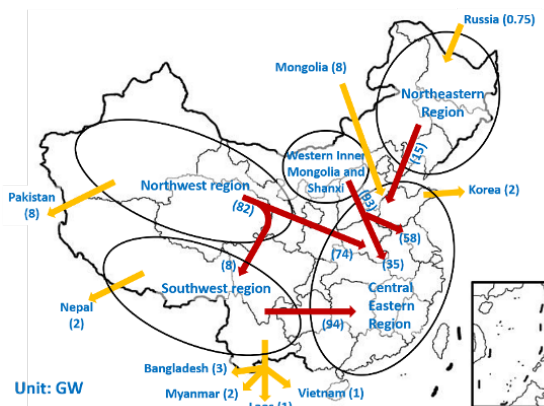


Figure 28: Interregional, inter-provincial and international power exchange capacities in 2050 [adapted from 179]

otherwise would be compromised due to the “strong DC weak AC” condition. Besides strengthening interregional transmission within China, the report also proposes to expedite international interconnections with four high capacity UHVDC lines with neighboring countries: Mongolia, Pakistan, Myanmar-Bangladesh, and Korea-Japan. The expected international transmission capacity to be built by 2025 is 28 GW, including four back to back HVDC schemes with Nepal, Myanmar, Laos, and Vietnam. The expected international capacity exchange by

2050 is 155 GW, as shown in Figure 28.

### Multi-terminal HVDC development in China

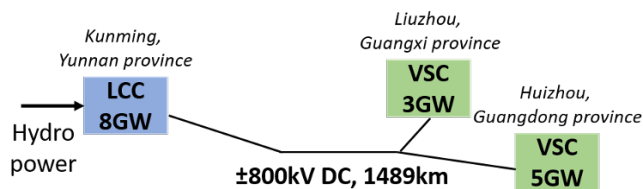


Figure 29: Wudongde three terminal hybrid UHVDC grid [adapted from 180]

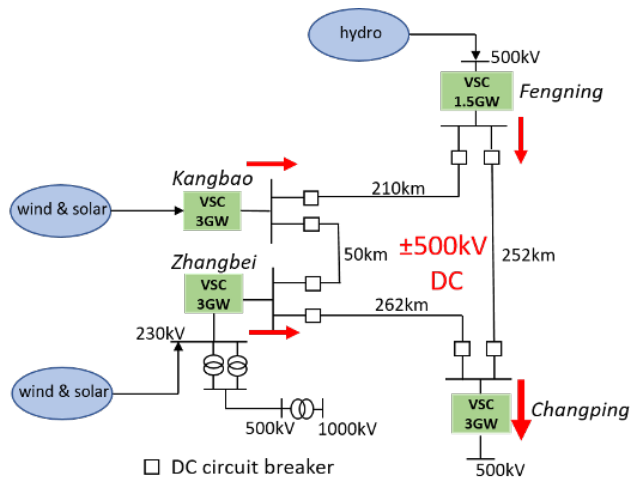


Figure 30: Zhangbei VSC-HVDC grid [adapted from 180]

China has also been leading the development of multi-terminal HVDC projects. Two representative projects are the three terminal  $\pm 800\text{kV}$ , 8 GW Wudongde HVDC grid, and the four terminal  $\pm 500\text{kV}$  3 GW Zhangbei VSC-MTDC grid. The Wudongde HVDC grid is the first high capacity hybrid LCC-VSC HVDC grid in the world. The 1489km UHVDC line delivers hydro power from the Yunnan province in the Southwest to Guangxi and Guangdong provinces in the east, as illustrated in Figure 29 [180]. The Zhangbei VSC-MTDC grid integrates various energy resources, such as wind, solar and pumped hydro in three sending stations, and delivers clean energy into the load center in Beijing, as shown in Figure 30 [180].

### 4.3.2 Northeast Asia

The Gobitec concept and the corresponding Asian Super Grid (ASG) represent the idea of producing clean energy from renewable energy sources in the Gobi and Taklamakan

Deserts, as well as from hydro power in the Russian Far East, and then delivering large volumes of power to the Northeast Asian load centers in China, South Korea and Japan [181]. The idea is similar to the DESERTEC concept proposed in the EUMENA region (see Section 4.2.2). A vision of the ASG was proposed in 2014 as shown in Figure 31 [182], establishing links between the electricity grids of China, Japan, Korea, Mongolia, and possibly Russia. An underpinning of the ASG is to facilitate trade in electric energy. Potential economic, social, and environmental benefits for Mongolia and other ASG countries have been studied in [183]. These benefits mainly include reduced system operation costs, increased reliability by sharing reserves, job creation, poverty alleviation, and a reduction of CO<sub>2</sub> emissions.



Figure 31: Asian supergrid [adapted from 182]

### 4.3.3 Summary for China and Northeast Asia: Benefits and Characteristics

China has made great progress in the development of ultra-high voltage (UHV) transmission. The developed UHVDC interconnections generally follow the “north to south” and “west to east” patterns, aiming to make accessible the low-cost, rich wind and solar resources from the remote areas to the major load centers. These investments result in benefits to China in the form of job creation and economic stimulus, decreased energy costs, and lowered decarbonization costs. In order to ensure reliability (particularly stability), UHVAC transmission has also been built mostly at the receiving end to strengthen the underlying AC grid. The Chinese government is dedicated to promoting the development of more UHV transmission in the future.

From a perspective of Northeast Asia, the idea of an “Asian Super Grid,” if implemented, would allow the major load centers in northeast China, Korea and Japan to access the massive amount of solar resource in the Gobi desert and the

hydro resource in the Russian Far East.

## 4.4 India and South Asia, Southeast Asia, and Australia

### 4.4.1 India and South Asia

There are five regional grids in India – Northern Region, Western Region, Southern Region, Eastern Region, and North-Eastern Region. They have been integrated to one synchronous grid through multiple AC and HVDC links since 2013, as shown in Figure 32 [184]. According to [185], the total installed renewable capacity in India has reached 88.8GW as of Aug 31, 2020, and has a target of reaching 101GW by the end of the fiscal year 2020-21. The National Electricity Plan (NEP) passed in 2018 [186] projects the share of non-fossil based installed capacity (nuclear, hydro, wind and solar) will increase



Figure 32: Existing and Planned Interregional transmission links in India [184] (used with permission)

to 49.3% by the end of 2021-22 and will further increase to 57.4% by the end of 2026-27. The 2018-2019 Annual Report from the India Ministry of Power [187] recognizes the need of enhancing interregional links. As of Mar 31 2019, interregional power transfer capacity of the National Grid in India is about 99,050MW, and is expected to reach 118,050 MW by 2021-22, as shown in Table 5.

To facilitate the transmission of clean hydro power from the hydro-rich north-east region, a three terminal  $\pm 800$  kV, 6,000 MW UHVDC line was built [188], capable of moving 6000MW of power across 1700km from the northeast region to the city

of Agra in north central India. Another  $\pm 800$  kV UHVDC line Raigarh-Pugalur of 1800km is also being built with a capacity of 6000MW connecting Raigarh in Central India to Pugalur in the southern state of Tamil Nadu, and is expected to complete in December 2020 [189]. It enables easier transmission of renewable energy from the south where there is excessive wind power to the north, and vice versa in low wind conditions to support the power deficit in the south. Along with the Raigarh-Pugalur UHVDC line, there is a parallel project of a 320kV HVDC line horizontally spanning 153 km in the southern region, using the VSC technology due to the limitation of right-of-way.

### Interconnection of India with the rest of South Asia

Centrally located in South Asia, India plays an important role in facilitating the planning of interconnections in South Asia countries for effective utilization of regional resources. Figure 33 [190] shows a conceptually proposed inter-regional HVDC interconnection with neighboring countries. India already has interconnections with many countries in the South Asian Association for Regional Cooperation (SAARC), such as Nepal, Bhutan, Bangladesh, Sri Lanka, and Myanmar [187]. Most of the existing interconnections are AC, whereas HVDC is also being considered for future interconnection, such as the

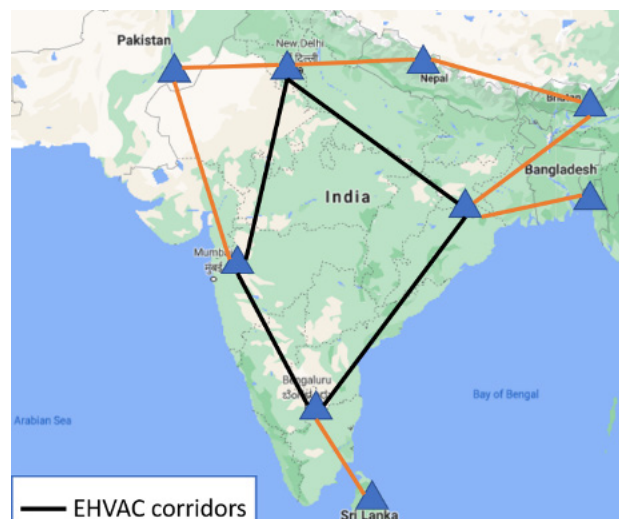


Figure 33: Energy corridors connecting regional grids and the grids of the member countries [adapted from 190]

2x500MW HVDC bipole line between Madurai (India) and New Anuradhapura (Sri Lanka). Various benefits are gained through these cross-country interconnections. For example, the interconnection with Bangladesh reduces the low frequency operation below 48.9Hz by 60%, reduces transmission losses, improves the voltage profile of West Bangladesh and reduces dependence on expensive gas and oil resources [184].

Table 5: Interregional transmission capacity of National Grid in India from 2018 to 2022

Region	Capacity (MW) up to Mar 2018	Capacity (MW) up to Mar 2019	Expected capacity (MW) by Mar 2022
East-North (ER-NR)	22530	22530	22530
East-West (ER-WR)	12790	21190	21190
<u>West-North (WR-NR)</u>	25320	29520	36720
East-South (ER-SR)	7830	7830	7830
<u>West-South (WR-SR)</u>	12120	12120	23920
East-North-east (ER-NER)	2860	2860	2860
<u>North-east-North (NER-NR)</u>	3000	3000	3000
<b>Total</b>	<b>86450</b>	<b>99050</b>	<b>118050</b>

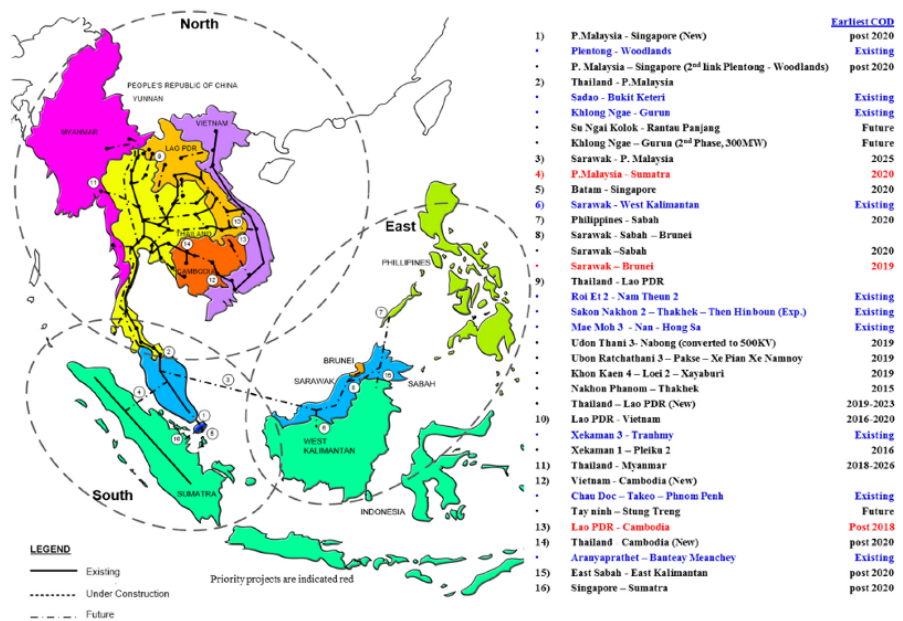


Figure 34: Geographical map of APG interconnections [197, 198] (used with permission)

In June 2020, Indian government initiated the One Sun, One World, One Grid (OSOWOG) Initiative to expedite the development of the renewable energy based global energy interconnection. The OSOWOG initiative is composed of three stages. Stage 1 intends to achieve the interconnection between Middle East, South Asia and Southeast Asia (MESASEA); Stage 2 intends to realize the interconnection of MESASEA with African power grid and achieve clean energy allocation in a wider geographic scale; Stage 3 will be the ultimate global energy interconnection to achieve worldwide clean energy sharing [192].

### Central Asia – South Asia interconnection

A recent Central Asia-South Asia project, commonly known as CASA-1000, is a \$1.16 billion project currently under construction [cxci]. It will build a three terminal 750km 1300MW HVDC transmission line along with a 477km 500kV AC transmission line, which allows power exchange between Central Asia and South Asia. The project will facilitate interregional and inter-seasonal resource sharing. For example, in winter, Pakistan can export excessive electricity to Tajikistan, Kyrgyzstan and Afghanistan, whereas in the summer, surplus hydro resources from the latter three countries can be exported to Pakistan. The construction started in May 2016 and is expected to be in operation in 2023 [192].

### 4.4.2 Southeast Asia

The energy development in Southeast Asia has been heavily relying on fossil fuels. However, the fossil fuel reserves are

diminishing quickly while the overall energy consumption in the region is increasing rapidly. In some developing areas, many people still burn wood and biomass for cooking and heating, which poses risks for people’s health and causes environmental pollution. Moreover, Southeast Asia is a major region impacted by global warming with rising sea level. All these factors [193] create urgency in regards to developing renewable energy resources to satisfy the fast growing electricity demand in a techno-economic and sustainable way. Although rich in renewable energy resources, especially in hydro, geothermal and solar, the region faces the challenge of geographical mismatch with load centers far away from these resources. For example, Myanmar and Lao PDR have abundant hydro resources whereas the main load centers are in Thailand and Vietnam. Therefore, developing interregional transmission is essential for a sustainable future with high shares of renewables in Southeast Asia.

ASEAN (Association of Southeast Asian Nations) power grid [194, 195] is an initiative to construct a regional power interconnection for South East Asia. Regional power trading has been limited to a series of uncoordinated bilateral cross-border arrangements, but multi-lateral power trading has been examined [196] and is shown capable of providing multiple benefits, such as reduced system costs, increased energy security and the ability to facilitate high share of renewable energy integration. Figure 34 shows the status of existing, ongoing and future interconnection projects in southeast Asia, whose combined capacities are 5GW, 6GW and 28GW, respectively [197, 198].



\*Numbers in MW and arrows show the maximum power flow between the interconnections and dominant directions  
 Figure 35: Optimal cross-border transmission capacities for ASEAN region in 2030 [199] (used with permission)

In a recent study [199], the authors identified the optimal cross-border transmission capacities in 2030 for the ASEAN power grid (APG) to promote renewable power generation as shown in Figure 35. The dominant power flow directions between 15 nodes of 10 countries are also shown on this map, which indicate the net electricity exporters to be Myanmar, Lao PDR, Cambodia, Sumatra (Indonesia), and Sarawak (Malaysia) because of the availability of low-cost generation resources in these regions (mostly hydro and geothermal). On the other hand, the net electricity importers are Thailand, Vietnam, P. Malaysia, Singapore, W. Kalimantan (Indonesia), E. Kalimantan, Brunei, Sabah (Malaysia) and Luzon (Philippines). The authors also compared the economic characteristics (capital and operational costs) of HVDC and HVAC technologies to interconnect the ASEAN countries. HVDC is shown to be more economic beneficial for many of the identified interconnections because of its higher energy efficiency, lower losses, and no need for reactive power compensation.

#### 4.4.3 Australia

Australia is an energy self-sufficient country rich in both fossil-based and renewable resources. It is a large continent with low population density, and reduction in energy consumption has been observed in recent years [200]. Coal and natural gas have been the major resources that are exported, but its abundant renewable resources are still underutilized. On the other hand, many of the neighboring Asia countries are in the middle of fast economic development with increasing energy consumption. Therefore, interconnecting the two regions would

allow electricity exchange and optimized sharing of generated renewable resources. By connecting the abundant renewable resources in Northeast Asian countries such as China and Mongolia with those in Australia, the averaging effects of large-scale connectivity could further benefit uncorrelated regional intermittencies and ensure an optimized resource allocation in a cost-effective manner.

Along this line of thought, a pan-Asia energy infrastructure (or Transnational Asian Grid) is proposed in [201], which is envisioned as an undersea HVDC cable running from the northern coast of Australia along the Indonesian archipelago and up into the Philippines, Malaysia, Singapore, and Indochina and then eventually into China, with the aim of exporting northern Australia's abundant solar resources to Southeast Asia. Figure 36 [201] shows major renewable energy resource distributions in Asia and the proposed pan-Asia Supergrid. Major steps have been made towards the implementation of the Australia-ASEAN Supergrid, a sub component of the pan-Asia energy infrastructure. The Australian-ASEAN power link (AAPL) currently developed by SunCable received endorsement from the Australian government in July 2020, and is expected to be in operation in 2027 at a cost of about \$16 billion [202]. The AAPL will integrate three cutting edge technologies – the world's largest solar farm of 10GW, largest battery storage facility of 30GWh and the world's longest HVDC of 4500km capable of providing 3GW of dispatchable power from Australia to Southeast Asia, capable of supporting 20% of electricity demand in Singapore [203].

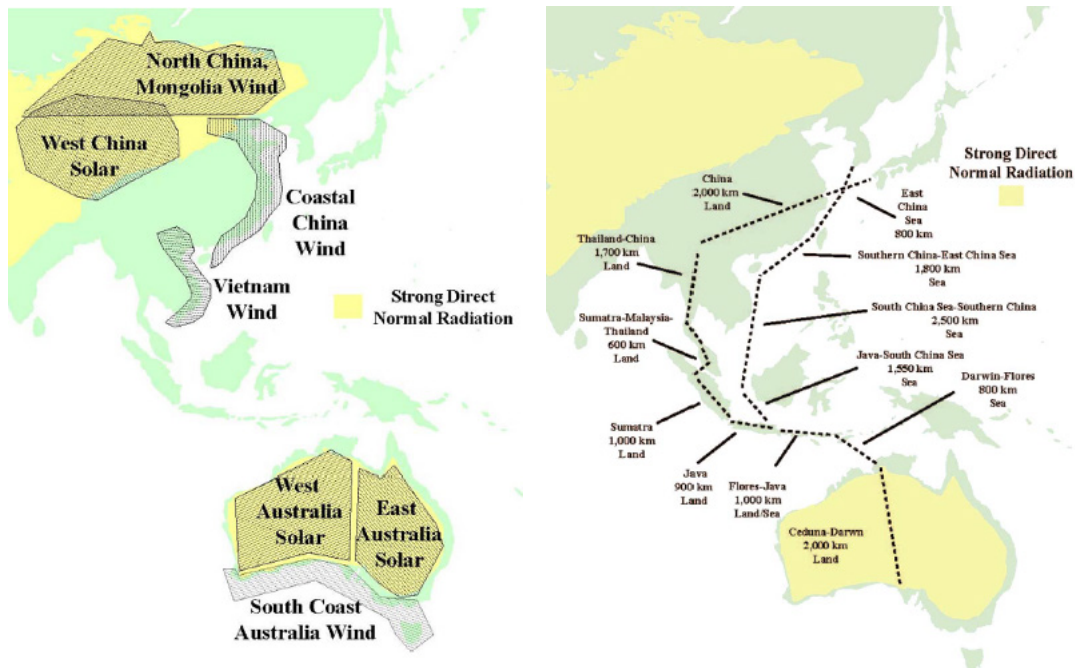


Figure 36: Asia-Pacific renewable resource distribution; proposed routes of pan-Asia supergrid [201] (used with permission)

The Australian National Electricity Market (NEM) covers the synchronously connected eastern and southern Australian transmission grids, and is composed of five markets, namely Queensland, New South Wales, Victoria, Tasmania, and South Australia. Due to the weak interconnection capacities between these markets, high pool prices up to \$10,700/MWh have resulted, and renewable energy resource developments have been hindered, such as wind development in South Australia and solar development in Queensland [204]. Furthermore, as conventional generation is retired, these weak interconnections cannot satisfy stability requirements in a grid with low synchronous inertia. For example, lack of interconnection support was the major reason behind the South Australian blackout in September 2016 after one of the interconnections was lost [204].

To strengthen the interconnection within NEM, the 1500MW undersea/underground Marinus link was proposed, which would be the 2nd Basslink interconnecting Tasmania to the mainland Australia [205] as shown in Figure 37. Besides contributing to stimulating economic growth and creating thousands of jobs (2800 jobs at peak construction), the link will enable integration of cost-competitive renewable energy, diversify the generation mix, increase supply security, reduce risks of relying on a single interconnector across Bass Strait and utilize the flexible control of the voltage source converter (VSC) technology. The first stage of the link with 750MW of capacity is expected to be in operation in 2028, and the second stage with the other 750MW in operation between 2030 and 2032 [206].

Similarly, a conceptual trans-Australian HVDC interconnector is proposed interconnecting Queensland and South Australia [205]. Two proposed routes, a direct route of 870 miles and a strategic route of 1000 miles, are shown in Figure 37. A preliminary study indicates a capacity of 700MW at a voltage of  $\pm 350\text{kV}$  or  $\pm 400\text{kV}$  would be an efficient design. The total



Figure 37: Marinus link and proposed routes for the Trans-Australian HVDC interconnector [adapted from 204]

life-cycle cost is \$1092million and \$1077million, with estimated benefits of \$1769million and \$2000million for the direct design and strategic design, respectively. The major benefits are identified to be help achieve renewable integration targets, create additional employment opportunities, stimulate regional economy, and increase competitiveness and security of NEM [204].

Besides the electricity supergrid, a hydrogen network is expected to be either a complementary or alternative strategy to support Australia's domestic energy demand and also the export industry. Hydrogen export has been identified as a national strategy in Australia which could worth \$1.7billion by 2030 and provide 2800 jobs [207]. Although currently not cost competitive as fossil fuel based resources, green hydrogen primarily produced by solar electrolysis is expected to reach cost parity by 2030 and some megaprojects are already taking place. For example, a 6500 km<sup>2</sup> project in Western Australia called "Asian Renewable Energy Hub (AREH) aims to power the local Pilbara region as well as export hydrogen to Japan and South Korea [208].

#### 4.4.4 Summary for South Asia, Southeast Asia and Australia: Benefits and Characteristics

Development and integration of cost-effective renewable energy resources are driving interregional transmission development in South Asia, Southeast Asia and Australia. In India, two major existing and near-term planned UHVDC corridors are the northwest to north central for integration of hydro resources in the northwest, and the north-south corridor for sharing wind resources in the south. India also serves an important role in interconnecting with other South Asian countries for improved resource sharing and improved grid reliability, such as providing frequency support to the grid in Bangladesh. The interconnection between South Asia and Central Asia is also being strengthened with the ongoing project CASA-1000, linking Pakistan with Central Asian countries Tajikistan, Kyrgyzstan, and Afghanistan for inter-seasonal resource sharing. In terms of Southeast Asia, although there is currently no high capacity interregional transmission in place, cross-border interconnectors are being actively developed in ASEAN countries with an expected total capacity of 39GW in the near future. Motivated by mitigating high pool prices and a desire to improve grid reliability, high capacity interregional transmission is also being proposed and developed in Australia. A conceptual trans-Australia HVDC line was proposed between Queensland and South Australia. One major ongoing project is the Marinus link which would be the 2nd interconnection between Tasmania and the mainland Australia, improving the grid reliability and supply security.

These interconnection projects serve to stimulate regional economies and create thousands of jobs. Lastly, the concept of an "ASEAN-Australia Supergrid" has received great interest, which would allow consumers in ASEAN to benefit from the low-cost solar resources in the northern part of Australia. If eventually linked with China on the other side, a pan-Asian supergrid interconnecting Australia, Southeast Asia, and China could be formed, and optimized resource allocation can be achieved in a cost effective manner.

## 4.5 Russia

Russia has vast resources in both fossil fuels and renewables. Although energy production in Russia still largely relies on gas (53%), coal (15%), and oil (21%) [209], the power sector has taken important steps towards modernization by building more renewable generation, mostly hydropower. In 2019, the share of hydropower and nuclear power reached 20% and 12%, respectively [210]. Other renewables (wind, solar, biopower, and geothermal) are still nascent, primarily because of low-cost gas (lower than in Europe and abundant in Russia), nuclear (about 20 new blocks are planned by 2030, half of them will replace retiring nuclear units) and hydro (abundant). Regardless, the government supports the development of renewable energy resources, with a target of reaching a total capacity of 5.8GW wind and solar by 2025 [211].

Russia is part of the Integrated Power System/Unified Power System (IPS/UPS) energy system. This is a large-scale synchronous transmission grid covering 15 countries, including ten countries of the former USSR, Mongolia, and the Baltic countries. Parts of Finland and some regions of China are also supplied by the IPS [212]. The Unified Energy System of Russia (UES of Russia) composed of 7 unified energy systems is shown in Figure 38, all of which are connected by high voltage power lines with voltage of 220-500kV and above and operate synchronously. As of Jan 1 2020, the total installed generation capacity of the UES of Russia is 246GW [213]. Currently, the Russia power system is composed of two main price zones [213] – the European Russia & Urals price zone and the Siberia price zone, as shown in Figure 39. The European Russia & Urals price zone accounts for 78% of wholesale market volume and is dominated by fossil fuel based and nuclear plants. The Siberia price zone accounts for the rest of 22% share in the energy market, operated by half hydro and half coal.

#### Interconnection with Northeast Asia

Remote areas of Russia such as Siberia and Far East are rich in hydro resources. About 78% of the hydropower's economic potential in these areas remains unutilized. Moreover, Russia's best wind resources are located at the Pacific Coast. As a result,





Figure 38: Unified Energy System of Russia (UES of Russia) composed of 7 united energy systems [213]



Figure 39: Price and non-price zones in Russia [214]

there have been multiple studies investigating interconnections between Russia and Northeast Asia. Studies have been performed by Russia, GEIDCO (China), Japan, Mongolia and KEPCO (Korea), and mainly focus on the idea of an Asian Super Grid (ASG), as introduced in Section 4.3.2. The recent study in [215] quantifies the benefits of such interconnections (Figure 40) and suggests cost-benefit allocation techniques, concluding that a grand coalition with which all participated countries agree on cooperation is the optimal and stable coalition, with \$7.1 billion total savings per year.

Despite these completed studies, the realization of ASG is still at an infant stage and requires long term effort. One 500kV line between Russia and Northeast China (Amurskaya – Heihe) was built in 2012. The line does not participate in the electricity market and is only for exporting power to China. There is an existing 1150kV UHVAC line with 5500MW of transfer capacity built in the 1980's designed to transfer electricity from Siberia and Kazakhstan to industrial regions in Urals [216].

#### Interconnection with West Asia

Although there is currently no active initiative, an agreement was recently signed between Russia, Azerbaijan, and Iran on a feasibility study of a project for an interregional line connecting the three countries, creating a North-South energy corridor [217].

#### Interconnection with Europe

An old HVDC link exists between Volgograd in Russia and Donbass in eastern Ukraine, built for hydro electric transmission from Volga hydroelectric station [218]. The link was first commissioned in 1965 with voltage rating of  $\pm 400$ kV and a power transfer rating of 750MW. This link is in a degraded operational mode at 100kV. Another interconnection with Europe is the Vyborg HVDC scheme between Russia and Finland consisting of four 250MW back-to-back converters, three of which commissioned in 1980's and one in 2001. This interconnection enables export of electricity to Finland, but is

only based on bilateral rules between the two countries without governing by the EU market framework [219]. The EU-Russia Energy Dialogue in 2013 [220] presents a roadmap for the development of energy relations between EU and Russia. A subcontinent-wide energy market is proposed to be built between EU and Russia by 2050 to facilitate the sustainable development of both regions. An EU–Russia Renewable Energy Plan or RUSTEC concept was proposed in [221], aiming to achieve a win-win situation between EU member states and Russia on a renewable based energy interconnection. There have also been discussions on enhancing the interconnection between Russia and Norway to support the industrial growth

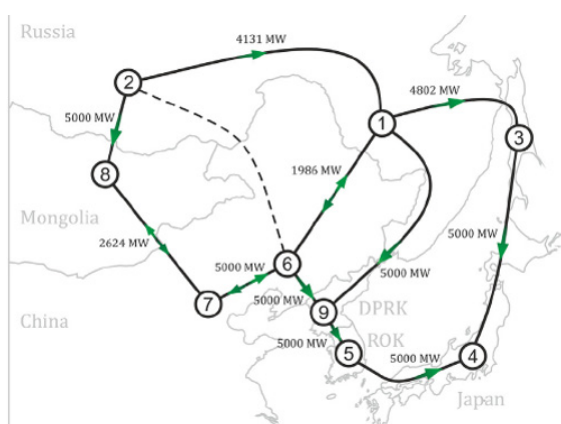


Figure 40: Optimal transmission capacities in the proposed ASG [215] (used with permission)

in northern Norway with the renewable potential in Russia [222]. The Eurasian Economic Union was established in 2014 to promote product exchanges across Europe and Russia. However, for political reasons, instead of adding interconnection, the electricity networks of Baltic States (Estonia, Latvia and Lithuania) are desynchronized from those of Russia and Belarus, and will be synchronized into the EU power grid by 2025 [223].

#### 4.5.1 Summary for Russia: Benefits and Characteristics

In general, Russia has not been active in planning and developing new interregional transmission lines. This is mainly because the current network is overbuilt, which was planned and mostly constructed in the Soviet times under a very optimistic economic forecast. The only existing HVDC schemes are the derated Volgograd - Donbass link between Russia and Ukraine, and the Vyborg back-to-back HVDC between Russia and Finland [224]. The feasibility of an interconnection with West Asia (Azerbaijan and Iran) is under study. Since the economic collapse in 1990's, and the "digitalization" of society,

electricity demand has been increasing very slowly, which would not justify the development of additional transmission lines. Studies have been performed to evaluate the potential opportunities to interconnect Russia with Eastern Europe and northeast Asia for large scale resource sharing. However, these studies are still at a conceptual stage without any further initiatives for actual implementation.

## 4.6 Africa

The electricity supply in Africa is unreliable and expensive in general, which only half of the population has access to. For example, western Africa has a high outage rate of about 44 hours per month with expensive electricity price as high as \$0.40 per kWh [225]. Insufficient transmission capacity leads to reliance on local expensive oil-fired or diesel generation which makes the cost recovery difficult for the public utilities. As shown in Figure 41, Africa is home to five regional power pools: Eastern Africa Power Pool (EAPP), Central African Power Pool (CAPP), Southern African Power Pool (SAPP), West African Power Pool (WAPP), and Maghreb Electricity Committee (COMEC). The COMEC and SAPP are relatively advanced while the rest are comparatively new and still developing regulatory systems and market rules. Trade across different regions remains low and is limited with transmission constraints. For example, around 1.8TWh of electricity were matched in the markets of SAPP in 2016/17 but were not traded because of transmission constraints [225]. Therefore, developing interregional power transmission both within and between the power pools could substantially reduce the energy cost while increasing the overall grid reliability. For example, increasing the interconnection with neighboring states within WAPP would reduce the cost of energy by one third at the consumer side, and at least 20% in annual financial savings at the power generation side in some energy constrained states [225].

A study conducted by Fraunhofer ISE [ccxxvi] shows that the electricity demand in Northern Africa can be covered completely by renewable energy with considerable potential to export electricity to Europe. The study also concludes that considerable economic advantages can be obtained in a high renewable scenario, leading to lower total cost. HVDC is recommended for both trans-national interconnectors as well as for a meshed overlay grid to facilitate the integration of renewables more economically because a transmission grid based on AC would require enormous grid capacities and thus high investments.

Increasing power sector integration can provide more affordable and reliable power across different regions. The need to invest in new capacity would be reduced with access to other markets. Reserves can be shared between different

regions, meaning the total capacity reserves maintained by each balancing area can be less. Increased integration can also increase the grid resilience by allowing the system to be more robust for seasonal imbalances and unexpected disturbances. Economies of scale at a regional level may also enable countries to proceed with large projects that would not be justified based on only domestic power demand. For example, Central Africa is very rich in hydropower resources, a result of the Congo River, the deepest in the world and the second longest in Africa. However, a huge mismatch exists between the significant hydropower potential and low energy demand in the area. Therefore, large-scale regional interconnections will be essential to promote the integration of the large scale hydropower [227]. Doing so could particularly benefit some of Africa's smallest and most energy-constrained countries; e.g., Liberia, Sierra Leone, Gambia, and Guinea-Bissau, Burkina Faso, Niger, and Mali [228]. The development of large-scale hydro dams is, however, under debate due to the huge financial risks, high potential of cost overruns and poor operating performance of existing dams in the sub-Saharan region. The study in [229] shows that with 35% of cost overrun (which is typically to be 70% or higher for large scale dams), the Congo Grand Inga project would become economically non-beneficial. Moreover, the development of mega hydro plants could bring substantial sustainability concerns, which is sometimes marginalized by the proponents.

In [230], the authors propose a cost optimal solution with HVDC grid as shown in Figure 42 for sub-Saharan Africa for 100% renewable by 2030, concluding that a 100% renewable resource based energy system is technically and economically practical for Sub-Saharan Africa to serve the total projected energy demand of 866TWh. More specifically, the HVDC interconnections play an important role in reducing the required generation and storage capacities, and thus reducing the levelized cost of energy (LCOE) from 58 €/MWh with a decentralized scenario to 55 €/MWh with a centralized grid, which could be further reduced to 47 €/MWh if combined with water desalination and industrial gas sectors via the power-to-gas (P2G) technology. Solar PV is identified to be the dominant technology supplying almost half of the total demand in sub-Saharan Africa beyond the year 2030 due to its declining LCOE, which is projected to decrease by 30-40% from 2020 to 2040. Similarly, solar is shown to be the best resource for Western Africa to achieve a low carbon future and will provide 81-85% of energy consumption in the region, as also indicated in [231], where the authors conduct a long-term expansion planning towards a 100% RE-based power system specifically for the West Africa. A strong transmission network is again identified to be critical, which helps reduce the LCOE, total system costs, total installed capacity, and curtailment of renewables. Similar conclusion is also drawn from [232], which states that the cost of solar could be reduced from 7.57 cents/kWh in 2015 to 4.43

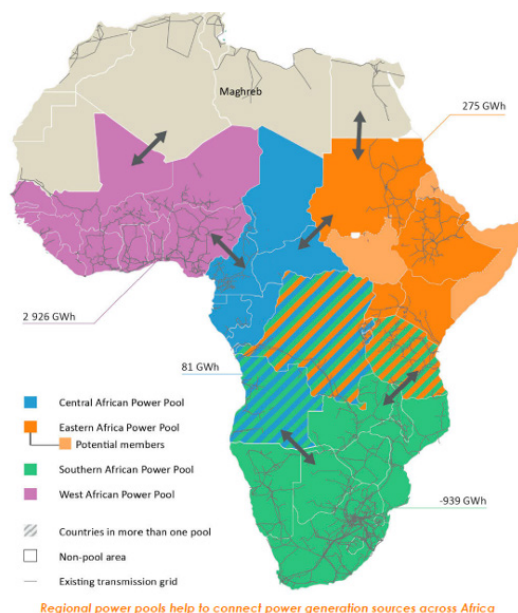


Figure 41: Electricity trade between power pools in sub-Saharan Africa, 2018 [227] (used with permission)

cents/kWh and further to 3.9 cents/kWh with cross-border interconnections.

Africa has an existing interregional high capacity HVDC line, Cahora Bassa, which was commissioned in the 1970's [233]. This line is capable of transmitting 1920MW of power along a 1420km route, connecting the hydroelectric generation station at Cahora Bassa Dam in Mozambique and Johannesburg in South Africa.

The most notable ongoing interregional high capacity transmission development in Africa is the 1068km 2GW Kenya-Ethiopia electricity highway [234], which aims to transfer large amounts of hydropower in Ethiopia to the Kenya. The project is estimated to cost \$1.26B, with shares of \$32M and \$88M between the Government of Ethiopia and Kenya, respectively. Construction of the project would support 4000 jobs (1600 in Ethiopia and 2400 in Kenya), with an additional of 125 jobs generated for operation and maintenance of the line. The project is expected to be completed by the end of 2020 [235].

In northern Africa, the most active development is in Egypt, which is involved in the EuroAfrica project connecting Africa with Europe [236]. The 2GW EuroAfrica interconnector will connect Egypt with Cyprus and Cyprus with Greece, with a total length of 1396km. The project has made significant progress as the final building permit was issued in Cyprus in August 2020 [237]. The first stage of the project between Egypt and Cyprus is expected to complete 1000MW of transmission capacity by 2022 at a cost of €2.5B, with the other interconnection between Cyprus



Figure 42: Sub-Saharan African sub-regions and HVDC transmission lines configuration [230] (used with permission)

### 4.7.1 Central America

As seen from Figure 43, Central American countries are linked together via a 230kV transmission system composed of 15 substations with a 1800km length. In 2014, more than 65% of the total energy output of 40.6TWh is served by renewable energy, mostly hydropower [239]. In order to promote the accelerated development and cross-border trade of renewable energies in Central America, IRENA created the Central America Clean Energy Corridor (CECCA) initiative [240], aiming to facilitate the integration of large shares of renewables into the regional transmission network known as the Central American Electrical Interconnection System (SIEPAC). SIEPAC is a regional interconnection system of six Central American nations. There have also been discussions to interconnect Central America with South America. In December 2019, a first ever power transfer connection between Colombia and Panama was proposed by ISA, which operates Colombia’s national power grid. The Colombia-Panama Electric Interconnection would not only consolidate the regional electricity market but also facilitate the integration of the Andean Community with Central America, whose markets are already organized through the SIEPAC network. Electrical energy exchange between the two countries would be enabled, along with access to cost competitive renewable energy resources, which could contribute to the economic and sustainable growth of both countries [241]. The

and Greece completing in 2023. The project offers significant socio-economic benefit of €10B for the three countries [238].

#### 4.6.1 Summary for Africa: Benefits and Characteristics

Although currently in a position with unreliable power supply and a generation mix dominated by the expensive oil-fired or diesel generation, the continent has huge potential for the development of renewable resources, for example, the huge solar potential in the Sahara desert of North Africa and a massive hydro resource along the Congo River in central Africa. Interregional high capacity transmission would be vital to facilitate the integration of these large scale renewable resources and reduce the cost of energy. A 100% renewable scenario has been shown to be technically and economically feasible for sub-Saharan Africa with the design of a continental HVDC overlay. There are several existing projects aiming for hydroelectric power integration in south and east Africa; in addition, Egypt has been actively participating in the interconnection with Europe through the EuroAfrica project.



Figure 43: Sketch map of Central American Interconnection [ccxliii] (used with permission)

## 4.7 Central and South America

500km ±300kV HVDC transmission line planned to launch in 2024 will have a capacity of 400MW, consolidating the regional energy market with bi-directional power flows with access to new renewable resources to facilitate the optimal use of energy

resources [242].

### 4.7.2 Brazil

The global oil crisis in the 1970s drove the Brazilian government to develop clean energy resources and reduce dependence on oil. The development of hydropower has been a major strategic goal since then. Brazil's electric generation is dominated by hydropower due to its massive hydro resources located in several river basins throughout the country. In 2018, more than 70% of the electricity was generated from hydro [ccxliv]. As most load centers are located far from hydroelectric sites, Brazil relies on long distance transmission to deliver the remotely generated and more economical hydroelectricity to the south. In addition, as hydroelectric plants were developed in several hydrographic basins, with different hydrological regimes, there was a need to implement interregional transmission systems to capture the synergistic gains arising from the hydrological diversity of river basins [245]. There are three major interregional long distance high capacity HVDC transmission systems in Brazil: Itaipu (1984), Madeira (2014), and Belo Monte (2017, 2019), all designed for hydroelectric integration, as shown in Figure 44 in blue.

The Brazilian auction procurement system for purchasing electricity stimulated the development of wind power in the northeast and south of Brazil. The total installed wind is expected to reach 24.2GW by 2024 [246]. Integration of the large scale wind in the Northeast as well as the expected increase in grid-connected solar PV would require even more transmission along the north-south corridor [247]. For example, a new  $\pm 800\text{kV}$  1460km HVDC system with a capacity of 4000MW is proposed to interconnect Graça Aranha in the northeast with Sylvania in the southeast [248] as shown in

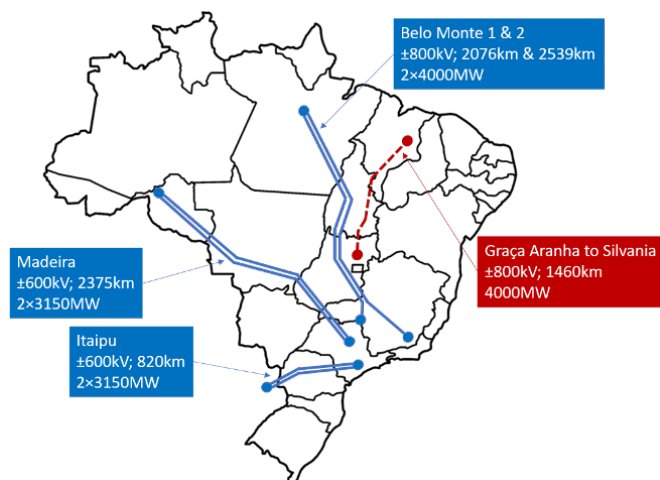


Figure 44: Existing (blue) and Planned (red) HVDC transmission in Brazil [adapted from ccxliv, 248]

Figure 44 in red. This HVDC line is the first of its type in Brazil in that there is no single power generation project driving it. Two major benefits resulting from this project are improved transmission capability to absorb more renewable generation from the northeast region, and relieved stress on the underlying 500kV AC network, especially in the raining season.

### 4.7.3 Chile

Chile has the largest solar development in the South America region due to its excellent solar resource in the Atacama Desert in northern Chile. However, the limited capacity of the existing transmission system hinders the integration and further development of these renewable resources. The two largest Chilean interconnected systems, namely the Sistema Interconectado del Norte Grande (SING) and the Sistema Interconectado Central (SIC), were recently unified into one synchronous grid but with relatively weak links. Also, a new 500kV AC line (Cardones-Polpaico) was recently built to strengthen the connection [ccl]; it not only increases the reliability of both subsystems, but also allows resource sharing between the northern renewables and the southern hydro resources. In order to harness the huge solar potential in northern Chile, a 1500km HVDC line with a transmission capacity of at least 4GW (2GW per pole) was recently approved by the Chile's national energy commission (CNE) and is expected to enter service by 2030 [251]. This new HVDC line will run from Kimal in the north to Lo Aguirre in the central south and allow massive renewable exchanges with reduced operating costs.

Development of long distance HVDC cross-border interconnections would play an important role in balancing and sharing the renewable energy resources across neighboring countries. Currently, the only cross-border interconnection in Chile is with Argentina but is not functioning [252]. The operation of this 345kV 268km transmission line between the SING and the Argentina Interconnection System (SADI) was suspended in 2017 after two and a half years' service due to instability concerns in face of contingencies, and is expected to remain down until the new Polpaico line is built [253]. Well-defined general regulation for international interconnections and market rules would better facilitate the operation of this interconnection between the two countries in the future. Chile's energy ministry recently started a study to investigate the legal feasibilities as well as economic benefits for up to four interconnection projects with Argentina, which is part of the Chile's Energy Roadmap 2018-2022 [254]. Interconnection between Chile and Perú is also being studied for the period of 2024-2038, with an AC line of 220 kV and 200 MW line connecting substations Los Héroes and Parinacota, in Tacna and Arica, respectively. Studies have shown the interconnection to be technically and economically attractive (internal rate of return~15%). Due to the difference of nominal frequencies (50Hz in Chile and 60Hz in Perú), a back-

to-back DC scheme is being planned [255].

#### 4.7.4 Latin America Supergrid

Supergrid planning studies have been conducted in Latin America, motivated by the urgent need of decarbonization under the COP21 in Paris, to make use of the continent's abundant renewable resources. Latin American countries exhibit high levels of undeveloped renewable energy resources, with potential approaching as much as 78000 TWh/year [256].

The authors in [257] identify potential energy integration projects with the addition of 10,000 km of new high voltage lines and 6500 MW of installed capacity. Figure 45 shows the existing and planned interconnections in Latin America [258]. A

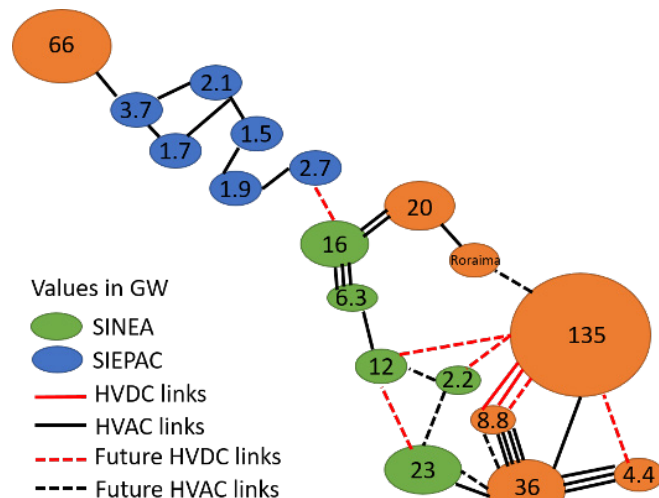


Figure 45: Power grids in Latin America 2017 [adapted from 258]

recent study [259] modeled an expanded grid enabled by HVDC links to facilitate a transnational electricity market, concluding that it can achieve climate goals and energy security goals simultaneously.

A supergrid with 37 DC nodes and 51 HVDC corridors is proposed in [260], with optimized investment cost. Table 6 shows the projection of net power injection into the supergrid at 2050. The design assumes all nodes are VSC with a DC voltage level of  $\pm 800$  kV.

#### 4.7.5 Summary Central and South America: Benefits and Characteristics

Central American countries are interconnected via a 230kV AC systems, whereas the countries in South America are currently

operated with very few transnational interconnections. Central and South America have abundant renewable resources. For example, the Atacama Desert in Chile is rich in solar, and the northern coasts of Colombia and Venezuela are rich in wind. Other regions such as the Orinoco, Caroni, and Caura river basins in Venezuela and northern Brazil enjoy abundant hydro resources. Structural asymmetries exist as large blocks of wind and solar are typically located in low populated areas. Brazil has been actively developing interregional high capacity transmission within the country for hydropower integration, and more recently, for wind integration from the northeast. Chile has near-term proposals to develop more interregional high capacity transmission within the country to harness the huge solar potential in the north. There have also been initiatives from the planning unit of Colombia to develop HVDC transmission to facilitate the integration of renewable energies located mostly in La Guajira in the north [261]. Although the wind and solar resource potential is high, restricted access to these large amounts of renewables across the continent could jeopardize the sustainable developments in each region. One way to make these resources economically viable in a transnational electricity market is through high capacity interregional transmission. Interregional transmission can also enable optimized and complementary sharing of the resources in different countries under different climate conditions. For example, when Colombia has a dry season, Ecuador has a rainy season. There are currently two interconnected AC systems in Central and South America, namely the Central American Electrical Interconnection System (SIEPAC) and the Andean electrical interconnection System (SINEA). SIEPAC is a regional interconnection system of six Central American nations. The SINEA is an initiative promoting interconnection projects between Chile, Colombia, Ecuador, Peru and Bolivia [262]. A similar initiative is Sistema Eléctrico Sur (Siesur), promoting interconnections between Argentina, Brazil, Chile, Paraguay and Uruguay [263]. Most system planning studies are at national levels, with few at the regional level. Transnational high voltage lines and a conceptual continental supergrid with 37 nodes are proposed to facilitate a transnational electricity market and to achieve climate goals. It is worth to note that the power system nominal frequencies are different between some South American countries. For example, Brazil, Perú, Colombia operate their power systems in 60Hz, whereas Chile, Argentina and Uruguay have 50Hz systems. Therefore, direct current technologies would be necessary when interconnecting these asynchronous AC systems of different frequencies.

## 4.8 Intercontinental Supergrids

There have been efforts to design intercontinental supergrids; although developing transmission at this scale seems unlikely due to political and economic barriers, it is significant that there

have been some reasonable designs studied and published. We briefly summarize some of these efforts here. One organization that has done so is the Global Energy Interconnection (GEI); they have proposed an energy transition approach [264] which includes a global supergrid [265, 266] to share renewable energy resource across continents with resource variability compensated by the geographical span [267]. Similar work has been promoted by the Global Energy Network Institute (GENI) [268], the Global Energy Interconnection Development and Cooperation Organization (GEIDCO) [269], and the Clean Energy Ministerial (CEM) initiative [270]. A university research group out of Finland has developed continental designs for every major area of the world [229, 230, 271-280], with similar conclusions that the levelized cost of energy (LCOE) is reduced with interregional transmission and high renewable penetration can be achieved; they also proposed a global design in [281] linking the Americas, Europe-MENA-Central Africa, and Asia, concluding that clear benefits exist for an integrated power system at a regional or continental level, but a global energy interconnection with ocean crossing lines provide marginal increments in economic benefits due to the

	DC Node	Demand [MW]	Generation [MW]	Injection to SuperGrid [MW]
1	Guatemala	6.167	6.119	-48
2	El Salvador	2.483	1.852	-631
3	Honduras	5.670	5.141	-529
4	Nicaragua	3.346	4.104	759
5	Costa Rica	2.220	20.255	18.035
6	Panama	13.574	6.631	-6.943
7	Colombia – Central	14.153	26.646	12.493
8	Colombia – North	8.492	14.146	5.654
9	Colombia – South	5.661	5.742	80
10	Ecuador	14.674	10.107	-4.568
11	Peru - Central	20.435	24.838	4.403
12	Peru – South	8.758	11.477	2.719
13	Bolivia	11.041	23.925	12.885
14	Chile – North	5.185	16.478	11.293
15	Chile – Central	14.518	12.902	-1.615
16	Chile – South	1.037	1.999	962
17	Argentina – North	7.143	7.773	630
18	Argentina – Central	11.905	10.691	-1.213
19	Argentina – East	16.666	14.719	-1.948
20	Argentina – South	952	5.119	4.167
21	Argentina – Southwest	3.809	9.326	5.516
22	Argentina – Southeast	7.143	6.375	-768
23	Uruguay – Central	2.820	3.696	876
24	Uruguay – North	940	1.009	69
25	Paraguay - Central	827	1.885	1.057
26	Paraguay – South	1.930	16.837	14.907
27	Brazil – South	58.361	36.119	-22.242
28	Rio Sao Pablo	97.268	59.795	-37.474
29	Brasilia	58.361	18.398	-39.963
30	Brazil – East	77.814	28.539	-49.275
31	Brazil – North	50.579	19.687	-30.893
32	Amazonas North	15.563	28.899	13.337
33	Amazonas Central	19.454	28.899	9.446
34	Amazonas South	11.672	28.899	17.227
35	Venezuela East	7.139	35.145	28.006
36	Venezuela Central	13.089	12.727	-362
37	Venezuela West	3.570	18.771	15.201

Table 6: Demand, generation and net injection to the supergrid – 2050 [260]

complexity of the system. Another study [282] performed by CIGRE working group C1.35 investigated the feasibility of a global electricity network, deploying 2600GW of transmission capacity worldwide. Their global supergrid design is shown in Figure 46.

Although not global, but rather intercontinental, the European Union sponsored a 2017 study to explore the possibility of interconnecting Europe and China via multi-terminal HVDC grid using VSC technology [283], with intent to harness the renewable energy resources in central Asia for supplying Europe. Different national interests and priorities are identified to be the most formidable obstacles to building such a large-scale DC grid, but complexity could be alleviated by the multiterminal configuration since it allows both full-length and segmented operation. Three proposed routes are shown in Figure 47.

For these proposed inter-continental designs, multiple nations are involved and interconnected via high voltage DC lines. Interoperability between multi-vendor DC systems is critical for secure and reliable operation of the overall grid. Moreover, financial and regulatory frameworks should be developed to facilitate the cross-border power exchange. An effort of such has already been made in Europe with the Article 16.8 of Regulation 2019/943 [284] on the internal electricity market, part of the “Clean Energy for All” package of legislation adopted in 2019, which sets a minimum of 70% of interconnector capacity should be made available for cross border trade, prohibiting the reservation of interconnector capacity for solving intra-zonal congestion or to facilitate intra-zonal trades [285]. Similar to the operation of the future offshore grid in the European North Seas which involves multiple states, cooperation of relevant national regulatory authorities is necessary to operate the inter-continental supergrid, and is likely to be more politically acceptable than setting up a new system wide institution for the same purpose [140].

Transmission design of any kind is a complex process; we do

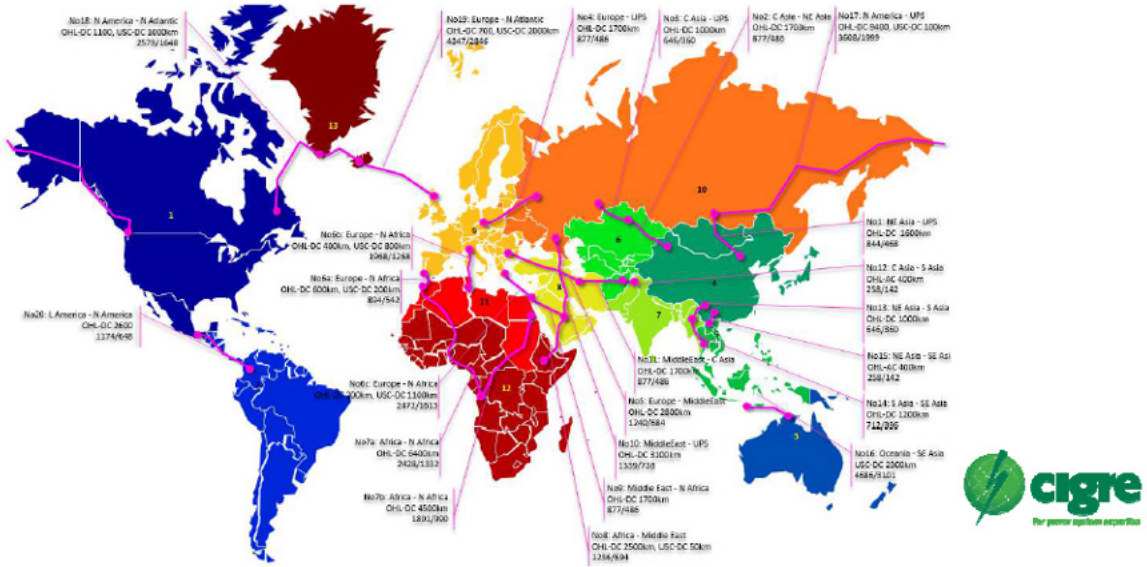


Figure 46: Global interconnections selected by CIGRE C1.35 [282] (used with permission)

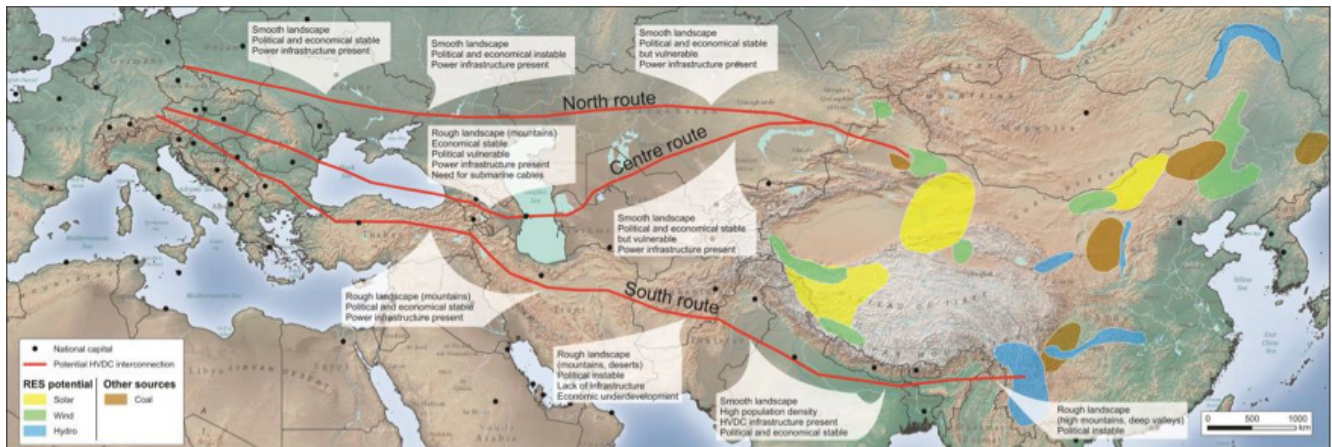


Figure 47: China-EU link [283] (used with permission)





# 05

## Interregional Transmission Design

not intend in this section to detail the entirety of this process. Rather, we seek to describe the technologies together with the steps necessary to identify and quantify benefits associated with interregional transmission design. Section 5.1 describes the most important technology choice in interregional transmission development: whether to use AC or DC transmission. Section 5.2 describes the additional choices one has if DC transmission is selected. Section 5.3 identifies the key steps associated with interregional transmission design.

### 5.1 Technology Choices: AC vs DC

An interregional transmission design should take advantage of the strengths of both AC and DC technologies, combining AC in doing what AC does best with DC in doing what DC does best. AC excels in local collection of resources because it provides what might be called “on-ramps” within an AC transmission network at relatively low cost via AC substations. Although HVDC networks with multiple terminals are possible, there are not yet many implementations and so experience with them is limited (as discussed in Section 5.2 below); even as multi-terminal HVDC technology matures, their use to provide multiple “on-ramps” may still not compete well with AC due to the cost of converters and DC breakers at each terminal. On the other hand, DC transmission is capable of moving power very long distances with low losses, making it economically attractive to move energy, ancillary services, and capacity from a region where it is low-priced to other regions where they are high priced.

In this section, we describe technology choices for interregional transmission, focusing on four main issues: (1) underground/underwater; (2) distance; (3) losses; and (4) connecting asynchronous grids.

#### 5.1.1 Underground/underwater Applications

There are two broad classes of technologies associated with building interregional transmission: AC or DC. In most cases, the decision depends on which one is least costly and which one maximizes the benefits. The only situation in which there is no choice is when a transmission path must be underground or underwater and exceeds about 60 miles. In this case, the capacitive effects of AC underground cables generate high line charging and significantly reduces transmission capacity (see Section 3.3). It is significant that DC transmission provides the option of deploying long-distance transmission underground.

#### 5.1.2 The Effect of Distance

For a given power transfer, the cost of overhead transmission is generally lower for DC than for AC when considering distances in excess of 350-450 miles. This is because, although DC substation equipment, dominated by the AC/DC converters, is more expensive than that of AC, the cost per mile of conductors, poles or towers, and right-of-way is less for DC, due to the fact that DC requires only two conductors whereas AC requires three (again, see Section 3.3). For long lines, the second influence outweighs the first.

#### 5.1.3 The Impact of Losses

For a given power transfer requirement, it is generally the case that DC transmission incurs less losses than a good AC transmission design; i.e., DC transmission is more efficient than AC. One reason for this is that AC transmission always moves both real (MW) and reactive power (MVARs). In contrast, DC transmission only moves real power. Thus, an AC current will be higher than what is required to move the real power alone,

which is not the case for DC. A second reason for the lesser AC transmission efficiency is skin effects; the effects of the time varying magnetic field interacts with the current flow to cause more flow at the periphery of the conductor. This results in nonuniform current density and therefore more losses.

Reference [286] provides an insightful comparison of different AC and DC designs for a 6000 MW transmission need, where each design is performed with a particular technology (AC or DC, at a chosen voltage 345, 500, or 765 kV for AC, and 500 or 800 kV for DC). Losses are computed for each of the five technologies for the 6000 MW loading at four different distances: 200, 400, 600, and 800 miles. The results are shown in Figure 48. Appropriate design requirements (e.g., substation spacing, reactive support) are satisfied for each technology and distance. With the exception of the 200 mile distance where the 765 kV design is very competitive, the two DC transmission designs always have the least losses.

#### 5.1.4 Connecting Asynchronous Grids

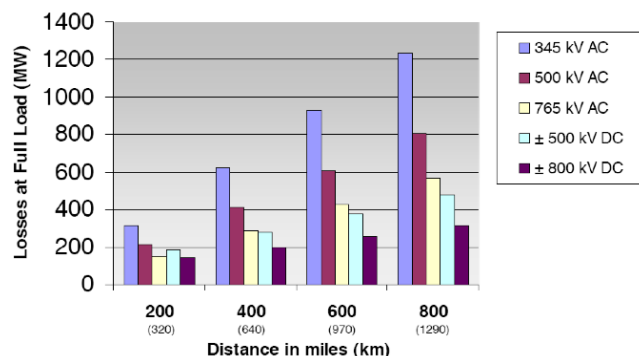


Figure 48: Comparison of losses for five transmission designs and four different distances [286] (used with permission)

When building transmission to interconnect what are otherwise

two asynchronous grids (meaning the generators in one grid are generating a voltage waveform that is out-of-phase with the other grid, as is the case in the continental US for the EI, WI, and ERCOT grids), use of AC synchronizes the two grids, whereas use of DC allows them to remain asynchronous. There can be non-technical reasons to avoid synchronization of two grids, as is the case with the ERCOT system [287]<sup>11</sup>, but otherwise, if the decision is based purely on economics and grid performance, both options should be evaluated.

The main performance benefit for DC is that the converters provide attractive control capabilities at little or no additional cost. As indicated in Section 2.1.3, control may be implemented through the converters that enables one grid to assist in the frequency recovery of another asynchronous grid following loss of large generation blocks [34, 35]. In addition, DC transmission using voltage source converters (VSC) instead of line-commutated converters (LCC) provides inherent reactive power support that, in design, increase the number of viable DC/AC interconnection points while, in operations, provide desirable voltage control capabilities in the AC network local to those interconnection points.

An important feature of using DC transmission to interconnect two asynchronous grids is that DC transmission capacity has no minimum value and so is dictated entirely by economics. This may not be the case when using AC transmission, because stability requirements for synchronizing two asynchronous grids will dictate that the capacity of the interconnecting transmission exceed a certain value. For example, efforts to synchronize the US Eastern and Western Interconnections via four AC tie lines resulted in synchronous operation beginning in 1967. However, because of “weak ac tie lines”<sup>12</sup> [288], resulting in a “large number of separations” [289], the two grids were permanently opened in 1975. It was later recommended that “if power transfers of over 500 MW would result in significant benefits, the feasibility of the interconnection should be pursued,” highlighting the need for a minimum transmission capacity in order to interconnect.<sup>13</sup> The fact that AC interconnection between two otherwise asynchronous grids

<sup>11</sup> The essence of this is based on (i) a preference of ERCOT utilities to remain outside of FERC’s regulatory jurisdiction; (ii) the fact that FERC has jurisdiction over any region participating in electric “interstate commerce;” and (iii) power exchange via AC transmission between two states is perceived to constitute interstate commerce. This is captured in [287]: “FERC’s jurisdiction is derived from the Federal Power Act (FPA). Under the FPA, entities subject to FERC’s plenary jurisdiction are known as ‘public utilities.’ The FPA gives FERC broad authority to regulate the activities of public utilities, including authority to ensure that public utility rates are just, reasonable, and non-discriminatory. ERCOT and its Market Participants are generally not subject to the plenary jurisdiction of FERC, and are therefore not considered public utilities under the FPA. FERC does not have plenary jurisdiction over ERCOT because electric energy generated in the ERCOT Region is not transmitted in ‘interstate commerce,’ as defined by the FPA, except for certain interconnections ordered by FERC that do not give rise to broader FERC jurisdiction.”

<sup>12</sup> The notion of “weak tie lines” is a condition that results in what is now considered to be a classical power system engineering problem called interarea oscillations, as described in many text books.

<sup>13</sup> The value of 500 MW should not be used to indicate what the minimum acceptable value might be today because the Western and Eastern Interconnections at the time of the 1979 study cited in [289] were of much less capacity than they are today, with reference [289] indicating 305 GW modeled in the EI and 87 GW modeled in the WI (today, the EI has over 800 GW and the WI over 260 GW). Indeed, the 500 MW was probably not a good indication of what the minimum transmission capacity should have been in 1979, since modeling capabilities were much less advanced at that time. Reference [288] (which provides an excellent historical account of the effort to synchronize the two grids from 1967-1975) explains

requires that capacity exceed a certain minimum for stability does not mean it cannot or should not be done. It just means that it is possible that a minimum AC transmission capacity may exceed the value that is economically desired (a point also identified in Section 3.3).

On the other hand, tying two grids together with a sufficiently large amount of transmission capacity has a tendency to strengthen the stability performance of a large percentage of both grids due to the increase of what is referred to as synchronizing power, a tendency to which DC transmission does not contribute.<sup>14</sup> In addition, use of AC transmission provides better accessibility than DC, offering a less expensive way to provide for local tie-ins.<sup>15</sup> This feature is not only important for the initial design but also for the future as new generation resources are developed, old ones are retired, and demand changes, i.e., “accessibility implies flexibility for needs that develop over the long term” [286]. Tapping into an existing AC transmission line requires a new AC substation (with transformer); tapping into an existing HVDC transmission line requires a new AC/DC converter station. Reference [49] indicates that a  $\pm 600$  kV DC converter station would cost approximately double that of a 500 kV AC substation. Indeed, there are technical constraints that preclude tapping for LCC-based HVDC, and even for VSC-based HVDC, tapping after the system has been built is a research topic. However, VSC-based HVDC may indeed be designed to offer multiple accessibility points; such an application is referred to as a multi-terminal network. We will address multi-terminal HVDC networks in the next section.

## 5.2 Technology Choices for DC

There are two different types of converter technologies used for implementing DC transmission. The older technology is referred to as line-commutated converters (LCC). LCC uses silicon-controlled rectifiers, also known as thyristors, to implement the converters. The advantage of thyristors is that they can be implemented with high AC/DC conversion capacity. The highest HVDC line ratings available today are LCC-based for bipole arrangements of  $\pm 600$  kV at 6GW, and  $\pm 800$  kV at

10GW [290].

Despite LCC’s excellent power handling capabilities, their use has been mainly for point-to-point configurations. They have been deployed in only a very few multi-terminal configurations [291].<sup>16</sup> This is because thyristor-based converters must change the voltage polarity at a bus to reverse flow on a line, and since multi-terminal networks necessarily have buses with more than two connected DC lines, LCC-based HVDC requires power flow on all such lines to be either into the bus or out of the bus, which greatly diminishes the operational flexibility of a multi-terminal network which uses them.

In contrast, VSC-based HVDC uses insulated gate bipolar transistors (IGBTs) which can reverse the flow by performing current reversal in the line, while maintaining constant polarity at the bus. This enables application of multi-terminal DC networks, providing the ability to address accessibility in the design stage when deploying DC transmission. However, there are still two drawbacks. The first is that VSC-based HVDC is not capable of achieving the power flow capacity of LCC-based HVDC, with the ratings of a recent VSC-based HVDC technology being  $\pm 640$  kV and 3GW [292]. The significance of this drawback is likely to lessen as VSC-based technologies continue to mature.

The second drawback is that DC faults are hard to interrupt because there is no natural current zero crossing; thus, in contrast to an AC circuit breaker, an HVDC circuit breaker must interrupt a very high current. With two-terminal (point-to-point) HVDC, when a DC circuit is faulted, one may interrupt the current on the AC side of the converter and still only affect the faulted circuit. However, with a multi-terminal network, interrupting the AC side connected to a DC bus that is serving more than one circuit will remove both of those circuits. This is unacceptable from a reliability point of view in that a single fault causes loss of two elements (referred to as an N-2 contingency). Thus, an HVDC circuit breaker has to create the zero current crossing. Several equipment manufacturers are now reporting that HVDC circuit breakers have reached a commercially viable stage [293, 294], but their deployment within HVDC multi-terminal networks increases the cost of

that under the AC ties, “...the exchange of large amounts of power between East and West was not viable, from a market point-of-view or a national stability point-of-view,” but that “...when they changed to dc ties, it really ‘started the ball rolling because it worked so well.’”

<sup>14</sup> It was in part this tendency that led American Electric Power (AEP) to design its high-capacity interregional grid with 765 kV AC transmission; see Section 4.1.1.

<sup>15</sup> This discussion on local tie-ins and tapping HVDC lines after they have been built is applicable beyond decisions to connect two asynchronous grids, i.e., it also applies to considerations of whether to use AC or DC for transmission links embedded within the same system.

<sup>16</sup> Reference [291] reports that at the time of its writing, there were six existing HVDC multiterminal systems. Three of them are LCC-based and three are VSC-based. The LCC-based systems include the Hydro Quebec to new England system connecting southeastern Canada with the northeastern US; the Sardinia-Corsica-Italy interconnection between mainland Italy and Sardinia; and one in India called the North-East Agra system that was under construction. The VSC-based multiterminal HVDC systems are all in China and include one in Nan’ao island in the southern part of the Guangdong province; one in the Zhoushan archipelago in China’s eastern coastal region; and one in Zhangbei to secure power to Beijing, which with three sending terminals of 1500MW each and one receiving terminal of 3000MW is the largest DC grid project in the world.

those networks significantly.

For a multi-terminal DC network with large number of converters, it is important to ensure the interoperability between multi-vendor DC systems. Europe has made some initial effort with regard to this aspect by defining standardized control interface for conformity tests of HVDC Software In the Loop (SIL) and Hardware in the loop (HIL) [295].

In considering technology choices for DC transmission, we revisit points made in Section 2.1.3 in relation to reliability. Because of the versatility associated with the IGBT in comparison to the thyristor, VSC-based HVDC provides some uniquely important control capabilities that are very useful in design and operation, including (i) reactive power supply and consequential voltage control capability; (ii) transient stability control; (iii) oscillatory stability control; (iv) frequency response; and (v) black start capability (appropriate references for each of these are given in Section 2.1.3).

We particularly emphasize point (i), the ability to provide reactive power and control the voltage. When using LCC-based HVDC, one must either limit terminals to only buses considered to be “stiff” (typically measured by the short circuit current at the bus, an indication of the ability to control the voltage at that bus), or, if the bus is not stiff, one must install additional voltage control equipment, e.g., switched shunt capacitors and inductors, a static var compensator, or a static synchronous compensator, consequently increasing the capital cost of the HVDC project. Of the voltage control options, the static synchronous compensator (also called STATCOM) is the most effective, but it is also the most costly. When deploying VSC-based HVDC, the converter is very similar to a STATCOM as it employs the same VSC technology. Whereas LCC-based HVDC requires reactive control, VSC-based HVDC provides it.

Finally, there has been some consideration of combining converter technologies within a single HVDC grid to take advantage of the greater capacity offered by LCC and the control capabilities and flexibility of VSC. One way to do this is to add VSC stations to existing LCC-HVDC systems to form hybrid multiterminal grids [296, 297, 298].

## 5.3 Design Approaches

The objective of this section is to identify the main steps associated with interregional transmission design in order to quantify its benefits. There are four main steps: techno-economic design; resource adequacy evaluation; contingency analysis and

control design; and resilience and adaptability evaluation.

### 5.3.1 Techno-Economic Design

A 2011 select committee report describing supergrid opportunities for Europe [12, ch. 3] found it makes more financial sense to develop an interconnected offshore network than to continue connecting renewable sources to the mainland on a site-by-site basis. One generalizable part of the rationale underlying this finding is that integrated network design, in contrast to piecewise development, employs systematic modeling of all benefits to result in a grid development plan that maximizes the benefit to cost ratio.<sup>17</sup> This is the objective of the techno-economic design approach described in this section. There are two main steps associated with techno-economic design: co-optimized expansion planning and production simulation.

#### Co-optimized expansion planning

The essence of this step is, given an existing transmission network of circuits, resources, and demands, select transmission and resource investments in terms of technology, location, capacity, and timing (i.e., which year) to minimize the net present worth of total investment and operating costs over a chosen decision horizon, e.g., 20 years. The tool used to implement this step is referred to as a co-optimized expansion planning (CEP) optimizer. The CEP computes, for the minimum cost investment strategy, the total costs of all investments and the total costs of all operating conditions over the decision horizon. Investments through time are driven by (i) demand growth; (ii) resource retirements; (iii) changes imposed by policy, e.g., renewable portfolio standards or carbon price. The CEP is used to evaluate the benefits of an interregional transmission or Macro Grid transmission development by running it with and without the transmission development; the case without the transmission development is referred to as the reference case. A benefit to cost ratio (BCR) is computed as

- The difference between the reference case and the transmission development case in terms of the sum total of all investment and operating costs (exclusive of the cost of the transmission development)
- divided by the cost of the transmission development.

Key modeling features required to characterize the benefits of interregional transmission include:

- *Network constraints:* These ensure power flows on the network satisfy the laws of physics and include power

<sup>17</sup> A series of one-off projects does have its advantages, however, in that such an approach may be better able to flex with changing conditions. Nonetheless, a systematic and integrated design, however, can be substantially de-risked with coherent public policy.

SB	Reference	Trans Design	$\Delta$
Total Line Investment	62.2	80.1	+18.9
Gen Investment	704.0	700.5	-3.5
Operations & maintenance	1507.5	1463.1	-44.4
B/C Ratio (orange/blue)	-	-	2.52

Benefit to Cost Ratio

$$= \frac{\text{GenRelatedSavings}}{\text{IncreasedTransCost}}$$

$$= \frac{\Delta\text{O\&M} + \Delta\text{GenInv}}{\Delta\text{Trans}}$$

$$= \frac{44.4 + 3.5}{18.9} = 2.52$$

Figure 49: Typical result generated by CEP

balance at each bus, Kirchhoff's voltage law, and power flows on each circuit within the circuit's capacity.

- *Operating conditions:* Each year's operating conditions are assessed through a selected but representative set of seasonal and diurnal times.
- *Resource constraints:* Investments or retirements that are certain may be forced via hard constraints.
- *Regional capacity and demand:* If regions are in different time zones, then regional production (for wind and solar) and demand are modeled on a consistent time basis.
- *Operating reserves:* Regulating, contingency, and ramping reserves are modeled with appropriate costs, and units are dispatched to provide energy and operational reserves at least cost.
- *Interregional dispatch:* Units are dispatched interregionally to enable identification of benefits associated with energy and operational reserve sharing.
- *Interregional or Macro Grid transmission development modeling:* The interregional transmission or Macro Grid transmission development may be modeled in year 1 as zero-capacity lines; constraints may be imposed to maintain certain desired features, e.g., equal capacities for all Macro Grid lines. The cost of both AC and DC substations and protection should be modeled, including the cost of DC breakers if HVDC grids are of part of the design.
- *Annual peak:* A single hour operating condition is modeled for each region's peak condition, with interregional sharing allowed, and demand increased by the planning reserve margin, e.g., 15%.

Figure 49 illustrates a typical CEP result together with the

calculation of the benefit to cost ratio. The metric return on investment (ROI) may also be computed which is similar to BCR, except that the numerator of the ROI subtracts off the denominator. In the example given in Figure 49, the ROI would be computed as  $(44.4 + 3.5 - 18.9) / 18.9 = 1.53$ , i.e., the return yields 153% of the investment.

### Production simulation

This step ensures the operational viability of the proposed plan by performing sequential hour-by-hour production simulation over the 8760 hours of the last year in the CEP decision horizon, for both the reference case and the case with the interregional or Macro Grid transmission development. This step is motivated by the fact that the operational modeling and temporal granularity in the CEP is necessarily coarse due to the CEP computational intensity. Important information obtained in this step is the operational utilization of the transmission development, the influence of the transmission development on the amount of congestion in the network and the amount of curtailment imposed upon renewable plants. In addition, this step provides validation for the operational cost savings computed in the CEP.

### 5.3.2 Resource Adequacy Evaluation

Resource adequacy is defined by the US North American Reliability Corporation (NERC) for the Reliability First Corporation region, as "the ability of supply-side and demand-side resources to meet the aggregate electrical demand (including losses)" [299, 300]. Another definition provided by the Northwest Power and Conservation Council is "A condition in which the region is assured that, in aggregate, utilities or other load serving entities (LSE) have acquired sufficient resources to satisfy forecasted future loads reliably" [301]. The essence of resource adequacy is that the extent to which a given power system can supply its demand throughout a year should be assessed. Such assessments are done for conditions expected to be encountered in a future year using tools such as General

Electric's Multi-Area Reliability Simulation (MARS) [302] and Astrape Consulting's Strategic Energy and Risk Valuation Model (SERVM) [303], to ensure that the system satisfies the industry-evolved performance requirement of having a loss of load expectation (LOLE) lower than one day in 10 years (i.e., 0.1 day in one year).<sup>18</sup>

There are at least three issues in considering the effects of interregional transmission on resource adequacy evaluation. The first is the extent to which regulators will allow firm commitments across the tie-capacity to be included in the evaluation and how they will be compensated for it. This issue is discussed in Section 2.1.1 under "Annual time diversity." The second is the extent to which tie-benefits are included in the evaluation. Tie-benefits enable a region to request assistance from another region via non-firm imports during emergency events [ccciv]. Although tie benefits are typically not contractually obligated, they are likely to be available and can be evaluated probabilistically [304]. However, various entities treat them differently. For example, some regions exclude them from the computed reserve margin; some include the full intertie capacity as a resource; and some do not include tie benefits at all [304]. The third issue is a technical one and involves the calculation of the reliability of the technology comprising the interregional transmission development, and if the technology is HVDC, substation converter reliability should be included in the analysis, and in the case of multi-terminal HVDC, the network topology should also be considered. Some early work on this issue indicated that resource adequacy was not particularly sensitive to the replacement of a double circuit AC line by a bipolar DC line [305]; more recent work on this issue is reported in [306].

### 5.3.3 Contingency Analysis and Control Design

#### Contingency analysis

So-called "N-1" contingency analysis is a standard part of transmission planning. All developed transmission systems in the world adhere to an N-1 standard (or an even higher performance requirement). Analysis to ensure N-1 thermal, voltage, and dynamic performance criteria are satisfied must ultimately be done for any interregional transmission design.

<sup>18</sup> A simplified approach which is built in to the CEP assesses only the peak demand condition to ensure the region has sufficient capacity to meet that condition, with some planning reserve margin (e.g., 15%). This establishes a reasonable lower bound on capacity that, if satisfied for the peak condition, ensures that all other conditions can be satisfied with high probability.

<sup>19</sup> This is a conservative assumption; in reality, both AC and DC transmission will have emergency flow limits that are higher than normal flow limits. These emergency limits are typically given in terms of a time-frame, e.g., "emergency 20 minute overload limits," which means that the line can withstand the additional flow for 20 minutes.

<sup>20</sup> If  $n$  is the number of lines added, each of capacity  $C$ , and  $C_0$  is the capacity of the existing underlying transmission system, and each line is allowed to be loaded in the pre-contingency condition to  $p$  percent of its capacity, then  $pnC + pnC_0 \leq (n-1)C + C_0$ , which simplifies to  $C/C_0 \leq (1-p)/(np-n+1)$ . If there is no underlying transmission, i.e.,  $C_0=0$ , then  $pnC \leq (n-1)C$ , in which case, for example, if  $p=0.666$ , then  $n \geq 3$ .

Any need for shunt or series reactive compensation, either switched or continuously controlled, is identified in this step.

A contingency-related design feature that is specific to interregional transmission is to ensure that the underlying AC transmission system will survive a contingency following outage of any one interregional transmission circuit. This feature imposes limits on added transmission capacity between the regions as a function of the percent of the total capacity that must remain unused and the number of circuits to be added. It is developed by requiring flow before loss of one line must be less than or equal to the total capacity after loss of one line.

For example, assuming the emergency loading limits of all transmission are the same as the normal loading limits<sup>19 20</sup> and that we must reserve 30% of each line's capacity to ensure post-contingency flows are within limits following outage of one line, then [307]

- the capacity of a one line addition is limited to 0.43 times existing underlying transmission capacity;
- the capacity of a two line addition is limited to 0.75 times existing underlying transmission capacity;
- the capacity of a three line addition is limited to 3.0 times existing underlying transmission capacity.

The fact that the maximum capacity of the transmission addition increases significantly when three lines are added is due to as the "rule of three" [308], which indicates high capacity interregional transmission should be built with no less than three lines in order to achieve a significant capacity addition without incurring large derating imposed by N-1 security. From another, related point of view, if interregional transmission is built according to this rule, the amount of reinforcement necessary for the existing, underlying transmission system need not be large.

#### Control design

Use of AC for interregional transmission will change system dynamics and therefore require additional studies and perhaps some retuning of existing controllers such as power system

stabilizers. There may be benefits associated with increased transfer capabilities for other transmission paths within the network. However, use of AC for interregional transmission imposes no new control design needs. This is not the case when using HVDC for interregional transmission, as the converter stations are controllers in themselves. Control design needs to be performed in order to effectively assess the benefit of these controllers for purposes of voltage stability, transient stability, oscillatory stability, and frequency response (see Sections 2.1.3 and 5.2 for references on these HVDC-related control functions). Benefits are improved system performance and expanded network transfer capabilities.

### 5.3.4 Resilience and Adaptability Evaluation

As indicated in Section 2.1.4, we identify high-consequence events as those in which a large amount of resources in a given region become temporarily or permanently unavailable; we characterize the ability of responding to such events, temporary or permanent, as resilience and adaptability, respectively. We assess these abilities in terms of their cost. The literature is not expansive on how to make these evaluations; two efforts to evaluate resilience include [41, 309], and an approach to evaluate adaptability is described in [310, 311]. These efforts have confirmed what can be intuitively understood, that interregional transmission diminishes impact and enhances recovery from such high-consequence events. The reason for this is that interregional transmission enables resources that are physically separated by great distance to be electrically located very nearly on the same busbar. Events that cause resources in one region to become unavailable are unlikely to influence another region that is so distant, yet the interregional connection enables those remote resources to assist in the afflicted region as if they were actually located there. And when a certain resource type becomes less available across multiple regions (e.g., should federal policy limit use of natural gas or nuclear), the ability to share energy, operating reserves, and capacity between the regions will diminish the cost to adapt to these changes.

It is unclear that interregional transmission should be designed to enhance resilience and adaptability, as if these features were the objective. There are other objectives to guide the design, based on normal operating conditions, e.g., those benefits assessed in the techno-economic design described in Section 2.1, including savings that result from resource diversity, weather diversity, time diversity, and improved reliability. However, improved resilience and adaptability is a tangible benefit that results from interregional transmission and should be evaluated for each possible design so that this benefit can be quantified.

# 06



## Conclusions

Our objective in this document is to provide answers to four questions. We conclude by addressing these four questions.

### 6.1 Worldwide Summary

*Question 1:* To what extent are the various regions of the world studying, planning, and building interregional transmission and Macro Grids?

*Response:* There is a very large amount of activity throughout the world in conducting studies to characterize the benefits associated with interregional transmission development. In terms of planned (with permitting and land acquisition underway) or recently developed (after 2014) interregional transmission, there is a great amount of activity in China and a significant amount in Europe and South America. Figure 1 shows that China is at 260GW of capacity, while Europe is at 44GW and South America is at 22GW. India has also been particularly active by recently developing 12GW of interregional transmission. North America has developed only 7GW of which the US has developed 3GW.

### 6.2 Benefits, Costs, and Characteristics for Successful Implementation

*Question 2:* What is the perception of interregional transmission and Macro Grids around the globe in terms of perceived benefits, costs, and characteristics for successful implementation?

*Response:* We address this in three parts:

- **Benefits:** There are six major benefits that countries around the world are seeking to obtain or are obtaining from building interregional transmission and/or Macro Grids: cost-reduction via sharing of energy, ancillary services, and capacity; economic development; improved reliability; enhanced resilience and adaptability; higher renewable levels; and lowered cost of reducing emissions. The US is in a position to obtain significant levels of all of these benefits via increased investment in interregional transmission. In addition, some less-developed nations see opportunities in terms of urbanization and electrification of what are otherwise purely agricultural communities. Africa in particular has an attractive opportunity to take advantage of very rich hydro and solar resources via development of a continent-wide Macro Grid.
- **Costs:** Although capital costs and operating costs for transmission lines and substations vary depending on the technologies deployed (e.g., AC vs. DC), these costs, though a significant percentage of the total all-in costs, are fairly predictable. On the other hand, there is high uncertainty regarding the cost of project initiation, planning, cost allocation, compliance, and siting processes. These uncertainties are due to the sheer number of industry organizations, local and national regulatory bodies, and approval and permitting agencies typically involved in these processes. This creates risk of cost variation and indeed of project termination, risks that reduce the willingness of potential partners to support such projects.
- **Characteristics for successful implementation:** There are three – an existing consensus to develop, an available funding approach, and public support (or at least a lack of public resistance). All three exist strongly in China, the consequence of which is that China, since 2014,



has built or is building almost three times the amount of interregional transmission capacity than the rest of the world combined. Although the US has built very little, developing these characteristics is definitely within reach. In terms of establishing consensus to develop, there is growing understanding of the benefits of interregional transmission, as indicated by the attention garnered by the recent Interconnections Seam Study, a representative sample of which includes [312, 313, 314, 315, 316, 317, 318]. Indeed, the current administration has recently signaled interest in interregional transmission via a congressional communication from FERC [319], and the Biden campaign has also been promoting it [320]. In spite of the difficulties the U.S. has had in obtaining federal siting authority (see Section 6.4) and the related emphasis on state's rights, the U.S. is better positioned than Europe in having, using, and increasing centralized authority. In terms of a funding approach, the presence of RTOs together with the precedent set by the success of the Eastern Interconnection States Planning Council (EISPC), and FERC's insistence on a "beneficiary pays" principle, suggests that the ability to identify a satisfactory approach to fund interregional transmission may not be difficult to obtain. The third characteristic, public support, will be facilitated via strong central leadership to bring the case to the American people; compensating states perceiving less benefit, and including the siting approaches under Section 6.4 may support this.

## 6.3 Engineering Design

*Question 3:* What basic steps are necessary in order to motivate and perform an engineering design of interregional transmission or Macro Grid?

*Response:* There are four main steps: techno-economic design; resource adequacy evaluation; contingency analysis and control design; and resilience and adaptability evaluation. Taking these steps results in quantification of the project's most significant benefits and costs (and computing benefit to cost ratio and/or return on investment), useful in cementing the commitment of all project partners. Additional engineering studies, including short circuit analysis, protection design, substation design, and line, structure, and insulator design, would be conducted before initiating construction.

## 6.4 Consolidating and Coordinating Mechanisms

*Question 4:* What potential consolidating and coordinating

mechanisms are necessary to accomplish an interregional transmission project in the U.S.?

*Response:* There are four areas where efforts to consolidate and coordinate processes would facilitate interregional transmission development.

- **Congested paths:** In the most recent US DOE Transmission Congestion Study [61], one figure showed the percent of time major transmission paths in the WECC are operated at 75% or more of their rated capacity. This figure is reproduced below. This kind of information, together with likely locations for siting future resources, is quite useful in motivating additional transmission investments. In addition, a "system-needs" study performed would be highly useful, similar to that performed by the European Network of Transmission System Operators for Electricity (ENTSO-E) and described in Section 4.2 [130]. Performing congested paths and "system-needs" studies that result from interregional transmission and Macro Grid designs would be highly informative; doing so might require development of a corresponding tool. A final comment here is to recognize that DOE has done well in seeking guidance and review of their transmission congestion studies; consideration should be given to forming a study group to perform them, where the study group is comprised of industry personnel.

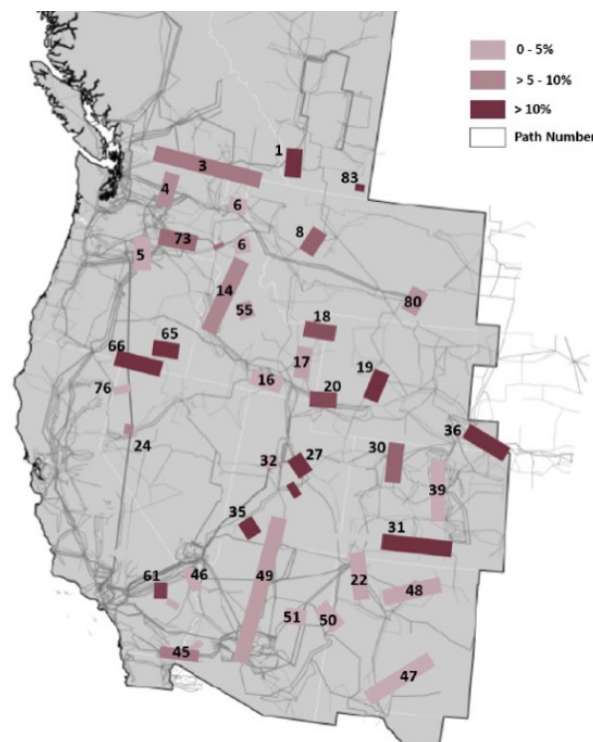


Figure 50: Congested paths in the North American Western Interconnection [61] (used with permission)

- Siting: Although the Energy Policy Act of 2005 (EPAct 2005) provided FERC with Section 1221 siting authority for transmission built in National Interest Electric Transmission Corridors (NIETC), this authority has been weakened by the courts and is now ineffectual. Recent attempts to facilitate federal involvement in siting using EPAct 2005 Section 1222 have also been unsuccessful. The technical solutions of using existing right-of-way where possible and underground otherwise, and ensuring all states have terminals (and therefore cannot be flyover), could be combined with federal and state policy change to identify a new approach to facilitate siting.
- Federal agency approval: The FERC has provided some benefit in this direction by granting the US DOE “lead agency” status for federal agency approvals, thereby coordinating and streamlining some of the processes. Additional efforts in this direction are needed.
- RTO-led engineering design: All seven US RTOs have established experience with respect to facilitating transmission design efforts. The US should capitalize on this experience in developing an integrated interregional transmission system. Non-RTO regions can be included. Such an effort should target a systematic and integrated design. This does not imply that merchant transmission developers cannot participate in building it, but rather, that each built link will be a part of a larger vision that best serves the nation

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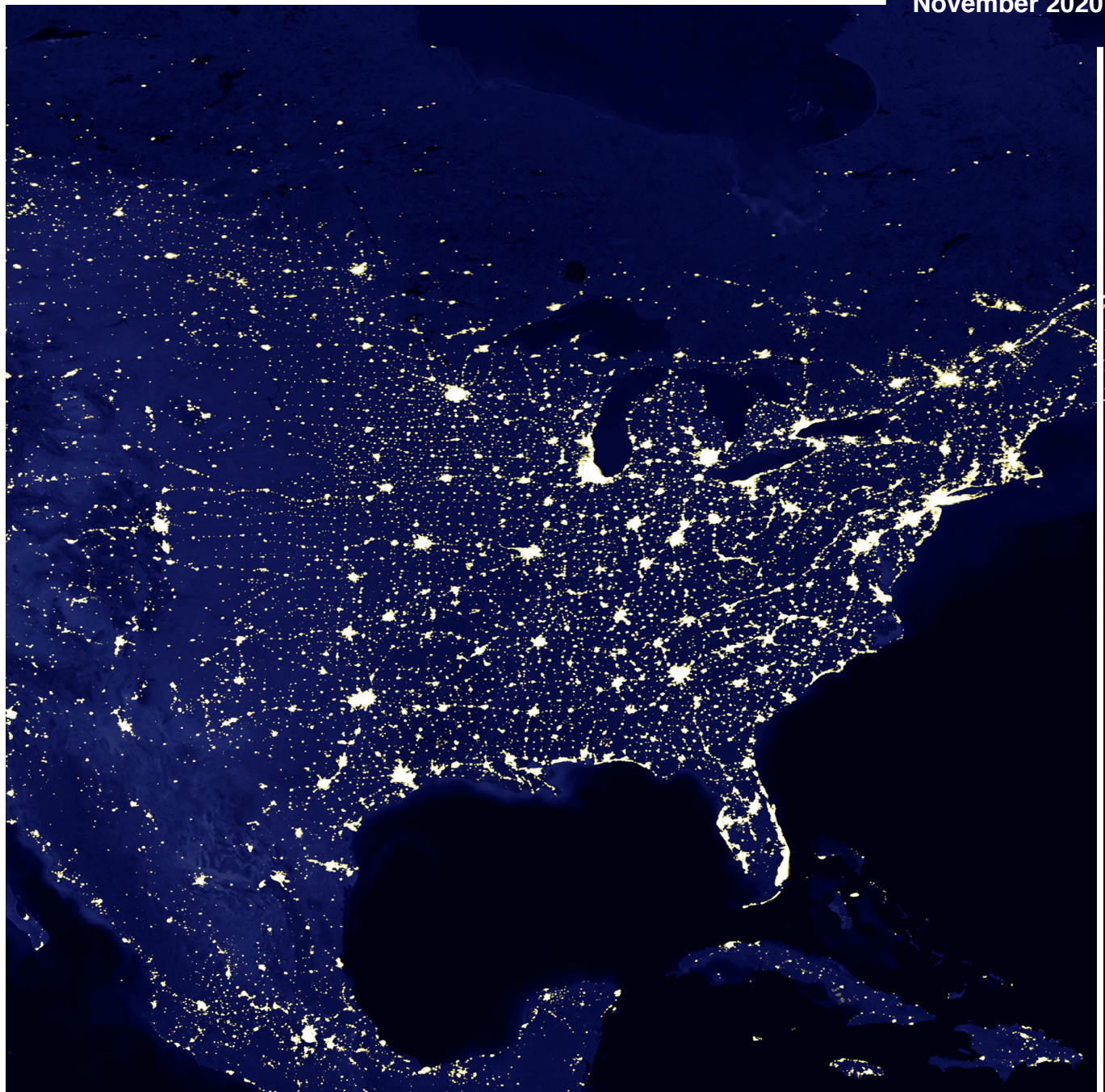
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Americans for a Clean Energy Grid (ACEG) is the only non-profit broad-based public interest advocacy coalition focused on the need to expand, integrate, and modernize the North American high-voltage grid.

ACEG brings together the diverse support for an expanded and modernized grid from business, labor, consumer and environmental groups, and other transmission supporters to educate policymakers and key opinion leaders to support policy which recognizes the benefits of a robust transmission grid. ACEG is a 501(c)(3) organization.