Interregional Renewable Energy Zones in National Transmission Analysis

David Hurlbut, Dylan Harrison-Atlas, and Jianyu Gu

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Preface

Interregional renewable energy zones (IREZs) envision long-distance transmission corridors anchored by zones with large amounts of low-cost renewable energy resources. The approach is modeled after similar successful models developed in Texas and the western United States.

This report serves two purposes. First, it provides a record of how the National Renewable Energy Laboratory (NREL) is identifying and analyzing IREZs for a national transmission study. The resulting transparency will help transmission providers and their stakeholders evaluate and justify the usefulness of IREZs in their regional transmission planning. The second purpose is to provide regional transmission providers with guidance if they instead choose to conduct their own analyses of renewable energy zones. The authors of this report acknowledge that local factors can strongly affect options for new transmission and that many of these factors are difficult to capture in a national analysis. Section 4 of the report converts the IREZ methodology used by NREL into steps that can be implemented by planning regions and states. Each step can be informed by publicly available information and by stakeholder input.

The authors are mindful of the concerns raised by the Federal Energy Regulatory Commission (FERC) in its notice of proposed rulemaking for transmission planning reform (FERC 2022). The nation's resource mix and the characteristics of its electricity demand are both changing radically from the staid predictability of the past. Further, these changes are happening against the backdrop of climate change, which is testing grid resilience with increasing frequency. Identifying future investments to replace, upgrade, and augment the nation's aging transmission infrastructure need new planning tools and new approaches.

The use of geographic zones for long-term planning is one of the tools FERC has asked parties to consider. The IREZ methodology described in this report is one way to approach the task. NREL has years of experience in advising states and countries around the world on the use of renewable energy zones. The authors have attempted to synthesize this experience in a transparent and replicable manner that can help utilities, transmission planners, and regulators test the usefulness of geographic zones in their long-term transmission planning processes.

Acknowledgments

The authors are indebted to Alejandro Moreno, Paul Spitzen, and Owen Zinaman of the U.S. Department of Energy (DOE) Office of Renewable Power for their support of this report. We are also grateful to Hamody Hindi and Carl Mas of DOE's Grid Deployment Office for their insightful guidance on integrating the interregional renewable energy zone concept within the scope of the National Transmission Planning Study.

This report benefitted greatly from improvements suggested by colleagues, including Jaquelin Cochran, Jeffrey Logan, Doug Arent, Trieu Mai, and Jarrad Wright from the National Renewable Energy Laboratory and Juliet Homer of Pacific Northwest National Laboratory. We are extremely grateful to Billy Roberts, NREL's chief cartographer, for the high-quality maps he provided for this project. Mike Meshek provided excellent editorial support for the report's final production, and Madeline Geocaris provided expert support for social media outreach.

List of Acronyms and Abbreviations

CREZ	competitive renewable energy zone
EIA	U.S. Energy Information Administration
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulatory Commission
IREZ	interregional renewable energy zone
ISO	independent system operator
km	kilometer
LCOE	levelized cost of energy
MW	megawatt
MWh	megawatt-hour
NEXRAD	Next Generation Weather Radar
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Database
NTPS	National Transmission Planning Study
PV	photovoltaic(s)
SAM	System Advisor Model
TSP	transmission service provider
WIND	Wind Integration National Dataset

Executive Summary

This report describes the methodology that the National Renewable Energy Laboratory used to identify interregional renewable energy zones (IREZs) for the National Transmission Planning Study. The aim is to develop a data-driven, replicable methodology for use in long-term regional and interregional transmission planning.

An IREZ is best understood as a conceptual collection point that is easily accessible to a very high volume of low-cost developable renewable energy potential, anchoring a major transmission corridor to load. The objective is to identify opportunities for new high-volume long-distance interregional transmission corridors: a limited number of lines with higher voltages, with reduced total cost per megawatt of transfer capability. Transmission corridors connecting IREZs to load centers do not replace network transmission connecting renewable resources serving local load. Rather, they address an emerging transmission planning issue caused by the nation's changing resource mix, decarbonization goals, and the limits of current planning practices: whether interregional exchange from a planning region with a surplus of low-cost renewables to one with a deficit might be cost-effective.

The IREZ methodology involves five steps:

1. Obtain the best available data on the potential productivity of wind and solar power.
2. Determine areas that are excluded from development.
3. Characterize the technical potential of the remaining areas.
4. Identify and analyze clusters of contiguous areas, applying criteria for:
    a. Reasonable thresholds for wind and solar resource quality (represented as the levelized cost of energy)
    b. The minimum quantity of developable potential within a reasonable distance from a transmission substation.
5. Identify and characterize hubs based on the remaining clusters, where "hub" means a central collection point for future renewable generators within a reasonable distance from the hub.

The success of this process depends on open and effective stakeholder participation. These steps involve a number of judgements on decision rules and data sources that will need to pass muster with stakeholders if they are to be defensible before regulators. Hubs that form the best match with load are included in grid planning, where infrastructure decisions are ultimately made.

Figure ES-1 shows the preliminary IREZ hubs resulting from this analysis. In the next phase of the IREZ work, the National Renewable Energy Laboratory (NREL) will conduct a load analysis that will match each transmission planning region's electricity demand with an optimal set of IREZ hubs. Less-competitive IREZs could be dropped if the analysis does not match them with a load region.

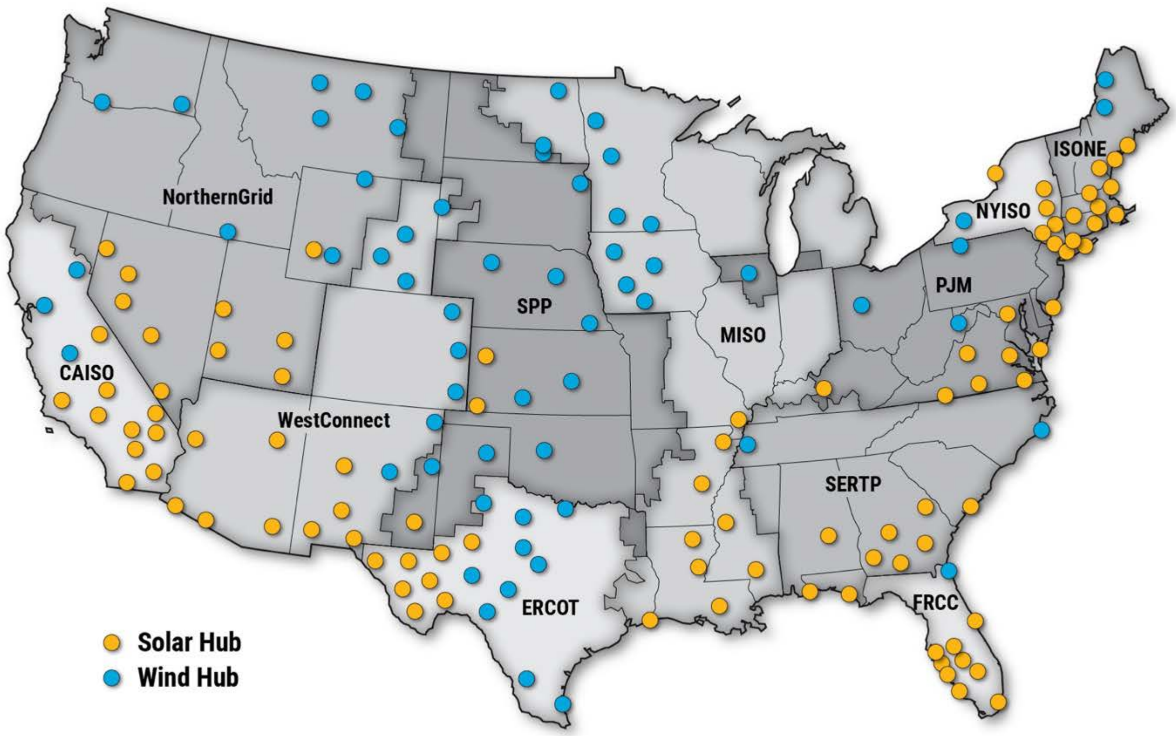

Figure ES-1. Preliminary IREZ hubs by transmission planning region

The map is by Billy Roberts, NREL.

Transmission planning for offshore wind differs substantially from the corridor planning addressed in the IREZ methodology. The Atlantic Offshore Wind Transmission Study is examining this special planning question. Leasing areas for offshore wind create *de facto* zones, thus there is no need to identify offshore wind zones in this analysis. Instead, the demand analysis that will be conducted in the next phase of IREZ work will adjust each region's potential need for IREZ resources by the amount of generation the region is expected to get from offshore wind power.

The next phase will also include an assessment of policy and stakeholder preferences for encouraging or discouraging renewable energy development in certain locations.

The report includes a section on how regional transmission planners might replicate the IREZ methodology if they elect to examine renewable energy zones themselves.

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1 What Is an Interregional Renewable Energy Zone?

1.1 The Rationale for Renewable Energy Zones

Interregional renewable energy zones (IREZs) as formulated in this report are designed to guide a specific type of transmission expansion: *corridors* capable of moving large volumes of renewable energy generation across a long distance. An IREZ is best visualized as a conceptual hub or collection point on the bulk power system that is easily accessible to a very high volume of low-cost developable renewable energy potential, anchoring a major transmission corridor to load. Interregional corridors are selected so that the all-in costs of the clean generation that is delivered to customers in targeted load centers compare favorably to the cost of other alternatives available to the local network.[1] Actions that reduce costs include:

- Accessing a large zone with high average wind speeds and high solar irradiance
- Minimizing "gen-tie" distances from a new generator to the nearest potential new transmission connection
- Increasing the size of transmission along a corridor to reduce line losses and achieve economies of scale
- "Right-sizing" a corridor to minimize future transmission expansion costs[2]
- Maximizing competition.

In the case of wind generation since the 2000s and utility-scale solar generation today, technologies using a renewable energy zone constitute a significant portion of the interconnection queue for many transmission providers, which suggests an intrinsic market demand for these technologies. However, their ability to provide maximum value depends on where the plant is sited. Unlike with coal and natural gas, the energy inputs used to generate electricity cannot be transported from one location to another: generators must be built where wind speeds and solar irradiance are high. If the transmission network into such locations is constrained, the natural demand for new wind and solar could be pent up or it could be forced into locations where the cost per megawatt-hour delivered is higher.

IREZs are not a universal solution for all transmission needs or for all technologies. For example, a renewable energy generator intended to serve local load would still connect to the local network. It would not need to share a transmission interconnection point with other generators. It would not be burdened with the cost of the transmission it would use, because those costs are already collected from retail customers on the network.[3]

Transmission for an IREZ, on the other hand, targets delivery to a distant load center via a single corridor. Multiple generators connect to the same line, which makes higher voltages economical. Higher voltages have lower line losses, lower cost per megawatt of capacity transfer, and lower cost per megawatt-hour delivered to customers if the lines are fully utilized. As a point-to-point

[1] Here, "network" refers to lines and other assets operated by the same transmission provider.
[2] An example is building a single-circuit transmission corridor that is double-circuit capable, with enough renewable potential in the source zone to provide the additional generation capacity when the demand materializes.
[3] A generator must pay for its interconnection studies, and it may have to pay for additional equipment on its side of the meter. The cost of the transmission network, however, is included in the utility's rate base.

corridor, the costs of an IREZ transmission line may be associated uniquely and exclusively with the generators connecting to it. Therefore, it might be reasonable to put IREZ transmission costs into a separate tariff schedule that allocates costs to load based on each load entity's expected benefits from the IREZ generators. In some cases, the cost might be assigned to generators using the IREZ corridor.[4] Thus the cost-benefit equation is more complicated for plants using an IREZ than it is for an individual generator destined to serve network load.

Changes in how the nation uses electricity, and changes in the technologies used to generate it, are creating new opportunities and new challenges. Traditional transmission planning is suited to improving the local network but not to creating interregional solutions that can unlock new sources of value for customers. The goal of this report is to demonstrate a methodology by which regional transmission planners might consider interregional options in conjunction with their current planning tools to meet the demands of a changing resource mix, changing customer demand, and cost-effective decarbonization.

1.2 No "If You Build It, They Will Come"

Renewable energy zones do not—and indeed cannot—create market demand that does not already exist. Zones only benefit clean energy technologies that are market-ready, where "market-ready" means the technology has reached a cost point that makes it competitive with other energy options and it has a significant presence in the interconnection queue. If the technology has not reached cost competitiveness, creating zones for that technology would add little to its commercial viability.

Put simply, there is no "if you build it, they will come" feature to renewable energy zones. Precommercial technologies do not benefit from zones and are better supported by research and development leading to better production processes and lower manufacturing costs. Creating zones for technologies that have not yet reached a point of demonstrated large-scale deployment runs the risk of building new transmission infrastructure that will not be used, thus creating an economic burden on electricity customers and society.

Rather, the strategy behind zones is "they are coming anyway, so let's build transmission to where they will do the most good." Renewable energy zones direct *already-existing* market demand for new generation to areas that will maximize competition and reduce costs.

1.3 Visualizing a Zone

An IREZ can be visualized as a hub on the future bulk power system that represents a potential collection point for a large amount of low-cost renewable energy. For identification and analysis, a hub is treated as a single collection point, although power flow studies might later indicate a need for the hub to be served by more than one injection point and several substations. Power flow studies take into account operational factors that do not affect salient attributes of an IREZ.

[4] For the purposes of this analysis, there is no economic difference between charging generators an IREZ access fee, and putting the cost of the IREZ corridor into a special transmission tariff schedule that is assessed to the load areas benefitting from the corridor. In either case, the cost of the transmission is ultimately passed on to the same group of end-use customers.

The zone has no geographic boundary. This is because a boundary would have no regulatory weight with respect to project siting and no usefulness in defining the zone's important attributes. A fixed perimeter to a zone would therefore be misleading. Gen-tie distance affects a generator's overall project costs, so as a general rule, sites farther from the collection point will naturally tend to be higher in cost and less feasible as hub resources, with or without setting an exact boundary.

1.4 Resource Diversity

The principle of open transmission access applies to an IREZ hub, so no type of generating resource is prohibited from interconnection. While in many cases the location of a hub might be based on a primary resource such as wind or solar, any generator that completes the transmission provider's steps for interconnection may use the line. It might not be possible to find gigawatts of geothermal, small hydropower, or biomass concentrated in the same zone, but these technologies could nevertheless provide enhanced value to a zone that is defined by wind or solar even if they were present in smaller quantities.

Resource diversity helps the economics of the transmission line because it can result in higher utilization of the line. In many areas, wind resources tend to be stronger at night than during midday. Solar generators normally peak at midday but have no output between sundown and sunrise. A combination of wind and solar, along with other renewable resources that might be available in the zone, results in a higher and more consistent usage of the transmission line and greater operational flexibility, which tends to reduce the cost of transmission per megawatt-hour of energy delivered to customers.

A recent operating day in Texas illustrates the benefits of colocation. Figure 1 shows hourly production values for wind and solar generators for August 17, 2022, limited to areas where wind and solar share access to transmission infrastructure in the state's established renewable energy zones (ERCOT 2022). Wind in West Texas and the Texas Panhandle is generally stronger in the evenings and lower during the day. Combining production for wind and solar resulted in a fairly consistent output for the day that avoided the strong diurnal variations of each resource individually.[5]

[5] Recent analysis shows that these synergies between colocated wind and solar generation are commonly found throughout the United States (Harrison-Atlas et al. Forthcoming).

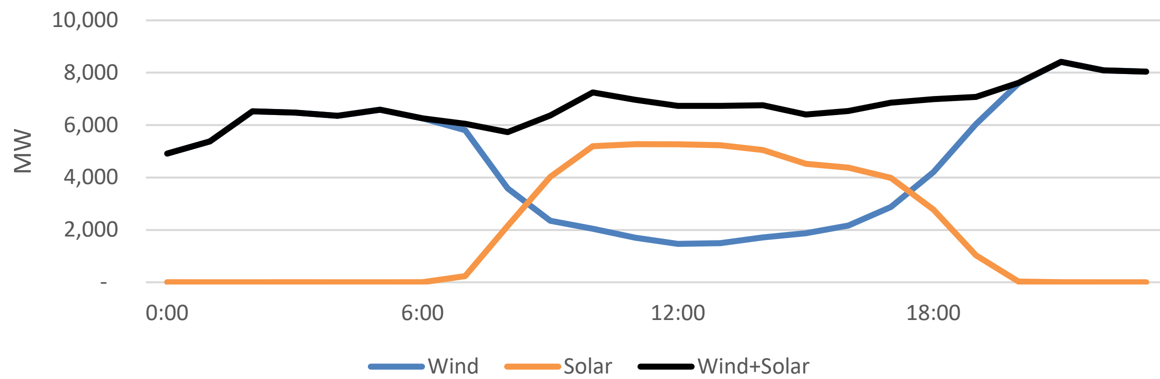


Figure 1. Actual wind and solar production in Texas' renewable energy zones, August 17, 2022

The curve for wind includes resources in the Electric Reliability Council of Texas' (ERCOT's) West and Panhandle wind regions. The curve for solar includes resources in ERCOT's Northwest, Far West, and Center West regions.

Source: ERCOT 2022

1.5 Competition

An IREZ contains significantly more developable potential than its connecting transmission can accommodate even after increasing the size of the lines. The abundance of siting options relative to transmission carrying capability encourages competition among renewable energy developers. In the Western Renewable Energy Zone analysis (Pletka and Finn 2009), for example, the computed developable potential for wind power was mathematically reduced by 75% for all zones after screening for land exclusions and resource quality. This smaller number represented a plausible input for studying the transmission that would access the zone.[6] The study assumed competition would determine which areas of the zone would actually be developed.

Surplus and competition promote additional cost savings. Buyers looking for a power purchase agreement can shop among several possible providers, which in turn encourages developers to put forward their best-priced offerings. Also, a "buyer's market" encourages actual development to happen promptly; if a project were to be delayed or canceled, it could be substituted with another.

Therefore, IREZ analysis *does not* assume the transmission build-out would fully accommodate each and every generator that wants an interconnection. It does assume that, even if wind or solar resource quality is homogeneous across the zone, some developers will do a better job than others of finding sites, securing power purchase agreements, and bringing capacity to the market.

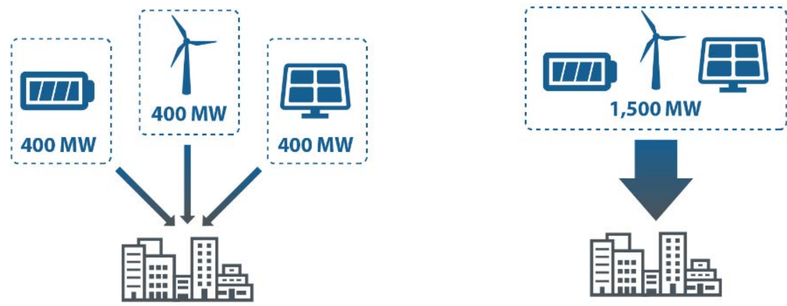
1.6 Economies of Scale with Respect to Transmission

Good wind and good solar resources are important to a project's cost-effectiveness, whether they connect to an IREZ or to the local network. However, IREZs are selected to achieve an

[6] This analysis does not apply a similar mathematical reduction. Therefore, when interpreting estimated capacity for wind and solar in an IREZ, the reader should note differences in each technology's capacity density. Rules-of-thumb used by NREL are 3 MW/km^2 for wind and 32 MW/km^2 for solar PV, based on empirical observations of developed projects.

additional savings: economies of scale with respect to the transmission line itself. IREZs maximize delivery of new renewable energy while using as few lines as possible. Economies of scale are achieved by using higher line voltages, consolidating many new transmission paths into a few, and using the new high-volume paths as fully as possible.

One 500-kV transmission line can deliver more electricity at less cost than three 230-kV lines, as illustrated in Figure 2. It also disturbs less land—one 200-foot right-of-way as compared to three 125-foot rights-of-way. Consequently, renewable energy zones also reduce the potential impact on wildlife habitat and other considerations that affect transmission siting.[7]



	Case 1: Three 100-mile 230-kV lines	Case 2: One 100-mile 500-kV line
Net deliverable (MW) to load[a]	1,160	1,489
Approximate cost of line and substations[b]	$583 million to $763 million	$401 million to $491 million
Cost per megawatt of transmission capability	$491,000 to $643,000	$338,000 to $414,000

Figure 2. Illustration of economies of scale for transmission

[a] Line capacity and loss factors taken from WECC (2019).

[b] Range represents the lowest and highest estimated costs for zones in the Midcontinent Independent System Operator planning region, with one new substation at the terminus of each line (MISO 2022).

The first case in Figure 2 is three single-circuit 230-kV lines, each capable of connecting 400 MW of generation resources. Each line has its own right of way from the resource to a common load center. The second case is one single-circuit 500-kV line capable of connecting 1,500 MW of generation resources, with each generator connecting to a single hub at the line's terminus. The cases can connect a comparable amount of generation, but the single larger line has a lower cost per megawatt of capability and loses less power in the transfer. In this generalized example, a single 500-kV line saves about 35% on the cost of transmission for every megawatt of capability. This does not include the savings in regulatory costs due to permitting and approving only one route rather than three.

This example illustrates the potential savings in transmission cost if an IREZ corridor is feasible. Naturally, the ability to increase the size a line depends on the concentration of developable

[7] On the other hand, an outage on a 500-kV line could have a larger system impact than an outage on a smaller line. A large line's single-contingency risk would depend on the topology of the grid and the grid's ability to adjust power flows to compensate for the outage.

renewable resources in the zone because the line needs to be used as fully as possible for it to be economically viable. It would not necessarily replace shorter, lower-voltage lines connecting local resources to local load, illustrating how the planning problem that IREZs address is different from transmission planning for the local network.

1.7 Interregional Application

Renewable energy zones are useful because wind and solar resources are significantly better in some areas than in others. IREZs quantify this heterogeneity across a large geospatial framework spanning several planning regions, so that the benefits of delivering wind or solar from one region to another might be tested. The question tested is:

> *Does the benefit of interregional exchange from a surplus region to a deficit region exceed the cost?*

Assume:

- "Low-cost renewables" means wind, solar, or any other renewable energy resource that can be developed in the region at a cost that is lower than the region's average cost of producing electricity.
- "Surplus region" describes a region with more low-cost renewable potential than its native load can use.
- "Deficit region" describes a region little or no low-cost renewables.
- "Interregional exchange" is low-cost renewable energy transmitted from a surplus region to a deficit region.

We do *not* assume that an interregional exchange would preclude the development of native renewables in the deficit region.[8] Rather, we assume the deficit region's native wind and solar projects would connect as network resources and that the cost of the transmission they would use would not be assigned to them directly. Conversely, we assume new transmission and new generation would be combined in a single cost-benefit analysis for the corridor. Consequently, the interregional exchanges would have an additional financial hurdle: transmission costs assigned to the generators either directly or indirectly that are not borne by native renewables in the deficit region.

Finally, we assume that interregional exchanges face no discriminatory hurdles in the deficit region and that they may compete fairly in the market on the basis of their costs relative to the cost of other resources. This is a simplifying analytical assumption for the purpose of evaluating interregional transmission options while holding all external considerations equal across all options. Institutional rules, stakeholder resistance to change, and other factors could impose barriers, but they are outside the IREZ analysis itself. The decision to address such barriers could depend on the potential benefits at stake, which is what an IREZ analysis quantifies.

While this analysis begins with generation cost savings, there are other benefits that can provide additional value. These include savings in operational costs due to temporal and geospatial

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[8] Resource modeling in the NTPS co-optimizes native renewables, interregional exchanges, storage, and new transmission.

diversity of weather impacts, and the smoothing effect of load diversity across a larger geography. We assume that these additional value sources can be studied in greater detail once the analysis has narrowed down options based on the cost of generation.

In this manner, IREZs can be tested to see whether they can fill a gap in regional and interregional transmission planning: opportunities for cost-effective exchanges of renewable energy from one region to another. IREZs provide a framework for analyzing a type of scenario that is not captured in current transmission planning processes.

1.8 IREZs and the National Transmission Planning Study

IREZs and the methodology described in the Section 2 were developed to support the National Transmission Planning Study (NTPS)[9] conducted by the National Renewable Energy Laboratory (NREL) and Pacific Northwest National Laboratory under the direction of the U.S. Department of Energy. The goals of the 2-year study are "to identify transmission that will provide broad-scale benefits to electric customers; inform regional and interregional transmission planning processes; and identify interregional and national strategies to accelerate decarbonization while maintaining system reliability" (DOE 2022).

The NTPS covers the contiguous 48 states and tests several nationwide approaches to transmission expansion. The analysis compares scenarios that rely mostly on expansion of local alternating current (AC) networks, expansion of high-voltage AC ties between regions with some direct current (DC) ties, and a high-voltage DC transmission overlay connecting all planning regions. Capacity expansion simulations co-optimize new generation, energy exports, new transmission, and energy storage simultaneously across the country.

NREL constructed this IREZ methodology to complement the NTPS scenario analysis in much the same way as a map inset provides detail on an area of special interest. A scenario examines effects across the entire power system, thereby capturing geographic interdependencies and overall social benefits. Scenarios also provide an empirical foundation for analyzing system reliability, resource adequacy, and resilience—all of which are not examined in the IREZ analysis. Instead, the IREZ analysis aims to take what scenario analysis says generally about power flows between regions and test specific options for interregional transmission corridors that are consistent with the scenarios. The next phase of the IREZ work will examine the alignment between IREZ corridors and the system outcomes from scenario analysis.

Our hypothesis is that a special analysis of zones and interregional corridors might help bridge the regulatory gap between nationwide scenario modeling and project development. There is no existing institutional framework for implementing a nationwide transmission plan. But a component of a nationwide scenario such as IREZ corridors can provide the specificity needed for affected stakeholders to explore benefits and options for cost allocation in a practical way that would support investment in new inter-regional transmission. The goal is to use the IREZ analysis to understand the distribution of cost-related benefits to specific regions, and to use the NTPS scenario analysis to understand system benefits like resource adequacy and reliability.

[9] For more information about the NTPS, see https://www.energy.gov/oe/national-transmission-planning-study.

2 Methodology

We locate zones based on spatially continuous areas with concentrated supplies of low-cost wind or solar generation potential. Wind and solar resources must meet two basic criteria to be included in an IREZ. First, they must be characterized as developable (i.e., not located in a site that would likely be excluded from development based on technical, regulatory, current industry best practices or other constraints). Second, primary resources must be among the cheapest found within the transmission planning region.

Throughout this section, we refer to "planning regions" as Federal Energy Regulatory Commission (FERC) Order 1000 transmission planning regions, and the Electric Reliability Council of Texas (ERCOT).[10] Planning regions, shown in Figure 3, are the foundational organizational unit for IREZ analysis.

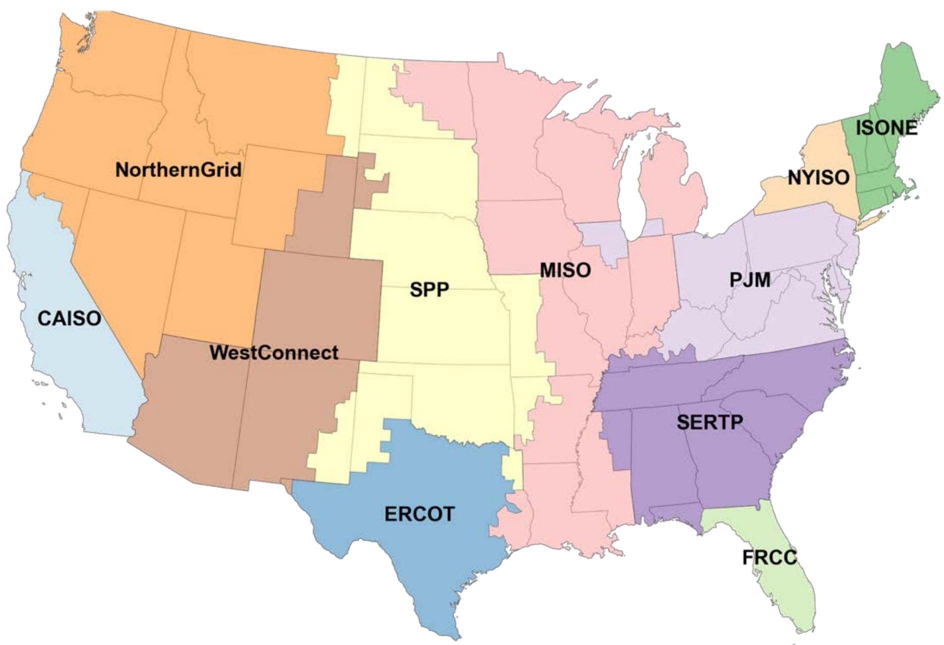

Figure 3. Regions used in the IREZ analysis

We applied five steps in identifying renewable energy zones, shown in Figure 4. The first step mapped out wind and solar resources using best available spatiotemporal resource data. The second step removed those locations considered unavailable for wind or solar development. The third step modeled technical potential of the remaining areas. Key outputs such as generation potential, available capacity, and economic information were used as inputs for subsequent steps. The fourth step applied spatial clustering to identify groupings of contiguous locations that have desirable attributes for inter-regional transmission planning. Clusters, which are the analytical precursors to zones, were refined and then characterized. For example, small, isolated clusters

[10] ERCOT is not under FERC jurisdiction. It is a single-state RTO with limited electrical and commercial connections to other states, and it is regulated by the State of Texas. We also combined the analysis for the Southeast Regional Transmission Planning and South Carolina Regional Transmission Planning regions.

that did not meet regional criteria were refined or removed from further consideration. Critical information provided for each cluster includes total capacity and its supply curve, which shows the cumulative energy supply available at different cost points. These clusters form the basis of an IREZ. The fifth step optimized the hub location, based on an assessment of least-cost connection points within the cluster. Hubs are the ultimate spatial representation for each zone and its associated attributes.

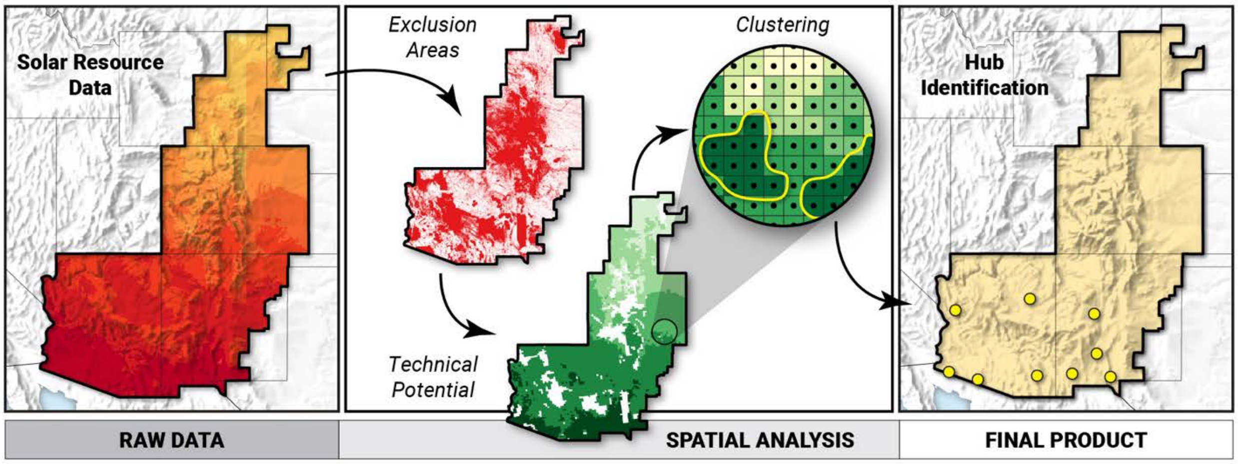

Figure 4. Workflow used by NREL to identify renewable energy zones

2.1 Resource Data

We used NREL's publicly available Wind Integration National Dataset (WIND) Toolkit and the National Solar Radiation Database (NSRDB) to model renewable power generation. Both data sets contain hourly data for multiyear periods and cover the contiguous United States. We captured interannual variability in resource quality using the full span of WIND Toolkit data (2007–2013). This period overlaps with the temporal coverage of the NSRDB (1998–2021), providing seven years' worth of time series data on wind and solar resources, which we used in this IREZ analysis.

The WIND Toolkit includes data on wind speed, pressure and air temperature covering multiple turbine hub heights at a nominal spatial resolution of 2 km by 2 km (Draxl et al. 2015). The NSRDB provides information on direct normal irradiance, diffuse horizontal irradiance, air temperature, and wind speed variables that are required to estimate solar photovoltaic (PV) power generation (Sengupta et al. 2018). The nominal spatial resolution of the NSRDB is 4 km by 4 km.[11]

2.2 Exclusions

Spatial exclusions identify lands that are likely undevelopable for utility-scale wind or solar. The exclusions are based on a combination of physical features, the built environment, social,

[11] More information on the WIND Toolkit is available at https://www.nrel.gov/grid/wind-toolkit.html. More information on NSRDB is available at https://nsrdb.nrel.gov/.

ecological, and wildlife considerations, as well as legal or jurisdictional restrictions that would constrain development of renewable infrastructure.

The list of exclusions used by NREL in its numerous renewable energy zone analyses and technical potential assessments for states and countries has evolved over time with extensive input from land use experts and other stakeholders. Today's reference regime represents current understanding of best practices for renewable energy siting (Lopez et al. 2021). Appendix A lists the specific criteria we used to exclude sites from the IREZ analysis.

Wind and solar differ in how they use land and in terms of their siting restrictions, so each has its own list of exclusions for certain categories of federal land, elements of natural landscapes, existing structures and setbacks, physical land characteristics, and protected lands.

2.3 Technical Potential

We evaluated wind and solar technology performance using the Renewable Energy Potential Model (referred to as the reV model, where V is a common scientific designation for electricity potential).[12] The reV model is designed for modeling of renewable energy, and it can efficiently estimate power generation and economic costs for different renewable technology configurations at upward of millions of locations (Maclaurin et al. 2019). A spatial framework enables reV to model fundamental geographic variation in resource quality and to represent spatial exclusions for renewable technologies.

We selected reference technologies and associated costs for PV and for wind. Both technology configurations were based on NREL's 2022 Annual Technology Baseline[13] using the Moderate Technology Innovation Scenario for projected costs in 2030 (NREL 2022). The moderate case for PV assumes that investment in research and development is consistent through time based on current levels and that no substantial innovations or new technologies are introduced. The moderate case for wind describes a technology innovation scenario wherein trends in scaling continue, transportation challenges are addressed, and turbine controls become more advanced through time.

The generic technology for solar was a monofacial single-axis tracking PV system with no panel tilt, a DC-to-AC wattage ratio of 1.3, a 96% inverter efficiency, and assumed losses of 14.1%. The PV losses account for availability as well as effects of soiling, shading, inverter mismatch, wiring and connection losses, light-induced degradation, and nameplate losses (Freeman et al. 2018).

The representative wind system was an onshore 5.5-MW wind turbine mounted at a hub height of 120 meters with a rotor diameter of 175 meters. Net losses, assumed to be 11.8%, account for availability, electrical losses, wake losses, turbine performance, curtailment, and additional costs related to environmental factors such as blade coatings, cleaning, and cold weather packages (Clifton, Smith, and Fields 2016).

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[12] For more information about the reV model, see https://www.nrel.gov/gis/renewable-energy-potential.html.
[13] For more information about the Annual Technology Baseline, see https://atb.nrel.gov/.

The reV model takes as input the wind or solar resource data sets and spatial exclusion data. It estimates generation potential using NREL's System Advisor Model (SAM),[14] which applies the generic technology configurations to each site's specific wind or solar resources. Hourly generation profiles were produced for 2007–2013. Results were also reported as multiyear average annual capacity factors. This information is provided at the spatial resolution of the resource data.

As a secondary procedure, reV intersects spatial exclusions at a resolution of 90 meters with generation potential, proportionally reducing the available capacity in the larger pixel by the amount of excluded land. The remaining capacity was then spatially aggregated to a resolution of 11.52 km by 11.52 km. Each of these pixels yields an estimate of technically available capacity and associated economic performance represented by an estimated levelized cost of energy (LCOE).

2.4 Clustering and Characterizing

We used a data-driven approach to identify renewable energy zones. The supply of high quality, low-cost renewable resources must be of sufficient capacity, relatively homogeneous, and spatially contiguous in order to constitute a zone. We analyzed this convergence of factors using spatial clustering techniques. These techniques essentially grouped spatially connected locations that shared comparable wind or solar LCOEs. Clusters are the analytical basis of IREZs.

The clustering procedures described in this section were performed independently for each transmission planning region. This approach recognizes the inherent variation in the quality, cost, and availability of wind and solar throughout the country. As a standard goal for each transmission planning region, we attempted to identify up to 10 discrete zones of each resource type.[15] Zones were defined based on specific criteria for either wind or PV, which we refer to as the primary resource type. Each zone also had some measure of the other resource type, which we refer to as secondary resources. Thus, an IREZ hub was defined by the zone's primary resource, but its supply curve included both primary and secondary resources. This approach captures zones that are rich in both resources.

Generally, four steps were needed to identify renewable energy zones. First, we screened each region's developable potential to the 25% of sites with the lowest LCOE.[16] Second, we applied a region-growing algorithm to transform the extracted areas into clusters. Region-growing algorithms have been widely used in computer visualization and geospatial data science fields to partition an image or raster data into meaningful groups based on the feature similarities defined between a seed pixel with neighboring pixels (Adams and Bischof 1994; Hojjatoleslami et al. 1998). The application of a region-growing algorithm to the IREZ analysis is explained in Section 2.4.1 below. Clustering was done independently for wind and PV. Finally, postprocessing techniques (also explained below) addressed overlaps between wind and PV clusters. This provided characterizations for each cluster based on the technical and economical properties of the primary and secondary resources associated with the cluster.

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[14] For more information about SAM, see https://sam.nrel.gov/.
[15] The cap on the number of clusters need not be 10.
[16] Applying the same percentage criterion to each region ensured that each region would have at least one zone.

2.4.1 Workflow for the Identification of Spatial Clusters

Clustering groups spatially connected sites (represented as 11.52 km by 11.52 km pixels) of comparable quality and cost. The method described here effectively transforms the region's lowest-cost 25% of potential into a discrete set of clusters, some of which become renewable energy zones. The clustering algorithm was based on an improved region-growing algorithm, which is detailed in this section. The workflow was applied separately for wind and solar resources in the planning region.

1. *Estimate the initial number of clusters within a region*. We presumed a renewable energy zone should contain a minimum capacity of 4 GW. This number is 33% more than the carrying capacity of a double circuit 500-kV transmission line, which we assumed to be representative of a new transmission connection to a zone (WECC 2019). Capacity potential in excess of transmission capability allowed room for competition in project development, and it provided a margin to account for site constraints not addressed elsewhere in the analysis. The capacity threshold allowed us to derive an estimate of the number of potential zones within a region, which we then used as a target to inform the number of spatial clusters. We informed the initial number of clusters, $N_{clusters}$, by dividing the total capacity of a region by 4 GW to yield K, a multiplier that captures the amount of regional resource capacity available above this threshold. The initial number of clusters was then estimated according to the following formula:
$$N_{clusters} = \begin{cases} 10, & K \geq 10 \\ [K], & 1 < K < 10 \\ 1, & K \leq 1 \end{cases}$$
The formula means a planning region will have at least one cluster and no more than 10 clusters per resource type. (Having at least one cluster in a region, even if its cost is relatively high, enables a quantitative comparison of that region's best resources with alternatives in neighboring regions.) We used $N_{clusters}$ as a starting point to guide the algorithm. Additional iterations determined the ultimate number of clusters, some of which could end up larger than 4 GW.
2. *Choose initial seeds*. The initial seeds are locations from which the clustering algorithm will start to grow as it iteratively attempts to group neighboring pixels. The traditional region-growing algorithm uses randomly selected pixels as the seed locations, which is not efficient. Here, we choose the initial seeds using a more tactical approach. Our method consisted of using each pixel's latitude and longitude as input features to a K-means clustering algorithm where we specified $N_{clusters}$ as the number of groups for it to partition. This allowed us to identify spatial groupings of input pixels of comparable size. From these groups, we identified the center-most pixel and used it as the initial seed. Each initial seed has a unique label. Note that the K-means algorithm used here is intended to support choosing the initial seeds only and the initial seeds would be iteratively adjusted in the next steps.
3. *Define spatial and attribute criteria for determining cluster membership and growth*. The spatial neighborhood determines whether a pixel may be considered as part of a growing cluster based on its proximity. We assumed pixels may be added to a cluster if they were within 23.04 km of a growing cluster; this threshold was double the spatial resolution of the input data (11.52 km). Locations may also only be considered members of a growing cluster if they are sufficiently similar to the seed in terms of their attributes. We used

the LCOE and spatial distance as two attributes for evaluating potential membership to a cluster. Similarity was estimated by computing the Euclidean distance between a neighboring pixel and the seed using both attributes. The shorter the Euclidean distance (i.e., higher similarity), the higher probability was that a neighboring pixel shared membership with its seed.

4. *Region growing*. We employed a simultaneous growing order to assign each seed's label to its neighboring pixels based on similarity. The simultaneous growing order allows region growing to group neighboring pixels without giving a stopping threshold. The region-growing algorithm continues until no additional spatially connected pixels for growing remain. This process may result in some isolated pixels that were not assigned to any cluster.
5. *Update the seeds and the number of clusters*. At this stage, the center of each cluster was recalculated as a new seed. If the total capacity of a cluster was less than 4 GW, and this cluster was spatially disconnected from any other cluster, the pixels in this cluster were dropped and not considered in the next step. If a cluster's total capacity was found to be less than 4 GW, but the cluster was spatially connected to another cluster, the number of target clusters would be reduced by one in the next step (i.e., two clusters would be merged, leading to fewer clusters). However, if the number of clusters had already been reduced to a single cluster, this cluster would not have been removed to ensure at least one cluster of each resource type was identified per region.
6. *Stabilize the clusters*. The algorithm repeated Steps 4 and 5 until the locations of seeds remained stable and there was no need to either reduce the number of clusters or drop any additional pixels lacking cluster membership.

2.4.2 Postprocessing Clusters

This step performed postprocessing to modify wind and PV clusters if they overlapped spatially. The postprocessing was necessary to avoid double-counting of shared land area that would otherwise have inflated estimates of total wind and PV capacity available.

1. *Process spatial overlap between a wind cluster and a PV cluster*. Double counting of capacity in areas shared by wind and PV clusters was avoided by following the rules outlined below:
    A. If the shared area of two overlapping clusters was more than 25% of the area of either of two intersected clusters, the two clusters were merged. The cluster of the resource type with higher average LCOE was merged into the intersected cluster of the resource type with lower average LCOE. The cluster with higher LCOE was dropped from clusters of its resource type. For example, if a cluster with low-cost solar overlapped a cluster with moderate-cost wind, the wind cluster was dropped and its resources were included in the supply curve of the expanded solar cluster.
    B. If the shared area of overlapping clusters A and B was not more than 25% of the area of either of the two intersected clusters, the clusters were modified as follows:

i. First, the capacity represented in the overlapped area was quantified. If removing that capacity from Cluster A resulted in its remaining capacity falling below 4 GW, the resources of that overlapped area were assigned to Cluster A and removed from Cluster B.

ii. If neither of the two clusters would fall below 4 GW capacity, the resources in the overlapped area were assigned to the cluster with the smallest area.

iii. If modification resulted in either of the two clusters falling below 4 GW capacity, the resources in the overlapped area were assigned to the cluster with the smallest area (i.e., to avoid that cluster's falling between the 4 GW threshold).

2. *Characterize the clusters*. Although each cluster was defined based on a primary resource type (i.e., either wind or PV), all clusters were likely to possess secondary resources, which should also be quantified as a key attribute of the cluster. Therefore, we characterized each cluster by its primary resources and its secondary resources. Specific variables to be characterized for both primary and secondary resource types included total capacity (GW), annual energy yield (TWh/year), average and 10^{th} percentile LCOE ($/MWh), multiyear average annual capacity factor, and a comprehensive supply curve.

   Recall that a cluster's location and geographic extent were defined by its primary resource (wind or solar), which was limited to the region's lowest-cost 25% of developable area for that resource. A cluster's secondary resources do not affect the cluster's location or extent and, therefore, need not be constrained to that resource type's regional LCOE threshold. The rationale was that the secondary resource brought a potential extra value, in that the cluster's resource diversity could lead to higher utilization of the transmission lines even if the secondary resource's LCOE was higher than the regional threshold.

2.5 Preliminary Hub Identification

The ultimate representation for each zone is a single hub that serves as a least-cost collection point (i.e., a transmission substation) for the wind and solar resources contained within the zone. We determined the location of each hub using a spatial optimization procedure that placed the conceptual substation such that it maximized the concentration of low-cost resources close to the hub. Specifically, the optimal location was one that jointly minimized LCOE and the cumulative intertie distance needed to harness the best available renewable resources. Steps to identify the hub locations are as follows:

1. *Calculate each pixel's intertie distance*. D_p is the spatial Euclidean distance between a potential wind or PV source pixel and a hub pixel. These distances were computed exhaustively for all possible hub locations.

2. *Calculate the cumulative intertie distance*. D_c is the cumulative intertie distance. It represents the total spatial Euclidean distance that would need to be traversed to linearly connect a hub to renewable generation sources placed at all pixels within a cluster. We computed this distance exhaustively for every pixel that is a possible hub location.

3. *Calculate each pixel's weight based on intertie distance*. For all possible hub locations, we computed each pixel's normalized weight based on intertie distance (D_p):
$$\lambda_p = \frac{1/D_P}{\sum_p^N 1/D_P}$$
where λ_p is the inversed distance weight, p is the indicator for a specific pixel and N is the total number of pixels within a cluster. The sum of λ_p across all pixels is one.

   The resulting values were used as an inverse distance weight to weight more strongly generation resources closer to the hub than those are in a more distant part of the zone.

4. *Compute average distance-weighted LCOE*. We multiplied each pixel's inversed distance weight by its LCOE. For all possible hub locations, we computed the average distance-weighted value across all source pixels, and we associate each hub location with this average distance-weighted LCOE value.
5. *Determine hub location*. From all possible hub locations, we selected as optimal the one that jointly minimized the vector [average distance-weighted LCOE, cumulative intertie distance].
6. *Characterize a hub*. Each cluster has one hub which inherits the cluster's attributes. The hub is represented as a point feature whose location is captured by latitude and longitude coordinates.

3 Preliminary Results

This section reports preliminary IREZ hubs using the method described in Section 2. They are preliminary in that they do not include two steps that will be applied in the next phase of the IREZ work in the NTPS:

- A demand analysis that will match hubs with regions where their resources are most likely to be competitive, including adjustments to account for energy a region obtains from offshore wind power
- Use of weighted preferences that could adjust the locations of some hubs to account for factors such as energy justice and commercial interest.

The demand analysis will match each transmission planning region's demand for renewable resources with an optimal set of IREZ hubs. Matching will be based on regional surpluses and deficits of low-cost renewable resources, benchmarked to expected total electricity demand in each region by 2035. Less competitive IREZs could be dropped if the analysis does not match them with a load region. The outcome of the demand analysis will be a specific set of interregional corridors identified by their potential benefits. The analysis will also provide region-specific information on questions about cost allocation, which will be critical to addressing regulatory questions affecting the actual development of interregional transmission.

Developers and load-serving entities may prefer some IREZs over others due to factors not captured in the exclusions used in the cluster analysis. Among these factors are energy justice considerations and local preferences to encourage or discourage energy development based on land characteristics. Preferred zones could also have tangible demonstrations of developer interest, such as land lease options, prior projects, and activity in the transmission interconnection queue focusing on the zone.

The NREL project team plans to develop and apply mathematical weights that will be incorporated into the hub location step described in Section 2.5 (page 14). For example, several Native American tribes, after discussion about the NTPS with NREL staff, indicated a positive interest in encouraging large-scale renewable energy development on their lands. The mathematical weights will locate IREZ hubs closer to tribes that have indicated a preference for interregional transmission access.

Weights for universal preferences will be developed through a stakeholder-informed methodology called the analytic hierarchy process. It is a structured technique for quantifying global preferences involved in decision making (Saaty 1988). It will aggregate preferences related to a discrete number of mappable social and ecological factors that are not otherwise addressed as outright exclusions shown in Appendix A. The resulting weights will be applied to a cluster's geospatial characteristics to adjust the location of an IREZ hub.

Figure 5 maps the preliminary IREZ hubs. As mentioned in Section 2.4, the methodology ensures each planning region has at least one cluster and thus at least one IREZ hub. Table 1 summarizes preliminary IREZ resources aggregated for each planning region. Table 2 provides a snapshot of the least-cost IREZ hubs.

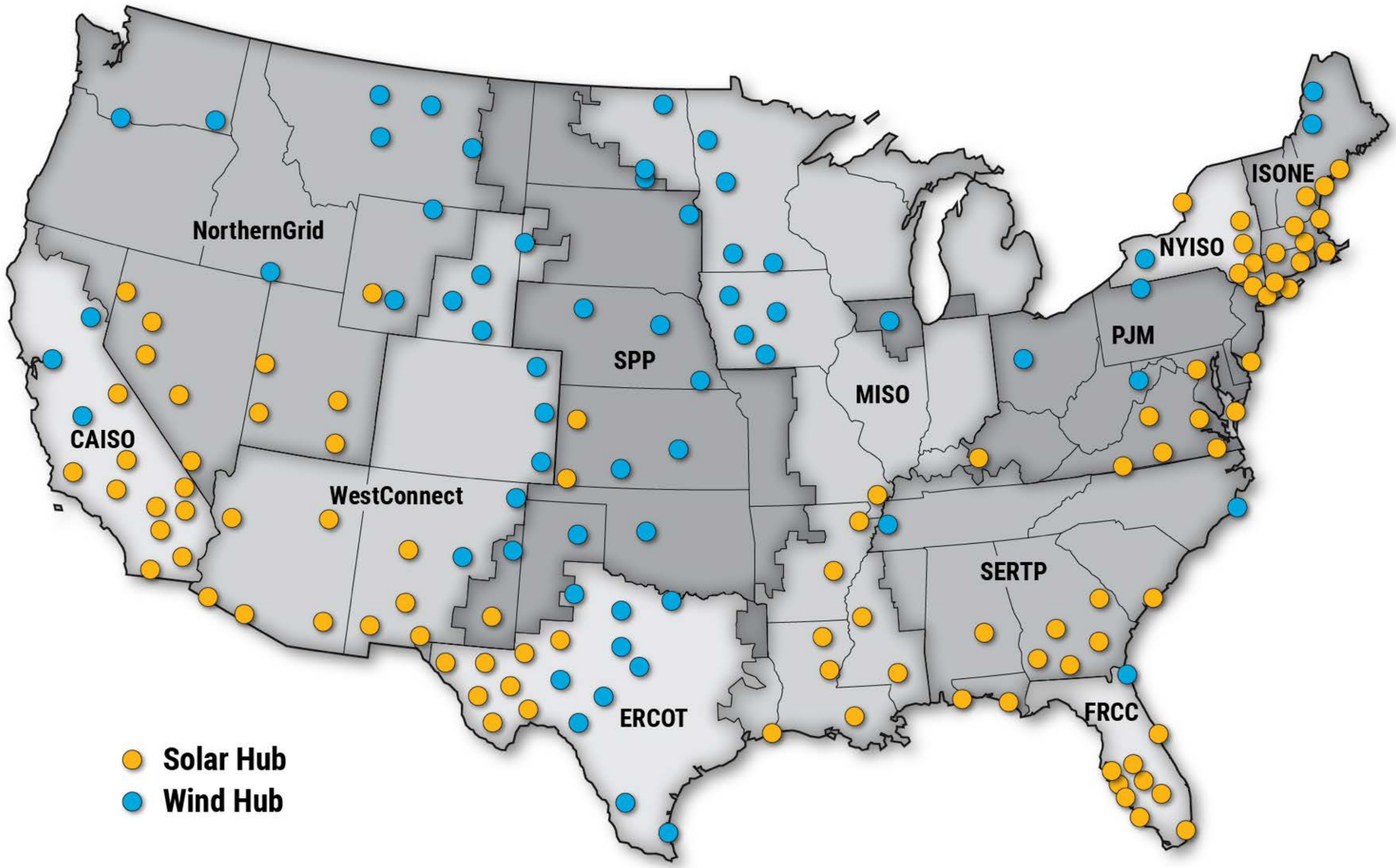

Figure 5. Preliminary IREZ hubs by transmission planning region.

Hubs are indicated by their primary resource type. Refer to Table 1 to compare quantities of resources contained in each region's IREZs. To download detailed data on the supply curves for each hub, see https://data.nrel.gov/submissions/194.

The map by is Billy Roberts, NREL.

Table 1. Summary of IREZ Capacity in Transmission Planning Regions

Region	Total IREZ Capacity (GW)		LCOE ($/MWh, median / 10th percentile)	
	PV	Wind	PV	Wind
ISO-New England	785	11	$37 / $35	$27 / $24
New York ISO	591	6	$38 / $36	$27 / $23
PJM	4,567	55	$35 / $33	$27 / $23
Southeastern Regional Transmission Planning	5,676	48	$31 / $30	$29 / $25
Florida Reliability Coordinating Council	770	5	$29 / $28	$33 / $30
Midcontinent ISO	14,109	274	$34 / $31	$23 / $21
Southwest Power Pool	12,763	436	$31 / $26	$21 / $20
ERCOT	6,492	380	$28 / $24	$23 / $20
NorthernGrid	11,581	970	$30 / $26	$37 / $25
WestConnect	9,247	705	$25 / $24	$34 / $22
California ISO	1,034	34	$25 / $23	$48 / $32

Zones with lowest 10th percentile LCOE for wind and PV are indicated in **bold**. The financial assumptions of LCOE are based on R&D Only Case using moderate scenario of Annual Technology Baseline 2021. (https://atb.nrel.gov/electricity/2021/financial_cases_&_methods).

Table 2. Preliminary IREZs with Median LCOE Less Than $25/MWh for Both Wind and Solar

Region (Hub ID)	Primary Resource	PV Capacity (GW)	Wind Capacity (GW)	LCOE ($/MWh, median/ 10th percentile)	
				PV	Wind
ERCOT (Hub 17)	Solar	357	26	$24 / $24	$25 / $20
ERCOT (Hub 20)	Solar	401	14	$24 / $24	$22 / $21
Southwest Power Pool (Hub 133)	Wind	1,879	32	$25 / $24	$21 / $19
WestConnect (Hub 154)	Wind	784	58	$24 / $24	$23 / $20

To download detailed data on the supply curves for each hub, see https://data.nrel.gov/submissions/194. The financial assumptions of LCOE are based on R&D Only Case using moderate scenario of Annual Technology Baseline 2021. (https://atb.nrel.gov/electricity/2021/financial_cases_&_methods).

4 Replicability of the IREZ Methodology

A planning region may use NTPS IREZs in its long-term regional planning. If the region decides to instead conduct its own analysis, it can convene a stakeholder process and proceed as follows:

- **Step 1:** Obtain the best available data on wind speeds and solar irradiance for the planning region.
- **Step 2:** Determine areas that are excluded from development.
- **Step 3:** Set threshold criteria for analyzing zones, including:
  - Reasonable thresholds for minimum wind speed and solar irradiance at potential sites for new wind and solar generators
  - The maximum reasonable distance of a gen-tie from a new renewable energy generator to a transmission substation
  - The minimum quantity of developable potential within a reasonable distance from a transmission substation
  - Presumptions about other measurable thresholds that stakeholders agree are useful.
- **Step 4:** Assess policy and stakeholder preferences for areas to encourage or discourage renewable energy development, including demonstrations of financial commitment by generators, consideration of energy justice, and other priorities identified by stakeholders.
- **Step 5:** Identify and analyze candidate hubs, where “hub” means a central collection point on the transmission system for future renewable generators within a reasonable distance from the hub. The location of hubs should aim to maximize the expected capacity factors of new wind and solar resources within a reasonable distance from the hub. Attributes of each candidate hub include the:
  - Approximate latitude and longitude of the hub
  - Type and quantity of renewable resources within a reasonable distance from the hub
  - Hourly production profiles of the hub’s primary resources during a typical meteorological year (if available)
  - Estimated levelized cost of energy for hub resources based on current project costs.
- **Step 6:** Obtain and report stakeholder consensus on final hubs, with at least one hub representing the region’s best renewable resources. If the consensus is that the region has no viable hubs, the planning entity should summarize the reasons. The list of final hubs (including the attributes of each hub) should be published on the transmission provider’s open-access, same-time information system portal.

Hubs may then be incorporated into long-term transmission planning scenarios.

4.1 Step 1: Best Available Data

NREL maintains detailed data on wind resources, solar resources, and technology costs. The data are publicly accessible, along with tools for estimating the effective cost of renewable energy technologies at specific locations. The WIND Toolkit and the NSRDB, which was used by NREL in the IREZ analysis, are both publicly available. Figure 6 shows average annual wind speeds for all locations in the contiguous United States covered by the WIND Toolkit. Figure 7 shows global horizontal irradiance for the United States.

NREL's Annual Technology Baseline provides nonproprietary, third-party estimates of current technology costs and performance, along with a range of forecasts for future costs. Annual Technology Baseline estimates are public and may be used as a starting point for developing a consensus on generic capital expenses, operating expenses, and other cost factors for technologies expected to be built in a zone.

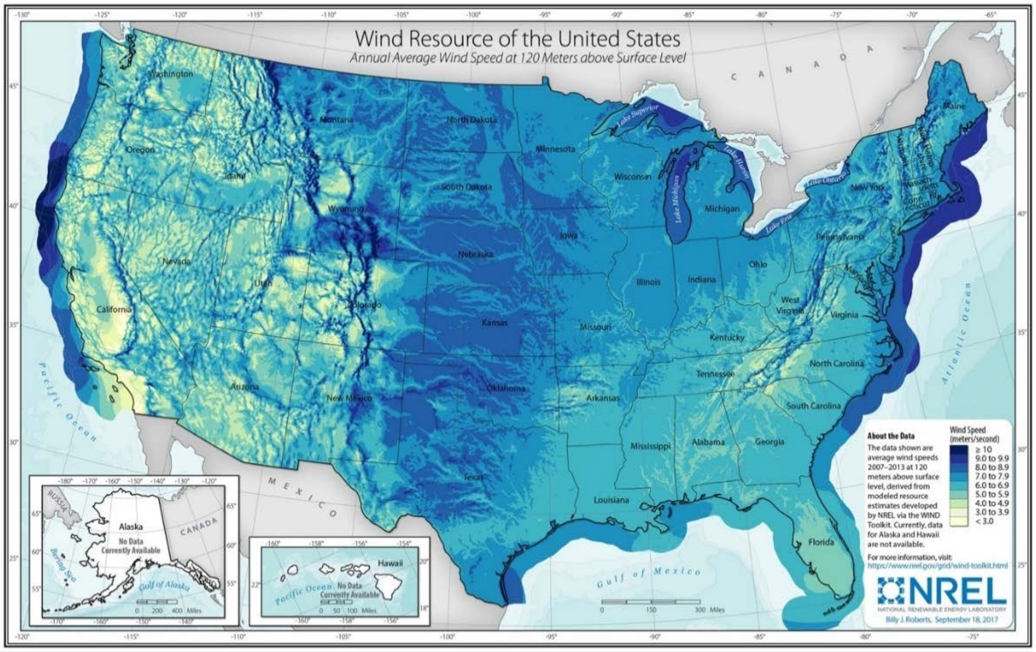

Figure 6. Wind resources at 120-meter hub height in the United States

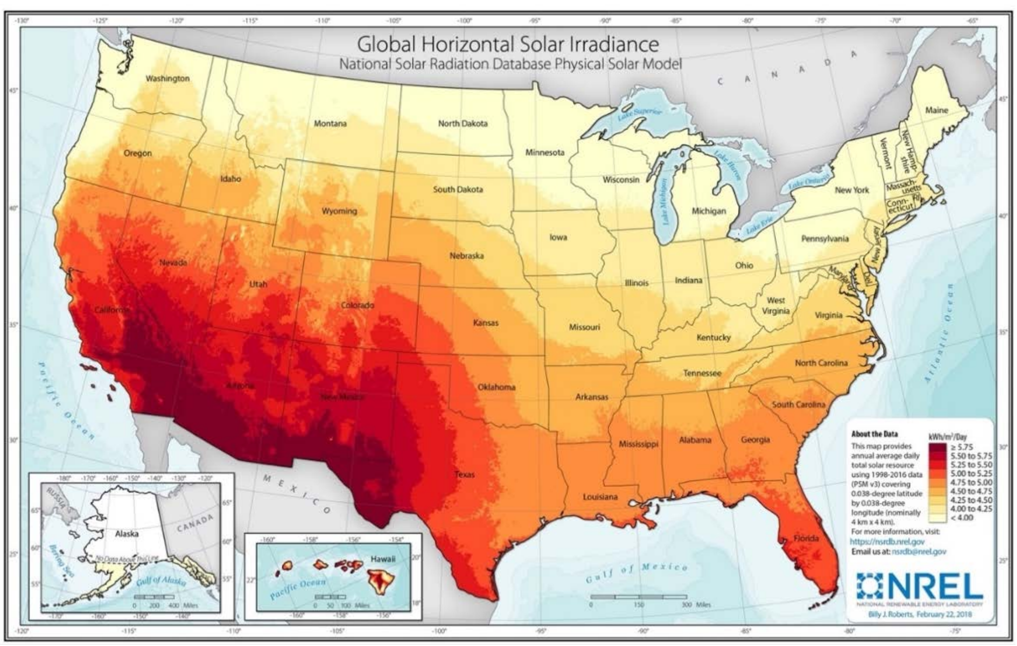

Figure 7. Global horizontal solar irradiance in the United States

4.2 Step 2: Exclusions

Appendix A lists the land use exclusions applied in the IREZ analysis. Regional planners may modify this list with input from relevant state and local officials as well as developers familiar with the region.

4.3 Step 3: Threshold Decision Criteria

The identification and comparison of zones uses a fixed set of decision criteria applied across the region. The criteria do not constitute rules or actual limits on development. Rather, they are subjective common-sense guidelines about factors that make development more or less likely at a given site. The previous section explains the criteria used by NREL in the IREZ analysis, but regional planners may apply other benchmarks supported by stakeholders. What is important is not the numeric value of the benchmark but rather its consistent application in the analysis.

At a minimum, decision criteria should identify reasonable thresholds for resource quality (e.g., wind speeds or solar irradiance), gen-tie distance, and a minimum for developable capacity that might access the hub.

4.4 Step 4: Preferences

This step takes into account factors that influence siting decisions but do not constitute absolute exclusions to development. It also represents an opportunity to examine important factors that do not normally enter into a technical analysis, such as energy justice and financial commitments by generators or load serving entities.

New mapping tools can help planners and stakeholders approach energy justice questions systematically and with a common base of information. These data sources include:

- The White House Council on Environmental Quality's Climate and Economic Justice Screening Tool[17]
- The U.S. Department of Energy's and Argonne National Laboratory's Disadvantaged Communities Reporter[18]
- The U.S. Environmental Protection Agency's Environmental Justice Screening and Mapping Tool[19]

FERC's transmission planning notice of proposed rulemaking provides guidance on how planners can gauge the depth of developers' financial commitment in different areas, including:

- The generation developer's existing energy resources within the zone
- The number and size of any interconnection requests from developers with completed facilities study agreements for generation within the zone
- A generation developer's leasing agreements with landowners within the zone
- A generation developer's letters of credit associated with generation it may develop in the zone

[17] For more information, see https://screeningtool.geoplatform.gov/en/#5.11/19.81/-82.06.
[18] For more information, see https://energyjustice.egs.anl.gov/.
[19] For more information, see https://www.epa.gov/ejscreen.

- Any merchant or other entity commitments to build (including deposits or payments to secure or fund) transmission facilities that would serve generation within the zone
- A generation developer's power purchase agreements with a credit-worthy counterparty associated with generation within the zone
- Any other factors for which generation developers have provided evidence as indications of commercial interest in developing generation within the zone (FERC 2022).

Formal methods for computing mathematical weights (e.g., the method NREL used in the IREZ analysis) may be useful, but they are not strictly necessary for this step if stakeholders can arrive at a consensus on how to apply regional preferences heuristically. What is critical is that the preferences are defensible and have stakeholder buy-in.

4.5 Step 5: Preliminary Hubs and Analysis

The functions of a preliminary zone are to focus the analysis, determine zone attributes, and enable comparison. The most important attributes of a preliminary zone are where the hub is located, the types of resources available, the hourly profile of the zone's primary resources during a typical meteorological year, and the projected cost of resources developed in the hub. Planners and stakeholders can use these attributes to compare preliminary hubs and decide which should be dropped from further considerations and which should be prioritized.

4.6 Step 6: Selection and Reporting Out of Final IREZ Hubs

Once planners, state authorities and stakeholders have reached consensus on a final list of IREZ hubs, the transmission providers can report the list on their open-access, same-time information system web portals.

5 Summary

NREL has developed an IREZ methodology to:

- Explore the geospatial factors that drive optimal IREZ hubs
- Test the identification of zones at a national scale in the NTPS
- Help bridge the institutional gaps between national modeling in the NTPS and future interregional transmission investment
- Provide regional planning entities with an adaptable template they can use as they seek transmission options for accommodating a changing generation mix and more sophisticated electricity demand.

NREL has used high-performance computing and other tools for the NTPS, but in fact, the IREZ template can be applied by transmission planners anywhere. The underlying wind and solar resource data are made publicly available through NREL. The selection of tools can be tailored to the circumstances of a given transmission provider's territory, guided by stakeholder input.

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Appendix A. Land Use Exclusions Applied in the IREZ Analysis

Table A-1. Spatial Exclusions for Land-Based Wind

Category	Variable
Federal land	Areas of Critical Environmental Concern (Bureau of Land Management)
	Inventoried Roadless Areas (U.S. Forest Service)
	National Battlefield
	National Conservation Area
	National Fish Hatchery
	National Monument
	National Park
	National Recreation Area
	National Scenic Area
	National Wilderness Area
	National Wildlife Refuge
	Wild and Scenic River
	Wildlife Management Area
Existing structures and setbacks	Airports
	Existing moratoriums
	Height limits
	Setbacks to transmission rights-of-way, railroads, rivers, roads, building structures (existing plus extrapolated 1.1x tip-height)
	Urbanized areas
Natural landscapes	Water bodies
	Woody wetlands 1,000 ft buffer
	Herbaceous wetlands 1,000 ft buffer
Physical land characteristics	Mountainous landforms and high (> 9,000 ft) elevation
	Radar (NEXRAD[a] 4 km; DoD 9 km)
	Shadow flicker: Over 30 hours exposure per year for 120m hub height turbine.
	Slopes > 25%
Protected areas	Land managed for biodiversity

Source: Maclaurin et al. 2019

[a] NEXRAD is Next Generation Weather Radar.

Table A-2. Spatial Exclusions for Utility-Scale PV

Category	Variable
Federal land	National Battlefield
	National Fish Hatchery
	National Monument
	National Park
	National Recreation Area
	National Scenic Area
	National Wilderness Area
	National Wildlife Refuge
	Wild and Scenic River
	Wildlife Management Area
	Inventoried Roadless Areas (U.S. Forest Service)
	Areas of Critical Environmental Concern (Bureau of Land Management)
Natural landscapes	Water bodies
	Woody and herbaceous wetlands
Land Use	Buildings
	Airports
	Railways
	Transmission rights of way
	Roadways
	Landmarks
	Parks
	Urban and suburban areas
	Natural gas a HGL petroleum crude pipelines
Physical Land Characteristics	Mountainous landforms and high (> 9,000 ft) elevation
	Slopes > 10%
Protected Areas	Land managed for biodiversity

Source: Maclaurin et al. 2019

Appendix B. Texas Competitive Renewable Energy Zones

This appendix is adapted from comments submitted by the U.S. Department of Energy in the Federal Energy Regulatory Commission's advance notice of proposed rulemaking on regional transmission planning.

Transmission zones for renewable energy development began in Texas with that state's Competitive Renewable Energy Zone (CREZ) program. Figure B-1 illustrates renewable energy development in Texas before and after the completion of the CREZ lines. Note that while CREZ transmission opened up new development opportunities, there was also an expansion of renewable development in other places on the network that were not part of the CREZ program.

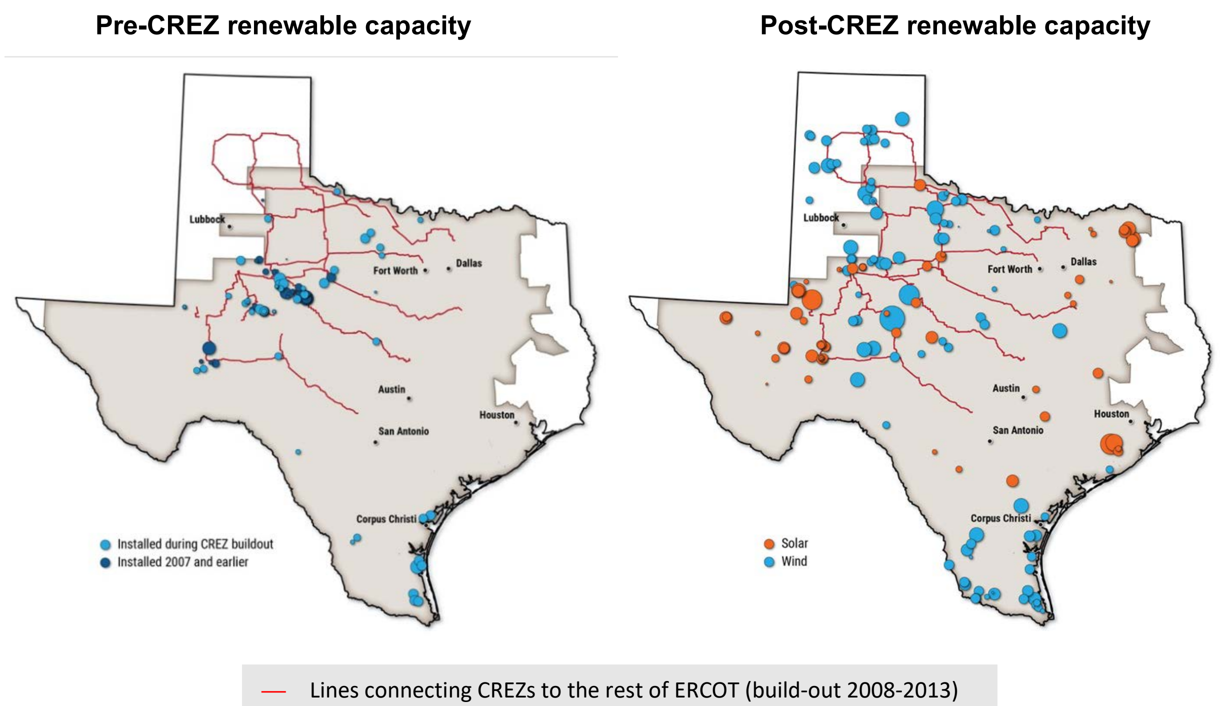

Figure B-1. Renewable energy in Texas before and after CREZ transmission

The Texas CREZ model includes:

1. A clearly defined regulatory pathway to transmission cost recovery that expands the criteria for demonstrating whether proposed transmission facilities are likely to be used and useful, consistent with applicable law and appropriate to the characteristics of renewable energy development[20]

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[20] For example, a large central station power plant and its long-distance transmission lines both take years to build. Reviewing and approving them in tandem makes answering the "used and useful" question straightforward. This expedient approach seldom fits the characteristics of wind and solar power, however, because generating plants are smaller and can be brought online faster than a large central station plant. Moreover, if a wind or solar project's ability to secure financing is conditioned on transmission availability, such conditionality would complicate the inclusion of that project as proof that a new transmission line would be used and useful.

2. A market-wide assessment of near- and long-term clean energy demand across many load-serving entities simultaneously, with the objective of identifying a combination of new transmission facilities and low-cost renewable energy zones that can reasonably be expected to meet the combined demonstrated demand and future demand in the most beneficial way
3. Renewable energy zones that are large enough to promote competition among developers.

The CREZ model arose from characteristics unique to the Texas market, but lessons and insights from the CREZ experience there that have informed the IREZ methodology described here.

B.1 Background

The CREZ model did not create commercial demand for renewable energy. Rather, it directed demand that was already extant to places where investment was most productive due to natural characteristics: consistently high wind speeds, consistent sunshine, and few obstacles to development. The CREZ model also relied on competition among developers. A CREZ was large enough that no single developer or group of developers acting in collusion could control enough sites to limit market entry by competitors. These two factors—good natural resources and competition—ensured load-serving entities and their customers could get wind power (and later solar power) at the lowest reasonable cost.

The CREZ concept lay dormant at the Public Utilities Commission of Texas (Texas Commission) for three years until changes in the law created an alternative path for satisfying the used and useful standard. In 2005, the Texas Legislature directed the Texas Commission to designate CREZs and to develop a transmission plan for them.[21] CREZ designation had to take into account the level of financial commitment by generators, and the transmission plan approved by the Texas Commission had to work "in a manner that was most beneficial and cost-effective to customers." Other provisions of the utility code were amended so that facilities that were in a CREZ transmission plan approved by the Texas Commission were deemed "used and useful to the utility in providing service … and are prudent and includable in rate base, regardless of the extent of the utility's actual use of the facilities."[22] The commission could set aside normal statutory requirements to consider "the adequacy of existing service" and "the need for additional service."[23] These would be determined by the Texas Commission in the CREZ proceeding consistent with the directives of the CREZ law.

[21] Tex. Util Code §39.904(g) required the Texas Commission to "(1) designate CREZs in which renewable energy resources and suitable land areas were sufficient to develop generating capacity from renewable energy technologies. (2) Develop a plan to construct transmission capacity necessary to deliver to electric customers, in a manner that was most beneficial and cost-effective for customers, the output from renewable generators in CREZs; and (3) consider the level of financial commitment by generators for each CREZ."
[22] Tex. Util Code §36.053.
[23] Tex. Util Code §37.056(c)(1) and (2), set aside by §39.904(h) with respect to an application for a certificate of convenience and necessity for a transmission project intended to serve a CREZ designated by the Texas Commission.

The Texas Commission's rule enacting the CREZ legislation was adopted December 1, 2006.[24] The rule states that in determining whether to designate an area as a CREZ, the Texas Commission shall consider the level of financial commitment by generators.[25]

> A renewable energy developer's existing renewable energy resources, and pending or signed [interconnection agreements] for planned renewable energy resources, leasing agreements with landowners in a proposed CREZ, and letters of credit representing dollars per megawatt of proposed renewable generation resources, posted with ERCOT, that the developer intends to install and the area of interest are examples of financial commitment by developers to a CREZ. The commission may also consider projects for which a TSP [transmission service provider], ERCOT, or another independent system operator is conducting an interconnection study; and any other factors for which parties have provided evidence as indications of financial commitment.[26]

The rule required ERCOT to provide a study of wind energy potential statewide. It also invited the Texas Parks and Wildlife Department to provide an analysis of wildlife habitat that might be affected by renewable energy development in a candidate CREZ, along with recommended mitigation measures.

The docket to select CREZs and an associated transmission plan began in January 2007, after ERCOT had submitted its study estimating wind potential across Texas and providing an initial assessment of transmission issues.[27] The ERCOT study was a prominent reference document in the CREZ docket. On a parallel track, as options for CREZs and transmission plans became more apparent, the Texas Commission opened another docket for a settlement conference addressing who should build which elements of the transmission plan. The Texas Commission issued its order designating CREZs and deciding a CREZ transmission plan on October 6, 2008, and it assigned transmission utilities' responsibilities on May 15, 2009. The last CREZ transmission element was completed and placed in service in December 2013.

B.2 CREZ Outcomes

Transmission charges to residential customers in the Oncor, CenterPoint, and American Electric Power's distribution territories (which include Dallas, Fort Worth, Houston, and Corpus Christi) increased from an average of $0.007/kWh at the beginning of the CREZ build-out to $0.013/kWh at the end of the build-out as CREZ transmission costs were added to utility rates (Figure B-1).[28] These figures include CREZ build-out costs as well as new transmission cost of service unrelated to the CREZ build-out.[29] Meanwhile, day-ahead wholesale energy prices in

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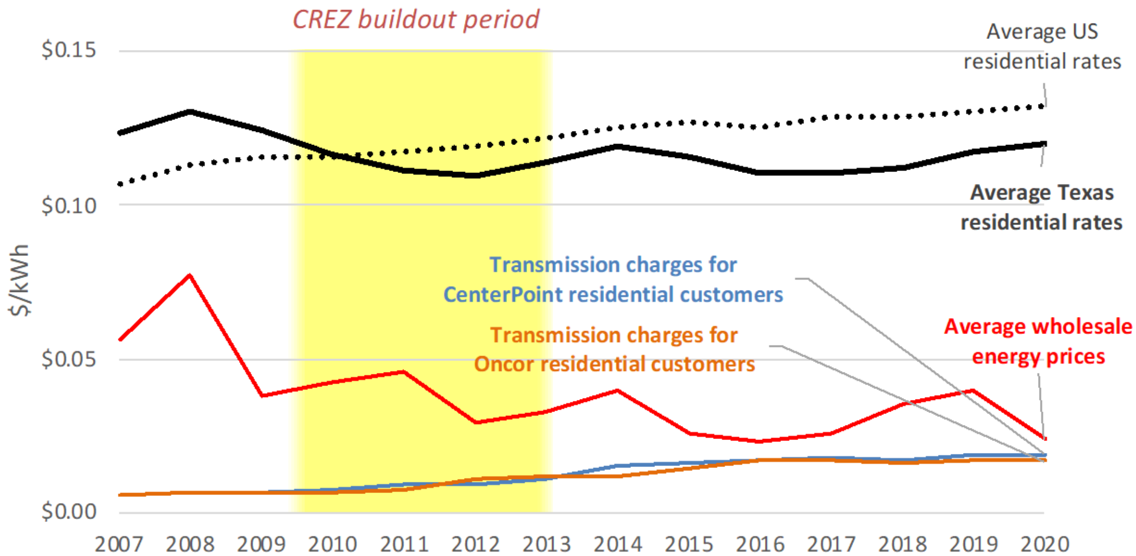
[24] Tex. Admin. Code 25.174.
[25] Tex. Admin. Code 25.174 (b)(4).
[26] Tex. Admin. Code 25.174(c)(1).
[27] Commission Staff's Petition for Designation of Competitive Renewable-Energy Zones, Docket No. 33672.
[28] Oncor and CenterPoint serve 35% and 26% of ERCOT load. American Electric Power's Texas Central and Texas North distribution utilities together serve 9%. ERCOT, 2020 Four Coincident Peak Load Calculation.
[29] The non-CREZ total cost of ownership is also recovered from all load via the postage stamp method. A precise estimation of the CREZ-related total cost of ownership would require a detailed examination of all transmission service providers' filings from 2009 through 2013, and to NREL's knowledge such a study has not been done. It is

ERCOT, which averaged $0.038/kWh during the build-out period, averaged $0.29/kWh for the years following the build-out.[30] The drop was due to lower natural gas prices and to the growth in wind power as developers expanded in the CREZs (Figure B-2). All told, the average residential customer in Texas paid less for electricity than the U.S. average after 2010, and after the CREZ build-out, the difference grew larger.[31]



Sources

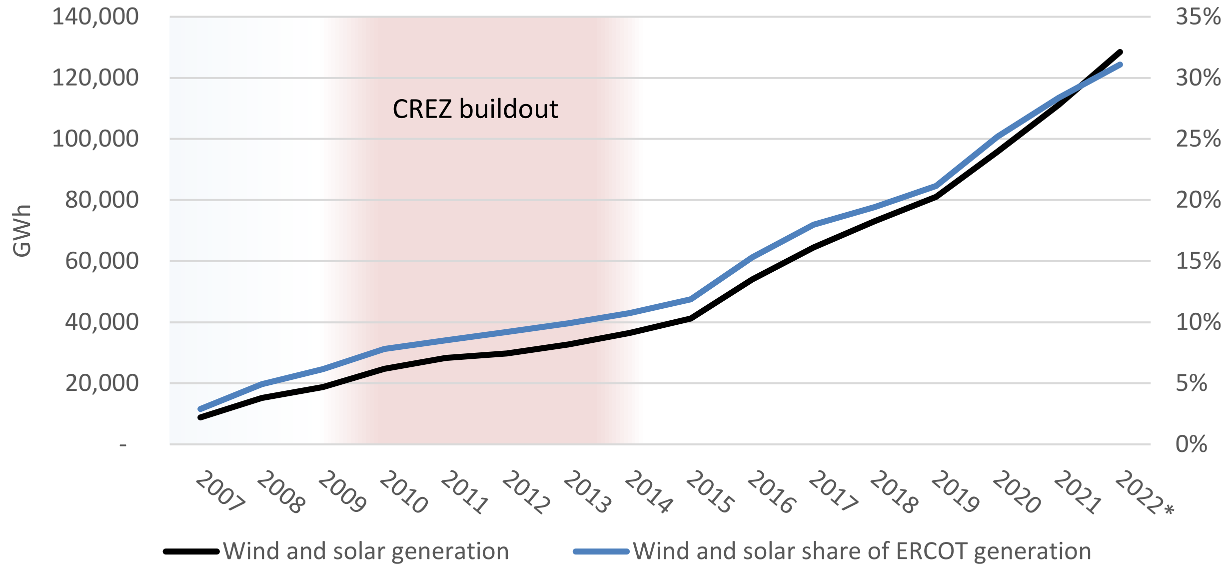
- Residential rates: Energy Information Administration, EIA Form 861 database
- Wholesale energy prices: Potomac Economics, State of the Market Reports, 2007–2020
- Transmission charges: Texas Commission, "Transmission and Distribution Rates for Investor Owned Utilities," http://puc.texas.gov/industry/electric/rates/TDR.aspx.

Figure B-2. Transmission component of residential rates during and after CREZ build-out

reasonable to conclude, however, that the CREZ-related total cost of ownership did not exceed $0.006 per kWh for customers in the Oncor, CenterPoint, or American Electric Power's distribution service areas, which make up 70% of ERCOT load.

[30] Potomac Economics, *State of the Market Report* (ERCOT), years 2012 through 2020.

[31] U.S. Energy Information Administration, Form EIA-861M database.



*12 months ending June 2022

Source: ERCOT, Fuel Mix Reports, 2007–2022

Figure B-3. Growth in wind, solar generation in ERCOT during and after CREZ build-out

A detailed analysis measuring the degree to which CREZ wind producers affected prices has not been done. Declining natural gas prices from 2014, one year after completion of CREZ transmission build-out, reduced the marginal cost of combined cycle plants and other generators fueled by natural gas, which *ceteris paribus* would reduce wholesale prices if natural gas generators were typically on the economic margin. However, adding wind capacity (which has near-zero marginal cost) would expand the ERCOT supply curve in a way that would also reduce wholesale prices, holding all other considerations unchanged. Thermal units with high heat rates that would otherwise be on the economic margin would be squeezed out, causing a lower-cost unit to be on the margin setting prices. Although each phenomenon's precise contribution to lower wholesale prices is uncertain without further analysis, one observation can be made: the effect of CREZ wind development was limited to Texas while the effect of natural gas prices was nationwide, and retail rates in Texas fell as rates increased in the rest of the United States as a whole.

CREZ development had collateral effects that became evident after the transmission build-out had been completed. One was utility-scale solar growth. Very few solar developers provided demonstrations of financial commitment during the CREZ proceeding. Nevertheless, there was a general recognition that daily production profiles for solar would be complementary to those of wind, so that the selected CREZs could accommodate solar resources once the economics of solar power improved. When solar costs fell, much of the first wave of development went to the CREZs in West Texas.

Shortly after the CREZ build-out in 2014, wind development accelerated in South Texas. Although ERCOT's initial study of statewide wind potential had identified this area as a candidate zone, the Texas Commission declined to include it as a CREZ due to insufficient indications of developer interest. This area has seen the retirement of about 2 GW of natural gas capacity since 2006,[32] making more transfer capability available on the existing transmission network without a CREZ-like build-out.

ERCOT's growth in renewable energy has been entirely market-driven since the completion of the last CREZ transmission element. The state mandate was for 5 GW of new renewable energy capacity, which was achieved 7 years early in 2008.[33] Texas also had a statutory planning target of 10 GW, which was reached 15 years early in 2010. In the first half of 2022, wind and solar provided 36% of ERCOT's total generation. [34]

B.3 Insights from the Texas CREZ Model

Texas' experience with the CREZ model suggests that identifying renewable energy zones works best once there is a clear regulatory path for addressing need and cost recovery en masse, as opposed to element-by-element additions to rate base. In Texas, the key was resolving the "used and useful" requirement. While each wind developer had the burden of demonstrating its own financial commitment to a candidate CREZ, it was the aggregate of all demonstrations that revealed which candidate CREZs had the greatest tangible commercial interest. This in turn built greater confidence in the practicality of a multielement transmission plan connecting all the final CREZs to load. A financial demonstration by one transmission utility proposing one transmission project would not have had the same weight.

The CREZ model anticipates future development will consist of (1) firm projects to meet demand by load-serving entities that are ready to secure power purchase agreements today and (2) projects that would be responsive to long-term market drivers but are too far into the future for counterparties to manage the commercial risk bilaterally today. When the Texas Commission was evaluating options for transmission plans for the final CREZs, it rejected a minimal option that would have satisfied only the demand firmly established at the time of the proceeding, noting that "[t]ransmission plans with lesser transfer capacity than [the selected plan] would leave little room for expansion, thereby not providing transmission resources ahead of renewable generation as directed by the legislation."[35] At the same time, the Texas Commission rejected two larger build-out options because of cost and the lack of sufficient evidence that the capacity could be integrated reliably if fully developed.

The risks of future generation project development are different when considering a large transmission plan. With a large plan, the consequences of one or a few proposed projects failing are smaller. One project built on speculation takes on project-specific risks, one of which is being replaced in the market by a competitor. When considering future demand on a larger scale, the market is indifferent as to whether one developer replaces another. Macro trends and policies are measurable and entail different species of risk, such as supply chain disruptions, impacts

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[32] Energy Information Administration, Form EIA-860M database.
[33] Tex. Util Code §39.904(a).
[34] ERCOT, *Annual Report on the Texas Renewable Energy Credit Trading Program*, various years, https://sa.ercot.com/rec/public-reports; and Interval Generation by Fuel reports through August 2021.
[35] Commission Staff's Petition for Designation of Competitive Renewable-Energy Zones, Docket No. 33672, Order on Rehearing at 46.

related to climate change, technological shifts such as electric vehicles. The CREZ model adapts to these new risks in ways that element-by-element transmission expansion does not.

This experience suggests other key lessons:

- **The Balance Between Firm and Future Demand:** A CREZ-like transmission plan that is built to meet firm demand and nothing more risks being undersized and oversubscribed by the time the new transmission facilities are complete. At the same time, under the Federal Power Act, rates to recover the cost of transmission must be just and reasonable with respect to current demand as well as future demand. In the Texas CREZ proceeding, the Texas Commission used reliability and cost criteria to determine how much future demand to accommodate in the transmission plan. For FERC to replicate this aspect of the CREZ model, it would need to identify criteria it might use to estimate a reasonable level of future demand.
- **The Role of Technical Analysis:** In the Texas CREZ model, the threshold issue was resolution of the issue of cost recovery for transmission improvements, which in Texas turned on the "used and useful" question. Resolving this issue was crucial to the model's success, but it is often overlooked in other analyses that have attempted to replicate the CREZ process. The tremendous improvements in wind resource assessments since the 2006 ERCOT study do not obviate the need to clarify the regulatory path to transmission approval before simulating power system operations or renewable energy potential. The U.S. Department of Energy's national laboratories have the technical capability to analyze transmission development options for linking renewable energy zones with the strongest demonstrations of national interest. In the end, however, success will depend on solving the legal questions—not on the technical analysis.