# Next Steps

Read diversity index references in that footnote below the diversity map.

Fix footnote formatting under Shannon Index, do the derivation, and develop more text to explain Shannon Diversity index. Goal of this is to better understand the index mathematically.

Consider counting # of HV connections (and incorporate voltage ratings of each connection) to neighbors by BA (from HILFD network data overlain with BA shapefile?)

Come up with a way to analyze import availability during extreme periods (e.g. highest net load period) by BA.

Do a generic broad analysis on import dependency during highest net load periods

Do a case-study approach that looks at import performance etc during selected extreme events in certain BAs

* Winter Storm Uri in Texas
* As the events of August 2020 in California and February 2021 in Texas demonstrate, supply shortfalls can have large economic and public health consequences

# Introduction

* Explain how reliability has become more of a concern today than it historically has been.
  + Today’s system: increasing variable supply like wind and solar and Retiring conventional generation.
  + Electrification and demand growth
  + Extreme events (increasing?)
* Understandably, planning approaches to ensure sufficient resources available to serve demand across the full year and under stressful grid conditions is an active area of research. *(opportunities for unused citation dump)*.
* One important component of this that is understudied is the role of imports in supporting future reliability for individual systems.
  + Difficult question: depending on the system, imports may play a significnat role in supporting reliability during stressful conditions, but is more uncertain than reliance on local resources. Imported resources are generally outside the direct of the local planning entity and depend on excess capacity in neighboring systems.
* Given the increased uncertainty associated with availability of imports, system planners may discount or not consider their contributions to reliabiltiy in future plans. (now transitioning to that nice Larsen 2023 quote)
* A crucial question to address in this research is “how should planners consider availability of imports from a capacity adequacy perspective in long term plans ? Larsen 2023 says it should be decided by policymakers and not individual market participants:

*We conclude that policy makers can go into one of two directions. The first option is to ignore cross-border trading in their planning. While this would create security of supply for individual countries [balancing authorities], it would come at the cost of very significant investment subsidies. The alternative is to rely on cross-border trade, an option which requires not only close cooperation and coordination, but also significant trust between the jurisdictions and institutions involved, to ensure sufficient capacity. The choice between these options is a political decision, to be made at the national and supranational levels, not by regulators, and even less by market participants.*

*Some [Newberry (2016)] make the case that capacity of interconnections with neighboring systems and the reliance on imports for reliability should be recognized in planning.*

*But how or by what method can one determine the level of capacity that can be relied on when needed?*

Analysis at BA level. Not much research done at this scale. Etc.

* Balancing Authority: *The responsible entity that integrated resource plans ahead of time, maintains Demand and resource balancing wihin a Balancing Authority Area, and supports Interconnection frequency in real time*
* Balancing Authority Area: *The collection of generation, transmission, and loads within the metered boundaries of the Balancing Authority. The Balancing Authority maintains load-resource balance within this area.*
  + [Glossary\_of\_Terms.pdf (nerc.com)](https://www.nerc.com/pa/Stand/Glossary%20of%20Terms/Glossary_of_Terms.pdf)

# Import Reliance

Import reliance is defined as the fraction of domestic consumption covered by net electricity imports over a period. This is a simple metric that is easy to interpret and commonly identified in the research literature on electricity supply security [1–4], sometimes also referred to “import dependence.”

Figure 1 displays import reliance by balancing authority. In general, it shows the areas in the U.S. with relatively higher levels of imports include the Northwest, Southwest, and Northeast. The highest levels of import reliance from 2016-2023 were among BA’s in the Northwest U.S. Specifically, Portland General Electric Company, Puget Sound Energy, and the City of Tacoma Department of Public Utilities had the highest shares of imports at 0.70, 0.57, and 0.48, respectively. Nearly all the imports into these three regions came from the Bonneville Power Administration BA.

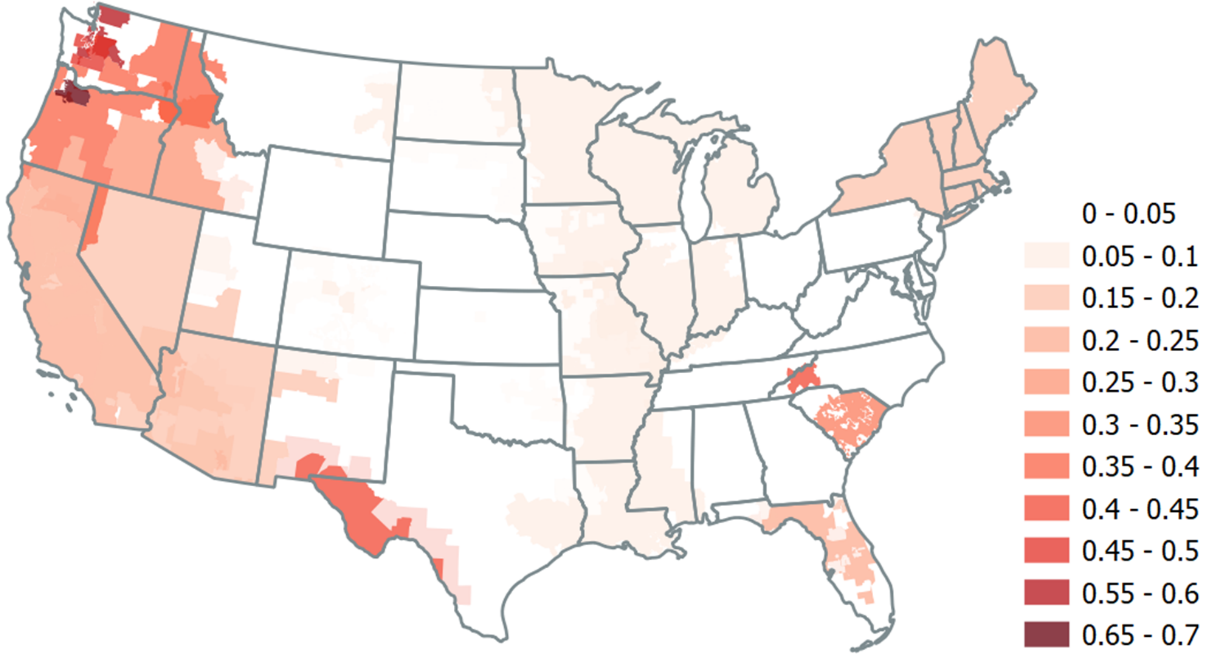


Figure 1 Import reliance as a share of total electricity consumption by U.S. Balancing Authority, 2016-2023.

There are a few additional import-dependent BA’s shown in Figure 1 that appear to be outliers relative to their neighbors. El Paso Electric Company in southwest Texas was 44% reliant on imports over the sample period; 67% of its imports were from Public Service Company of New Mexico and 30% from Tuscon Electric Power.

Duke Energy Progress (DEP)in the Carolinas is administratively split into two BAs in the west and the east part of its footprint. DEP west is 42% reliant on imports and significantly smaller than the DEP east. Most DEP west imports come from its neighboring Duke-controlled BAs. In this way, the high level of import reliance DEP west may not reflect significant import reliance risk from the perspective that Duke as a parent company likely owns and controls much of the resources being traded across the multiple BAs it administers in the Carolinas.

Duke Energy Florida (DEF) is also relatively import-reliant at 24% compared to its neighboring BAs. It is relatively diverse in its sources of imports and, unlike the Duke BAs in the Carolinas, does not trade with company affiliates. Rather, 32% of its imports were from Florida Power & Light, 26% from Florida Municipal Power Pool, 24% from Seminole Electric Cooperative. It also receives smaller levels of imports from Gainesville Regional Utilities, Southern Company, and Tampa Electric Company.

The import reliance metric is simple to calculate and interpret and provides an accurate perspective on the reliance of a balancing authority on electricity supply physically located outside its territory. In this way it presents a useful starting point for an analysis. It is important to note that “import reliance” is not necessarily a concern- there are likely good reasons when a BA imports electricity to supply local demand. Many studies have shown economic efficiency gains from trade available when two regions integrate electricity trade [5–10]. From this literature, one may conclude that any BA’s not relying on imports are leaving economic efficiency opportunities on the table. However, the magnitude and characteristics of electricity trade efficiencies vary depending on the underlying characteristics of individual systems, including resource mix, demand characteristics, and geographic traits.

There are also reasons why expanding regional electricity trade could be more costly than the available benefits. One potentially significant barrier is if the physical links connecting two BAs are already congested, alongside the sometimes-prohibitive cost of building new electric transmission lines [11]. Others include the fact that integration and associated regional efficiencies associated with electricity price equalization will produce some losers underlying the total economic improvements to the region [12]. Potential losers from regional integration include electricity customers facing higher costs in exporting BAs and producers facing reduced profits in importing BAs [13]. Other factors to consider for a better understanding of the observed trading situation between neighboring BAs are the political relationship between the regions, market trading rules, and other institutional realities that could create to trading friction or other sources of risk associated with expanded trade [14]. Sometimes regional integration is accompanied by efforts to expand BA territory, which can involve an expansion of centralized control over dispatch and resource adequacy to a grid operator in one of the regions. It is sometimes tempting to analyze and pursue trading opportunities from an economic efficiency lens without considering the potentially significant political cooperation needed as a foundation for lasting economic integration [15,16].

Furthermore, the import reliance metric is limited in assessing reliability risk is that it does not account for relevant characteristics of the contractual arrangements underlying electricity imports. For example, a balancing authority whose imports are provided under firm delivery arrangements may have lower reliability risk than a BA that relies on significant imports purchased from a spot market.

The import reliance metric also does not incorporate the diversity of external sources of supply, which is a relevant factor for assessing reliability risk. A region relying on imports may be more reliable if it has many different sources of external supply. In contrast, a balancing authority that is heavily reliant on imports from a single large plant may have higher risk. A similar perspective that is not captured in the import reliance metric is the number of interconnections over which electricity imports flow into the BA of interest. A region reliant on imports over a single transmission line has greater reliability risk than one with multiple lines providing some redundancy if one experiences an outage. These two perspectives are analyzed further for U.S. BA’s in subsequent sections.

# Import Diversity

A diverse set of import sources is beneficial for reliability for multiple reasons. Reduced dependency on one or a small number of exporters increases the probability of available supply when needed. Regions may have climate and weather differences, which can improve the availability of variable supply, and may support mitigating local extreme events such as a heat wave, natural disaster, or infrastructure failure. (Get some citations for this opening)

*Draft some text that motivating the importance of a BA electricity import diversity could be useful indicator from a Resource Adequacy perspective.*

*Another paragraph or few sentences bringing us to the concept of formal diversity metrics and in particular the Shannon Index*

The Shannon Diversity Index was developed in communication theory to measure the quantity of information included in a communication signal [17]. Since then, it has commonly been applied as a measure of diversity for a range of applications, notably for species diversity in ecologic systems [37–39]*.[[1]](#footnote-1)*

The Shannon Diversity Index applied to an electric balancing authority is defined in equation

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  |  | *(1)* |

Where is the share of imports from neighboring BA that it imports from, relative to total demand in the balancing authority of interest. Mathematically, is inversely related to the geoemetric mean of the relative shares such that a higher value describes a system with a more diverse set of imports. It can be shown that is the geometric mean of the relative shares [1] [40]. This relationship shows a relatively concentrated (less diverse) set leads to a higher geometric mean and a lower H value. Find the source and do the derivation If a system’s entire electricity demand was served by a single source of imports ( and all other ), then this diversity metric would equal zero.

Conversley, for a given set of import sources , the diversity metric is maximized when all are equal (e.g. ). This is the case when a system’s imports are provided equally by all its trading partners such that one isn’t more dominant than others, and is the maximally “diverse” import situation for a given set of trading partners . Finally, the diversity metric increases with more trading partners (e.g. a higher ), all else equal.

This diversity index has been widely considered in energy security-focused studies as a metric for diversity of primary energy and energy import sources, commonly at the nation-state level [18–31]. Less common are studies utilizing metrics to assess electricity generation diversity [32–35]. This study is the only one the author is aware of that applies a formal diversity index to assess diversity of electricity imports among electric balancing authorities within the United States.

Figure 2 maps the diversity index at the BA-level across the United States.

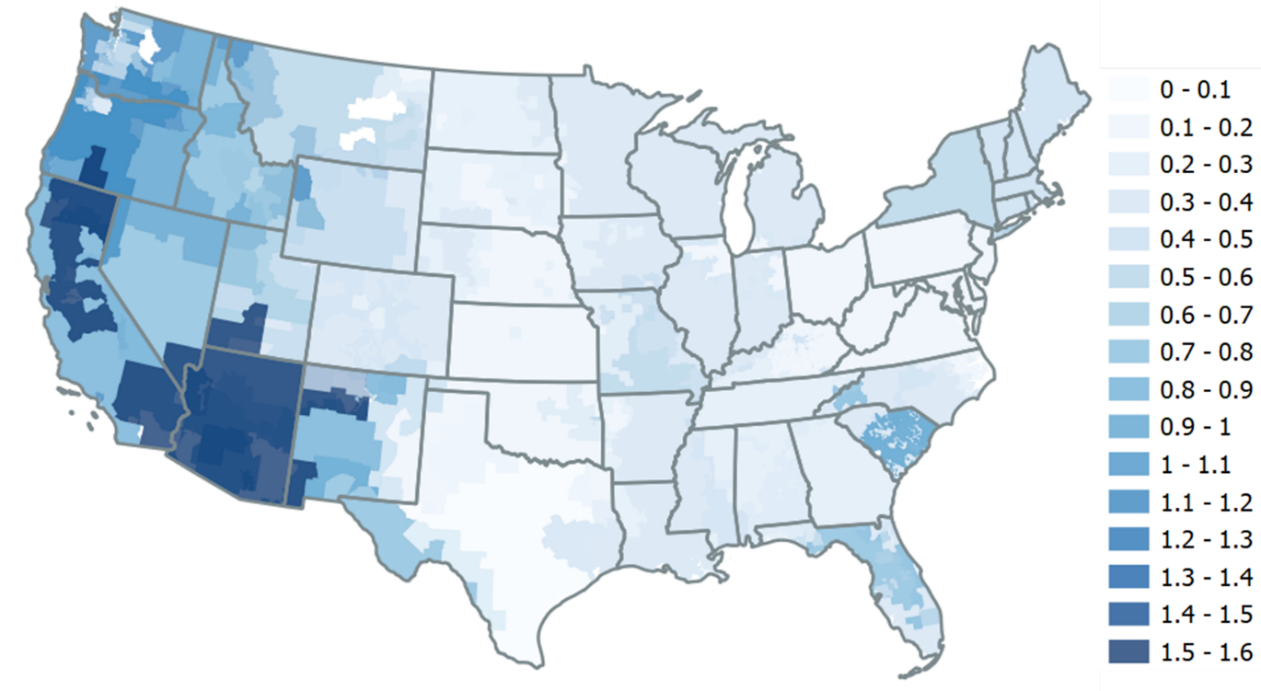


Figure 2 Import diversity metric by U.S. Balancing Authority, 2016-2023

* *Southwest and northern CA stand out above the rest.*
* *WALC has a high/funky import dependency value because it is getting lots of power to “pass throguh” BA. Impoting lots from AZ and passing it along as exports to CA (probably the big Nuclear plant). Note this example as (a downside?) special case to keep in mind when evaluating BA import diversity metrics for BA’s that “pass through” lots of power for economic reasons.*
* *AZPS stopped producing nuclear at the end of 2019 in the data, went from an exporter to an importer at this time. It appears maybe Palo Verde was double counted in both AZPS and SRP, and then AZPS stopped including it at the end of 2019, while SRP continud reporting the full Pverde output in its BA.*
* *This leads to a caveat with use of Balancing Authority definition and BA-level metrics, that it may not capture the nuances of the imports situation for multiple BA’s that are well integrated, or have firm contractual rights to capacity physically outside its borders.*

~~UPDATE TO SHANNON Index fo rreasons provided in footnote 13 of Kruyt 2009 A black and white symbol

Description automatically generated~~

~~Stirling (1999) in his elaborate work on diversityfavours the Shannon index over the HH index, based for 2 reasons. First, the~~

~~Shannon index retains rank ordering under variations of logarithm base, whereas~~

~~the rank ordering of different systems changes as the exponent of the Simpson~~

~~index changes. As there is no fundamental argument why the exponent should be~~

~~2, this raises doubts with regard to the ﬁrmness of the results obtained, since by changing an apparently non-related parameter, the outcome will differ. Second,~~

~~the Shannon index displays the property of additivity with respect to taxonomy.~~

~~This means that when classifying options based on several criteria, the index score~~

~~for the system classiﬁed according to criterion a, plus the index score for the~~

~~system classiﬁed according to criterion b should amount to the same as the index~~

~~score for the system classiﬁed according to the combined criterion ab. This is~~

~~mathematically represented as f(ab) ¼ f(a)+f(b), with a and b sets of options under~~

~~different classiﬁcations and f the index or function in question~~

~~In many applications of these concentration or diversity indices, the market share value (p) cannot be greater than one. In our case, it can in situations where a BA is importing more than it consumes. This can occur if a BA’s imports “pass through” to be consumed by another neighbor, generally when it is a small BA that is well-integrated with its neighbors. When this occurs, the Import Diversity metric goes negative, but in our reporting we truncate the value at 0, since a “negative” diversity metric is difficult to interpret. In contrast, a value of 0 “import diversity’ implies that all of the local demand is satisfied by imports from a single neighbor.~~

~~for each neighboring balancing authority importing into the region with total electricity consumption equal to over the period of interest.~~

~~Many studies on energy security utilize a similar diversity (or the inverse for a “concentration” metric) applied to primary sources of energy at the nation-state level. (check Kruyt et al. 2009 as possible citation here, and any others) Cite Kruyt’s approach in the appendix, and a bunch of their citations that apply diversity to fuel supply.~~

~~It doesn’t have the same interpretation when used commonly for market shares, but still gives a relative quantitative comparison of import diversity across BAs.~~

*~~Include some key stats of the HHI distribution so BA’s have something to benchmark their systems agains.~~*

# HVDC Interconnectors

# Imports during stressful events

# Other Data characteristics

Hourly Demand and interchange variables can cover 2016-2023

Generation by fuel type covers 2018-2023

# Balancing Authority Shapefile

Balancing area shapefiles were used from Homeland Infrastructure Foundation-Level Data (HIFLD)’s “Control Areas” dataset CITE

# Literature review and discussion

* From a reliability perspetive, it is important to evaluate how “import dependent” BAs operate during times when demand is highest and/or the available supply and reliability of the grid is stretched near the limit.

# Appendix

Table 1 Import reliance (net imports divided by domestic consumption) for USA balancing authorities with annual average demand >500 MW.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Name** | **Total** | **2016** | **2017** | **2018** | **2019** | **2020** | **2021** | **2022** | **2023** |
| Portland General Electric Company | 0.7 | 0.71 | 0.75 | 0.67 | 0.73 | 0.75 | 0.71 | 0.75 | 0.65 |
| Puget Sound Energy, Inc. | 0.57 | 0.47 | 0.51 | 0.54 | 0.44 | 0.3 | 0.73 | 0.79 | 0.68 |
| City of Tacoma, Department of Public Utilities, Light Division | 0.48 | 0.36 | 0.38 | 0.51 | 0.67 | 0.45 | 0.46 | 0.45 | 0.58 |
| El Paso Electric Company | 0.44 | 0.55 | 0.52 | 0.39 | 0.36 | 0.42 | 0.44 | 0.46 | 0.36 |
| Duke Energy Progress West | 0.42 | 0.64 | 0.66 | 0.56 | 0.58 | 0.26 | 0.19 | 0.19 | 0.17 |
| Avista Corporation | 0.4 | 0.43 | 0.46 | 0.4 | 0.4 | 0.35 | 0.33 | 0.36 | 0.38 |
| Seattle City Light | 0.39 | 0.29 | 0.35 | 0.35 | 0.45 | 0.37 | 0.37 | 0.39 | 0.52 |
| PacifiCorp West | 0.37 | 0.14 | 0.13 | 0.22 | 0.36 | 0.4 | 0.39 | 0.61 | 0.75 |
| South Carolina Public Service Authority | 0.32 | 0.27 | 0.32 | 0.28 | 0.39 | 0.38 | 0.33 | 0.36 | 0.3 |
| Tucson Electric Power | 0.3 | 0.38 | 0.4 | 0.24 | 0.28 | 0.32 | 0.28 | 0.3 | 0.22 |
| Idaho Power Company | 0.29 | 0.32 | 0.22 | 0.23 | 0.22 | 0.27 | 0.34 | 0.4 | 0.27 |
| Balancing Authority of Northern California | 0.25 | 0.25 | 0.23 | 0.26 | 0.17 | 0.28 | 0.25 | 0.4 | 0.16 |
| California Independent System Operator | 0.24 | 0.28 | 0.26 | 0.28 | 0.25 | 0.27 | 0.25 | 0.22 | 0.14 |
| Duke Energy Florida, Inc. | 0.24 | 0.26 | 0.26 | 0.26 | 0.25 | 0.25 | 0.23 | 0.2 | 0.24 |
| JEA | 0.2 | 0.07 | 0.06 | 0.27 | 0.33 | 0.15 | 0.25 | 0.28 | 0.31 |
| Los Angeles Department of Water and Power | 0.19 | 0.17 | 0.15 | 0.16 | 0.15 | 0.17 | 0.19 | 0.25 | 0.27 |
| Western Area Power Administration - Desert Southwest Region | 0.18 | 0.24 | 0.34 | 0.3 | 0.16 | 0.1 | 0.08 | 0.13 | 0.11 |
| ISO New England | 0.17 | 0.16 | 0.16 | 0.17 | 0.19 | 0.2 | 0.16 | 0.14 | 0.14 |
| Nevada Power Company | 0.17 | 0.17 | 0.22 | 0.2 | 0.17 | 0.17 | 0.17 | 0.17 | 0.15 |
| Arizona Public Service Company | 0.16 | 0 | 0 | 0 | 0 | 0.24 | 0.37 | 0.34 | 0.4 |
| New York Independent System Operator | 0.16 | 0.16 | 0.18 | 0.17 | 0.16 | 0.14 | 0.18 | 0.19 | 0.16 |
| Public Service Company of Colorado | 0.07 | 0.12 | 0.11 | 0.07 | 0.07 | 0.08 | 0.05 | 0.04 | 0 |
| Associated Electric Cooperative, Inc. | 0.06 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.09 | 0.08 | 0.11 |
| Midcontinent Independent System Operator, Inc. | 0.06 | 0.07 | 0.08 | 0.06 | 0.08 | 0.09 | 0.06 | 0.05 | 0.06 |
| PacifiCorp East | 0.05 | 0.04 | 0.07 | 0.05 | 0.07 | 0.06 | 0.03 | 0.02 | 0.04 |
| Public Service Company of New Mexico | 0.05 | 0.02 | 0.01 | 0.09 | 0.08 | 0.05 | 0.04 | 0.05 | 0.06 |
| PowerSouth Energy Cooperative | 0.04 | 0.02 | 0.01 | 0.02 | 0.07 | 0.07 | 0.08 |  |  |
| Florida Municipal Power Pool | 0.04 | 0.05 | 0.06 | 0.05 | 0.03 | 0.03 | 0.02 | 0.03 | 0.05 |
| Louisville Gas and Electric Company and Kentucky Utilities Company | 0.04 | 0 | 0 | 0 | 0.03 | 0.06 | 0.07 | 0.09 | 0.12 |
| Duke Energy Progress East | 0.03 | 0.02 | 0.02 | 0.03 | 0.03 | 0.03 | 0.05 | 0.04 | 0.03 |
| Duke Energy Carolinas | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 |
| Florida Power & Light Co. | 0.02 | 0.05 | 0.04 | 0.01 | 0.01 | 0 | 0 | 0 | 0 |
| Public Utility District No. 2 of Grant County, Washington | 0.02 | 0.01 | 0.02 | 0.02 | 0.03 | 0 | 0.01 | 0.02 | 0.06 |
| Tennessee Valley Authority | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.03 | 0.04 | 0.02 |
| NorthWestern Corporation | 0.01 | 0 | 0 | 0.01 | 0.01 | 0.03 | 0.02 | 0 | 0 |
| Dominion Energy South Carolina, Inc. | 0.01 | 0 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 | 0 | 0.01 |
| Salt River Project Agricultural Improvement and Power District | 0.01 | 0.06 | 0.04 | 0.03 | 0 | 0 | 0 | 0 | 0 |
| Southwest Power Pool | 0.01 | 0 | 0 | 0 | 0.01 | 0.01 | 0.01 | 0 | 0.01 |
| Tampa Electric Company | 0.01 | 0.01 | 0.01 | 0.01 | 0 | 0.02 | 0.02 | 0.02 | 0.02 |
| Bonneville Power Administration | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Electric Reliability Council of Texas, Inc. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| PJM Interconnection, LLC | 0 | 0.01 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Southern Company Services, Inc. - Trans | 0 | 0 | 0 | 0.01 | 0.02 | 0 | 0 | 0 | 0 |
| Western Area Power Administration - Rocky Mountain Region | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 2 Import diversity (measured by Shannon Diversity Index) by USA balancing authorities with annual average demand >500 MW.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Name** | **Total** | **2016** | **2017** | **2018** | **2019** | **2020** | **2021** | **2022** | **2023** |
| Western Area Power Administration - Desert Southwest Region | 1.53 | 1.39 | 1.44 | 1.3 | 1.25 | 1.38 | 1.22 | 1.28 | 1.58 |
| Bonneville Power Administration | 1.19 | 1.09 | 1.15 | 1.06 | 1.07 | 1.1 | 1.14 | 1.23 | 1.21 |
| Los Angeles Department of Water and Power | 1.19 | 0.04 | 1.19 | 1.21 | 1.21 | 1.07 | 1.19 | 1.25 | 1.29 |
| PacifiCorp West | 1.1 | 0.85 | 0.92 | 0.85 | 1.12 | 1.1 | 1.13 | 1.2 | 1.25 |
| Tucson Electric Power | 1.09 | 1.08 | 1.07 | 0.97 | 1.1 | 1.06 | 1.12 | 1.08 | 1.01 |
| Salt River Project Agricultural Improvement and Power District | 1.04 | 0.98 | 0.95 | 0.92 | 0.66 | 0.49 | 1 | 1 | 1.1 |
| Arizona Public Service Company | 0.96 | 0.84 | 0.85 | 0.84 | 0.64 | 0.78 | 0.5 | 0.55 | 0.41 |
| South Carolina Public Service Authority | 0.93 | 0.84 | 0.92 | 0.88 | 1.01 | 1.01 | 0.93 | 0.94 | 0.88 |
| Public Service Company of New Mexico | 0.86 | 0.55 | 0.69 | 0.91 | 0.89 | 0.88 | 0.83 | 0.88 | 0.96 |
| California Independent System Operator | 0.84 | 0.86 | 0.83 | 0.85 | 0.82 | 0.89 | 0.86 | 0.81 | 0.64 |
| Duke Energy Florida, Inc. | 0.8 | 0.81 | 0.84 | 0.83 | 0.78 | 0.79 | 0.76 | 0.71 | 0.79 |
| Nevada Power Company | 0.79 | 0.73 | 0.8 | 0.74 | 0.67 | 0.79 | 0.85 | 0.83 | 0.74 |
| Duke Energy Progress West | 0.77 | 0.9 | 0.91 | 0.86 | 0.76 | 0.58 | 0.57 | 0.61 | 0.49 |
| Idaho Power Company | 0.75 | 0.76 | 0.73 | 0.75 | 0.65 | 0.81 | 0.64 | 0.77 | 0.63 |
| Avista Corporation | 0.71 | 0.66 | 0.64 | 0.66 | 0.69 | 0.62 | 0.72 | 0.75 | 0.81 |
| El Paso Electric Company | 0.71 | 0.75 | 0.73 | 0.63 | 0.63 | 0.58 | 0.67 | 0.74 | 0.65 |
| Balancing Authority of Northern California | 0.64 | 0.45 | 0.54 | 0.53 | 0.59 | 0.63 | 0.6 | 0.72 | 0.72 |
| PacifiCorp East | 0.62 | 0.59 | 0.65 | 0.61 | 0.65 | 0.6 | 0.59 | 0.54 | 0.5 |
| NorthWestern Corporation | 0.58 | 0.47 | 0.52 | 0.53 | 0.54 | 0.62 | 0.61 | 0.62 | 0.62 |
| Florida Municipal Power Pool | 0.57 | 0.59 | 0.6 | 0.52 | 0.56 | 0.55 | 0.54 | 0.54 | 0.59 |
| New York Independent System Operator | 0.55 | 0.52 | 0.56 | 0.56 | 0.54 | 0.53 | 0.57 | 0.57 | 0.5 |
| Associated Electric Cooperative, Inc. | 0.52 | 0.49 | 0.51 | 0.48 | 0.45 | 0.51 | 0.57 | 0.53 | 0.55 |
| Public Utility District No. 2 of Grant County, Washington | 0.51 | 0.46 | 0.45 | 0.48 | 0.5 | 0.44 | 0.52 | 0.47 | 0.6 |
| Puget Sound Energy, Inc. | 0.51 | 0.45 | 0.49 | 0.42 | 0.48 | 0.1 | 0.5 | 0.49 | 0.54 |
| ISO New England | 0.47 | 0.46 | 0.46 | 0.47 | 0.5 | 0.51 | 0.45 | 0.42 | 0.42 |
| Louisville Gas and Electric Company and Kentucky Utilities Company | 0.46 | 0.39 | 0.43 | 0.44 | 0.4 | 0.36 | 0.43 | 0.47 | 0.45 |
| Seattle City Light | 0.46 | 0.45 | 0.42 | 0.46 | 0.45 | 0.47 | 0.5 | 0.4 | 0.42 |
| Dominion Energy South Carolina, Inc. | 0.4 | 0.34 | 0.37 | 0.38 | 0.4 | 0.41 | 0.42 | 0.44 | 0.41 |
| Western Area Power Administration - Rocky Mountain Region | 0.4 | 0.34 | 0.35 | 0.27 | 0.27 | 0.3 | 0.45 | 0.41 | 0.45 |
| JEA | 0.37 | 0.24 | 0.24 | 0.38 | 0.39 | 0.34 | 0.41 | 0.42 | 0.43 |
| Midcontinent Independent System Operator, Inc. | 0.37 | 0.37 | 0.4 | 0.34 | 0.39 | 0.43 | 0.35 | 0.35 | 0.35 |
| Portland General Electric Company | 0.37 | 0.46 | 0.42 | 0.47 | 0.37 | 0.27 | 0.3 | 0.25 | 0.26 |
| Tampa Electric Company | 0.37 | 0.33 | 0.33 | 0.27 | 0.3 | 0.39 | 0.42 | 0.45 | 0.41 |
| Duke Energy Carolinas | 0.35 | 0.36 | 0.32 | 0.31 | 0.33 | 0.34 | 0.33 | 0.36 | 0.37 |
| City of Tacoma, Department of Public Utilities, Light Division | 0.33 | 0.36 | 0.36 | 0.33 | 0.22 | 0.36 | 0.34 | 0.35 | 0.27 |
| Florida Power & Light Co. | 0.32 | 0.38 | 0.36 | 0.31 | 0.31 | 0.26 | 0.27 | 0.28 | 0.31 |
| Duke Energy Progress East | 0.31 | 0.29 | 0.28 | 0.31 | 0.28 | 0.31 | 0.33 | 0.37 | 0.3 |
| Tennessee Valley Authority | 0.29 | 0.26 | 0.27 | 0.29 | 0.27 | 0.27 | 0.29 | 0.33 | 0.3 |
| Public Service Company of Colorado | 0.25 | 0.28 | 0.28 | 0.23 | 0.23 | 0.25 | 0.23 | 0.21 | 0.09 |
| PowerSouth Energy Cooperative | 0.23 | 0.16 | 0.15 | 0.17 | 0.31 | 0.29 | 0.29 | 0 | 0 |
| Southern Company Services, Inc. - Trans | 0.22 | 0.19 | 0.21 | 0.22 | 0.22 | 0.24 | 0.22 | 0.25 | 0.2 |
| PJM Interconnection, LLC | 0.17 | 0.15 | 0.19 | 0.21 | 0.25 | 0.08 | 0.07 | 0.11 | 0.13 |
| Southwest Power Pool | 0.12 | 0.09 | 0.09 | 0.09 | 0.09 | 0.21 | 0.11 | 0.1 | 0.1 |
| Electric Reliability Council of Texas, Inc. | 0.02 | 0.01 | 0.01 | 0.03 | 0.03 | 0.02 | 0.02 | 0.03 | 0.02 |

# Bibliography

[1] Osorio S, van Ackere A, Larsen ER. Interdependencies in security of electricity supply. Energy 2017;135:598–609. https://doi.org/10.1016/j.energy.2017.06.095.

[2] Sovacool BK, Mukherjee I. Conceptualizing and measuring energy security: A synthesized approach. Energy 2011;36:5343–55. https://doi.org/10.1016/j.energy.2011.06.043.

[3] Lilliestam J, Ellenbeck S. Energy security and renewable electricity trade—Will Desertec make Europe vulnerable to the “energy weapon”? Energy Policy 2011;39:3380–91. https://doi.org/10.1016/J.ENPOL.2011.03.035.

[4] Ren J, Dong L. Evaluation of electricity supply sustainability and security: Multi-criteria decision analysis approach. Journal of Cleaner Production 2018;172:438–53. https://doi.org/10.1016/J.JCLEPRO.2017.10.167.

[5] Das A, Halder A, Mazumder R, Saini VK, Parikh J, Parikh KS. Bangladesh power supply scenarios on renewables and electricity import. Energy 2018;155. https://doi.org/10.1016/j.energy.2018.04.169.

[6] Yuan M, Tapia-Ahumada K, Reilly J. The role of cross-border electricity trade in transition to a low-carbon economy in the Northeastern U.S. Energy Policy 2021;154:112261. https://doi.org/10.1016/j.enpol.2021.112261.

[7] Bahar H, Sauvage J. Cross-Border Trade in Electricity and the Development of Renewables-Based Electric Power: Lessons from Europe. Paris: OECD; 2013. https://doi.org/10.1787/5k4869cdwnzr-en.

[8] Crozier C, Baker K. The effect of renewable electricity generation on the value of cross-border interconnection. Applied Energy 2022;324:119717. https://doi.org/10.1016/j.apenergy.2022.119717.

[9] Abrell J, Rausch S. Cross-country electricity trade, renewable energy and European transmission infrastructure policy. Journal of Environmental Economics and Management 2016;79:87–113. https://doi.org/10.1016/j.jeem.2016.04.001.

[10] Dahlke S. Integrating energy markets: Implications of increasing electricity trade on prices and emissions in the Western United States. International Journal of Sustainable Energy Planning and Management 2020;25. https://doi.org/10.5278/ijsepm.3416.

[11] Joskow PL. Lessons Learned From Electricity Market Liberalization. The Energy Journal 2008;29:9–42. https://doi.org/10.5547/ISSN0195-6574-EJ-Vol29-NoSI2-3.

[12] Blumsack S. Measuring the Benefits and Costs of Regional Electric Grid Integration. The Energy Law Journal 2007;28.

[13] Oseni MO, Pollitt MG. The promotion of regional integration of electricity markets: Lessons for developing countries. Energy Policy 2016;88:628–38. https://doi.org/10.1016/j.enpol.2015.09.007.

[14] Pineau P, Lefebvre V. The value of unused interregional transmission: Estimating the opportunity cost for Quebec (Canada). International Journal of Energy Sector Management 2009;3:406–23. https://doi.org/10.1108/17506220911005768.

[15] Moore S. Evaluating the energy security of electricity interdependence: Perspectives from Morocco. Energy Research & Social Science 2017;24:21–9. https://doi.org/10.1016/j.erss.2016.12.008.

[16] Yang M, Shi X, Zhou Y, Xiang J, Zhang R. Deepening regional power connectivity: Beyond the industry-centric perspective. Energy Research & Social Science 2022;90:102614. https://doi.org/10.1016/j.erss.2022.102614.

[17] Shannon CE. A mathematical theory of communication. The Bell System Technical Journal 1948;27:379–423. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x.

[18] Ang BW, Choong WL, Ng TS. Energy security: Definitions, dimensions and indexes. Renewable and Sustainable Energy Reviews 2015;42:1077–93. https://doi.org/10.1016/j.rser.2014.10.064.

[19] Ranjan A, Hughes L. Energy security and the diversity of energy flows in an energy system. Energy 2014;73:137–44. https://doi.org/10.1016/j.energy.2014.05.108.

[20] Matsumoto K, Doumpos M, Andriosopoulos K. Historical energy security performance in EU countries. Renewable and Sustainable Energy Reviews 2018;82:1737–48. https://doi.org/10.1016/j.rser.2017.06.058.

[21] Erahman QF, Purwanto WW, Sudibandriyo M, Hidayatno A. An assessment of Indonesia’s energy security index and comparison with seventy countries. Energy 2016;111:364–76. https://doi.org/10.1016/j.energy.2016.05.100.

[22] Chuang MC, Ma HW. Energy security and improvements in the function of diversity indices—Taiwan energy supply structure case study. Renewable and Sustainable Energy Reviews 2013;24:9–20. https://doi.org/10.1016/j.rser.2013.03.021.

[23] Zhang L, Yu J, Sovacool BK, Ren J. Measuring energy security performance within China: Toward an inter-provincial prospective. Energy 2017;125:825–36. https://doi.org/10.1016/j.energy.2016.12.030.

[24] Ren J, Sovacool BK. Quantifying, measuring, and strategizing energy security: Determining the most meaningful dimensions and metrics. Energy 2014;76:838–49. https://doi.org/10.1016/j.energy.2014.08.083.

[25] Wang D, Tian S, Fang L, Xu Y. A functional index model for dynamically evaluating China’s energy security. Energy Policy 2020;147:111706. https://doi.org/10.1016/j.enpol.2020.111706.

[26] Song Y, Zhang M, Sun R. Using a new aggregated indicator to evaluate China’s energy security. Energy Policy 2019;132:167–74. https://doi.org/10.1016/j.enpol.2019.05.036.

[27] Martchamadol J, Kumar S. An aggregated energy security performance indicator. Applied Energy 2013;103:653–70. https://doi.org/10.1016/j.apenergy.2012.10.027.

[28] Jewell J, Cherp A, Riahi K. Energy security under de-carbonization scenarios: An assessment framework and evaluation under different technology and policy choices. Energy Policy 2014;65:743–60. https://doi.org/10.1016/j.enpol.2013.10.051.

[29] Jun E, Kim W, Chang SH. The analysis of security cost for different energy sources. Applied Energy 2009;86:1894–901. https://doi.org/10.1016/j.apenergy.2008.11.028.

[30] Lin B, Raza MY. Analysis of energy security indicators and CO2 emissions. A case from a developing economy. Energy 2020;200:117575. https://doi.org/10.1016/j.energy.2020.117575.

[31] Kruyt B, van Vuuren DP, de Vries HJM, Groenenberg H. Indicators for energy security. Energy Policy 2009;37:2166–81. https://doi.org/10.1016/j.enpol.2009.02.006.

[32] Grubb M, Butler L, Twomey P. Diversity and security in UK electricity generation: The influence of low-carbon objectives. Energy Policy 2006;34:4050–62. https://doi.org/10.1016/J.ENPOL.2005.09.004.

[33] Chalvatzis KJ, Rubel K. Electricity portfolio innovation for energy security: The case of carbon constrained China. Technological Forecasting and Social Change 2015;100:267–76. https://doi.org/10.1016/J.TECHFORE.2015.07.012.

[34] Dilek S, Konak A. Resource Diversification in Turkey’s Electricity Generation. Journal of Original Studies 2022. https://doi.org/10.47243/jos.3.2.03.

[35] Cox E. Assessing long-term energy security: The case of electricity in the United Kingdom. Renewable and Sustainable Energy Reviews 2018;82:2287–99. https://doi.org/10.1016/J.RSER.2017.08.084.

[1] Osorio S, van Ackere A, Larsen ER. Interdependencies in security of electricity supply. Energy 2017;135. https://doi.org/10.1016/j.energy.2017.06.095.

[2] Sovacool BK, Mukherjee I. Conceptualizing and measuring energy security: A synthesized approach. Energy 2011;36:5343–55. https://doi.org/10.1016/J.ENERGY.2011.06.043.

[3] Lilliestam J, Ellenbeck S. Energy security and renewable electricity trade—Will Desertec make Europe vulnerable to the “energy weapon”? Energy Policy 2011;39:3380–91. https://doi.org/10.1016/J.ENPOL.2011.03.035.

[4] Ren J, Dong L. Evaluation of electricity supply sustainability and security: Multi-criteria decision analysis approach. J Clean Prod 2018;172:438–53. https://doi.org/10.1016/J.JCLEPRO.2017.10.167.

[5] Das A, Halder A, Mazumder R, Saini VK, Parikh J, Parikh KS. Bangladesh power supply scenarios on renewables and electricity import. Energy 2018;155. https://doi.org/10.1016/j.energy.2018.04.169.

[6] Yuan M, Tapia-Ahumada K, Reilly J. The role of cross-border electricity trade in transition to a low-carbon economy in the Northeastern U.S. Energy Policy 2021;154. https://doi.org/10.1016/j.enpol.2021.112261.

[7] Bahar H, Sauvage J. Cross-Border Trade in Electricity and the Development of Renewables-Based Electric Power. OECD Trade and Environment Working Papers 2013. https://doi.org/10.1787/5k4869cdwnzr-en.

[8] Crozier C, Baker K. The effect of renewable electricity generation on the value of cross-border interconnection. Appl Energy 2022;324. https://doi.org/10.1016/j.apenergy.2022.119717.

[9] Abrell J, Rausch S. Cross-country electricity trade, renewable energy and European transmission infrastructure policy. J Environ Econ Manage 2016;79:87–113. https://doi.org/10.1016/j.jeem.2016.04.001.

[10] Dahlke S. Integrating energy markets: Implications of increasing electricity trade on prices and emissions in the Western United States. International Journal of Sustainable Energy Planning and Management 2020;25. https://doi.org/10.5278/ijsepm.3416.

[11] Joskow PL. Lessons learned from electricity market liberalization. Energy Journal 2008;29:9–42. https://doi.org/10.5547/ISSN0195-6574-EJ-VOL29-NOSI2-3.

[12] Blumsack S. Measuring the Benefits and Costs of Regional Electric Grid Integration. Energy Law Journal 2007;28.

[13] Oseni MO, Pollitt MG. The promotion of regional integration of electricity markets: Lessons for developing countries. Energy Policy 2016;88. https://doi.org/10.1016/j.enpol.2015.09.007.

[14] Pineau PO, Lefebvre V. The value of unused interregional transmission: Estimating the opportunity cost for Quebec (Canada). International Journal of Energy Sector Management 2009;3:406–23. https://doi.org/10.1108/17506220911005768.

[15] Moore S. Evaluating the energy security of electricity interdependence: Perspectives from Morocco. Energy Res Soc Sci 2017;24:21–9. https://doi.org/10.1016/j.erss.2016.12.008.

[16] Yang M, Shi X, Zhou Y, Xiang J, Zhang R. Deepening regional power connectivity: Beyond the industry-centric perspective. Energy Res Soc Sci 2022;90. https://doi.org/10.1016/j.erss.2022.102614.

[17] Ang BW, Choong WL, Ng TS. Energy security: Definitions, dimensions and indexes. Renewable and Sustainable Energy Reviews 2015;42:1077–93. https://doi.org/10.1016/J.RSER.2014.10.064.

[18] Ranjan A, Hughes L. Energy security and the diversity of energy flows in an energy system. Energy 2014;73:137–44. https://doi.org/https://doi.org/10.1016/j.energy.2014.05.108.

[19] Matsumoto K, Doumpos M, Andriosopoulos K. Historical energy security performance in EU countries. Renewable and Sustainable Energy Reviews 2018;82:1737–48. https://doi.org/https://doi.org/10.1016/j.rser.2017.06.058.

[20] Erahman QF, Purwanto WW, Sudibandriyo M, Hidayatno A. An assessment of Indonesia’s energy security index and comparison with seventy countries. Energy 2016;111:364–76. https://doi.org/https://doi.org/10.1016/j.energy.2016.05.100.

[21] Chuang MC, Ma HW. Energy security and improvements in the function of diversity indices—Taiwan energy supply structure case study. Renewable and Sustainable Energy Reviews 2013;24:9–20. https://doi.org/https://doi.org/10.1016/j.rser.2013.03.021.

[22] Zhang L, Yu J, Sovacool BK, Ren J. Measuring energy security performance within China: Toward an inter-provincial prospective. Energy 2017;125:825–36. https://doi.org/https://doi.org/10.1016/j.energy.2016.12.030.

[23] Ren J, Sovacool BK. Quantifying, measuring, and strategizing energy security: Determining the most meaningful dimensions and metrics. Energy 2014;76:838–49. https://doi.org/https://doi.org/10.1016/j.energy.2014.08.083.

[24] Wang D, Tian S, Fang L, Xu Y. A functional index model for dynamically evaluating China’s energy security. Energy Policy 2020;147:111706. https://doi.org/https://doi.org/10.1016/j.enpol.2020.111706.

[25] Song Y, Zhang M, Sun R. Using a new aggregated indicator to evaluate China’s energy security. Energy Policy 2019;132:167–74. https://doi.org/https://doi.org/10.1016/j.enpol.2019.05.036.

[26] Martchamadol J, Kumar S. An aggregated energy security performance indicator. Appl Energy 2013;103:653–70. https://doi.org/https://doi.org/10.1016/j.apenergy.2012.10.027.

[27] Jewell J, Cherp A, Riahi K. Energy security under de-carbonization scenarios: An assessment framework and evaluation under different technology and policy choices. Energy Policy 2014;65:743–60. https://doi.org/https://doi.org/10.1016/j.enpol.2013.10.051.

[28] Jun E, Kim W, Chang SH. The analysis of security cost for different energy sources. Appl Energy 2009;86:1894–901. https://doi.org/https://doi.org/10.1016/j.apenergy.2008.11.028.

[29] Lin B, Raza MY. Analysis of energy security indicators and CO2 emissions. A case from a developing economy. Energy 2020;200:117575. https://doi.org/https://doi.org/10.1016/j.energy.2020.117575.

[30] Kruyt B, van Vuuren DP, de Vries HJM, Groenenberg H. Indicators for energy security. Energy Policy 2009;37:2166–81. https://doi.org/10.1016/J.ENPOL.2009.02.006.

[31] Grubb M, Butler L, Twomey P. Diversity and security in UK electricity generation: The influence of low-carbon objectives. Energy Policy 2006;34:4050–62. https://doi.org/10.1016/J.ENPOL.2005.09.004.

[32] Chalvatzis KJ, Rubel K. Electricity portfolio innovation for energy security: The case of carbon constrained China. Technol Forecast Soc Change 2015;100:267–76. https://doi.org/10.1016/J.TECHFORE.2015.07.012.

[33] Dilek S, Konak A. Resource Diversification in Turkey’s Electricity generation. Journal of Original Studies 2022;3. https://doi.org/10.47243/os.3.2.03.

[34] Cox E. Assessing long-term energy security: The case of electricity in the United Kingdom. Renewable and Sustainable Energy Reviews 2018;82:2287–99. https://doi.org/10.1016/J.RSER.2017.08.084.

[35] United States Department of Homeland Security. Homeland Infrastructure Foundation-Level Data, Control Areas. Https://Hifld-GeoplatformHubArcgisCom/Datasets/Geoplatform::Control-Areas/About n.d.

[36] Shannon CE. A mathematical theory of communication. The Bell System Technical Journal 1948;27:379–423. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x.

[37] Margalef R. Information Theory in Ecology. General Systems 1958.

[38] Pielou EC. The measurement of diversity in different types of biological collections. J Theor Biol 1966;13:131–44. https://doi.org/10.1016/0022-5193(66)90013-0.

[39] Peet, Robert K. The Measurement of Species Diversity Robert K. Peet Annual Review of Ecology and Systematics , Vol. 5. (1974), pp. 285-307. Annu Rev Ecol Syst 1974;5.

[40] Hill MO. Diversity and Evenness: A Unifying Notation and Its Consequences. Ecology 1973;54:427–32. https://doi.org/https://doi.org/10.2307/1934352.

1. [↑](#footnote-ref-1)