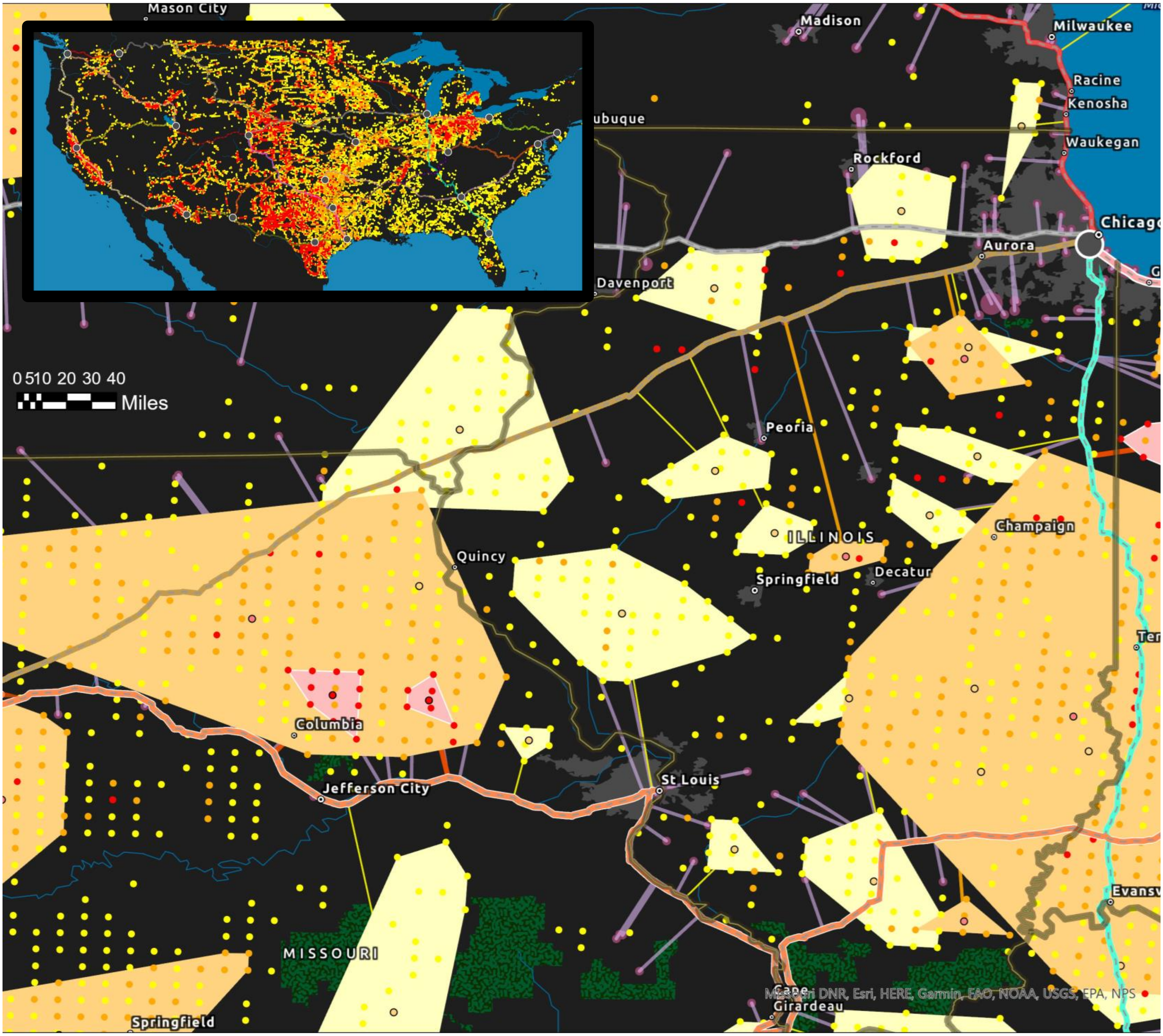

Railroad Opportunities for Transmission Expansion: A Comparative Analysis

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Author’s Note

This project is undertaken as a culminating requirement to my graduate degree in the Science of Geographic Information Systems and Technology. I have attempted to showcase my competencies in spatial statistics, geospatial vector analysis, network analysis, raster processing and Visualization. This project was advised by Professor Ramachandran Sivakumar.

All text and figures have been produced in accordance with the MLA-Style barring a paragraph spacing of one point five for conciseness. All Maps have been generated with the image facing North up with the legend in an appropriate position. The standard representation of the contiguous United States in the North American Datum of 1983 UTM Zone 11N projection with EPSG Code: 26911.

Abstract

Study looks to understand the feasibility of seventeen selected railroad corridors to act as potential HVDC transmission lines in the green economy transition. Supply clusters of solar energy are derived and assessed in relation to demand along railroad corridors. It is found that the railroad line from Seattle, Washington to Kansas City, Kansas has the highest potential based on the standardized weighted index developed for the analysis of the selected corridors. Different methods for evaluation are discussed as part of the study.

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Introduction

This project focuses on alternative geographic solutions to transmission expansion.

In recent years, the infrastructural challenges to the “Green Economy” transition have come into spotlight particularly post the improved capacity and the lowering of costs associated with photovoltaic cells production which was the initial deterrent for the first two decades of the 21st century. Currently, it is the transmission grid.

Americas transmission grid is largely outdated and unequipped for the increase in energy production that the next few decades will be accompanied [Lerner, 2003; Lesser, 2014; Metke & Ekl, 2010]. Many lines are old, prone to easy dismantling due to climate disasters and developed for limited load carrying capacity. Additionally, renewable energy integration possesses technological challenges as well since fluctuating production is uncharacteristic of the power plants which have been powering the nation since the late industrial revolution. To keep up with the change in the energy markets, the transmission grid will need to be revamped and expanded.

Experts suggest that the first line of improvement must regard a switch to High-voltage Direct Current Transmission Lines since they dissipate less energy over long distances [Halder, 2013]. Long distances from civilization are characteristic of renewable energy sources and therefore new transmission must be developed to carry these to population centers. This is especially true for Solar and Wind Energy as they are more plentiful in the central portions of the nation while the population is more densely situated in the Northeast. Additionally, they have the potential to carry more energy than HVAC lines with similar specifications and are specifically suited to changing loads and power draws which the latter are not [Musau et al., 2016].

As transmission expansion develops, one of the major barriers is land acquisition as it requires negotiations with multiple private landowners and has created several long-drawn-out legal battles in the past [Jamieson, 1989; Sidak et.al, 1997]. 'Railroad Right of Ways' are envisioned as single owner land passages that will overcome this barrier. Land acquisition form private property has been a problem that the United States has not had to face for a very long period.

This project seeks to understand the geographical contexts of supply and demand of energy, other important dimensions of transmission expansion and the network topology of railroads to identify the feasibility of specific corridors to fulfill the ability to bridge the nation's transmission gap.

Literature & Overview

This section delves into the geometry of transmission systems, the literature surrounding its conundrum in renewable energy expansion, the different methods that have been utilized to assess the viability of solar farms and the viability of transmission lines and the spatial geography of the American railroad system. No literature exists with particular application to the use of railroad right of ways in laying underground transmission cables. Although, literature from the 1980's has posited the idea of overhead transmission lines [Taflove, 1984; Frazier, 1986]. Therefore, methods utilized in various other assessment are transferred to this paper. The following few paragraphs discuss the elements of the transmission network followed by a review of the methods and the current social scenario regarding transmission expansion.

Origin – Power Plants

There are three important considerations when it comes to the planning of energy systems from a geographic perspective. First is the point of Origin which refers to the power plants based on conventional fossil fuels that have traditionally powered American settlements. The United States has typically relied on coal powered electricity generation for running its national electrical grid. Overtime with increased environmental consciousness and the cognizance of climate change impacts, several shifts in the energy industry have been observed which include: -

- **A decline in Coal and shift to Natural Gas:** This results in lower emission as it is less carbon – intensive and more economical due to the invention of the ‘fracking’ method of extraction.
- **Increased patronage of renewable source such as Solar and Wind:** The U.S has enormous renewable energy potential and this shift has been promoted by federal incentives, technological advances leading to lower costs and increased public awareness [Figure 1].

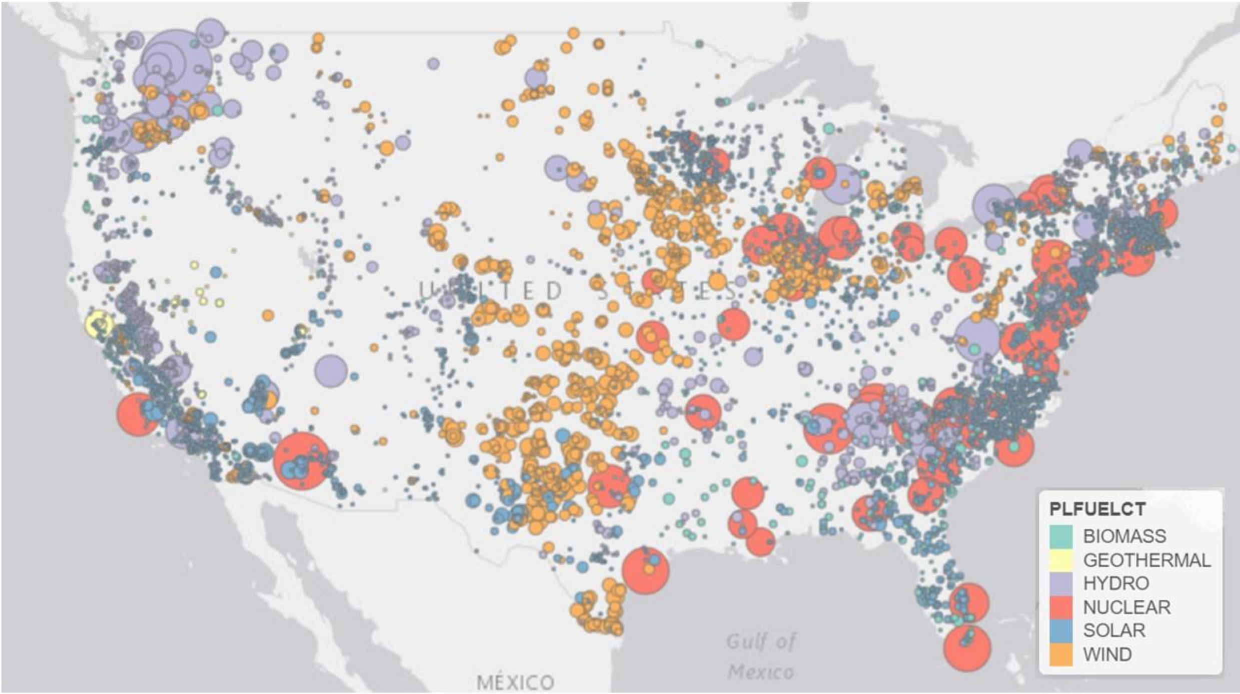


Figure 1: Map of Renewable Energy Power Plants in the U.S.A. Nuclear energy has the highest actual capacities followed Hydro power plants. Solar plants are more numerous in number but will lower capacities. Likely due to their being Community Solar projects.

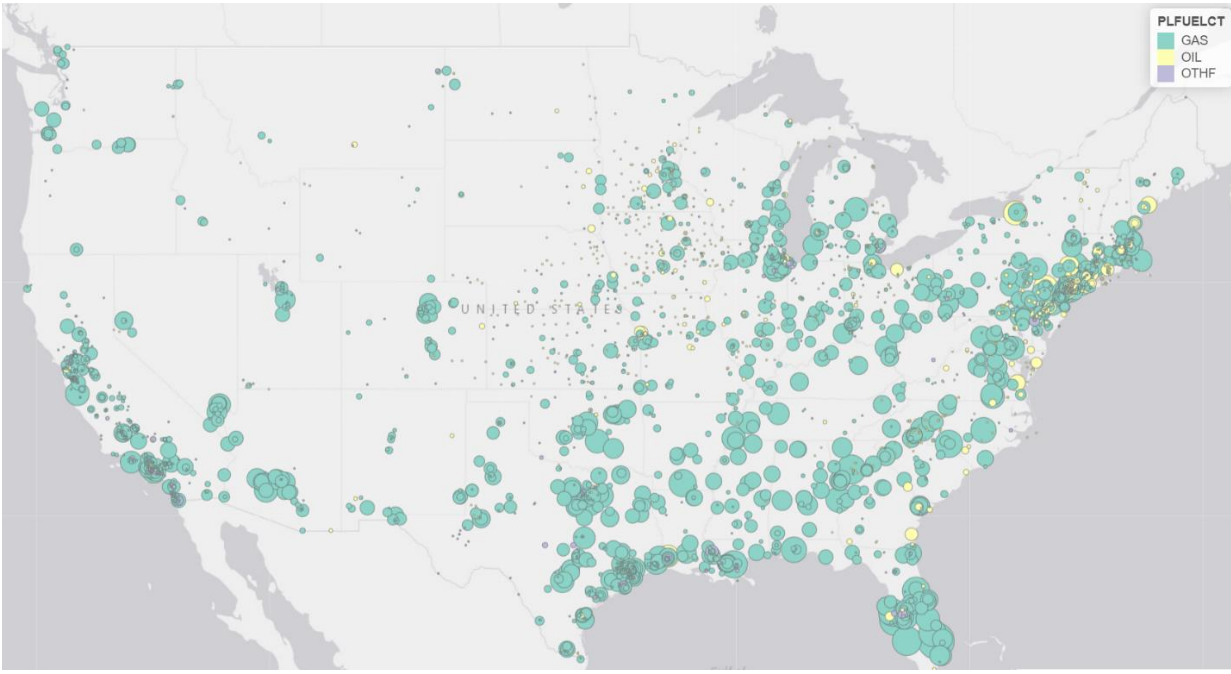


Figure 2: Map of Fossil fuel power plants. Natural Gas is more numerous in number and capacity as it is more energy efficient for a unit and is also easier to transport through pipelines.

Gas has superceded Coal as the major power plant source [Figure 2]. Wind Sources are distributed from Texas to the Midwest. We are not considering this for our analysis as Wind is largely concentrated to a single region as opposed to Solar. Nuclear by far has the largest capacities of energy generation in a point concentration. Solar plants are of much smaller capacity possibly due to the foundational costs of setting up. There are over 8000 Renewable Energy Plants as compared to 2700 Fossil Fuel Powered Plants. This is because each FF powered unit has more capacity as comapred to RE plants which are more easily developed by private small scale players.

Note that on closer observation, the location of RE sources is more widely distributed than conventional fossil-fuel powered plants. The average distance of a RE plant from its nearest high load center is 4 times than the distance of a fossil-fuel plant. This metric will not change as RE expansion occurs as the source of Solar, Wind and other sources cannot be moved which presents one of the major problems to expansion and transmission capacity [Negro et al., 2012].

Demand – Corridor Cities

The second consideration is the point of Demand which refers to the Cities, Towns and other Industrial, Commercial or Agricultural sector specific settlements that are the main consumers of the power plants. Demand varies considerably between settlements in addition to the fuel source of the power plants that they draw energy from which results in different Greenhouse Gas Emissions (GHG) levels. Load quantity is typically a reflection of population as characteristics of energy consumption remain largely similar across the nation. Per capita consumption varies considerably as urban morphology and energy efficiency measures change [Osorio et al., 2012; Perkins et al.,2009]. For instance, New York City which has a higher population then comparable cities such as Houston and Chicago have a much lower per capita consumption due to its urban density and other policy factors. Demand points similarly are geographically consistent. These provide fixed nodes against which a transmission grid is planned and designed. The railroads selected further ahead in the analysis is overlaid with the top cities for consumption below for context [Figure 3].

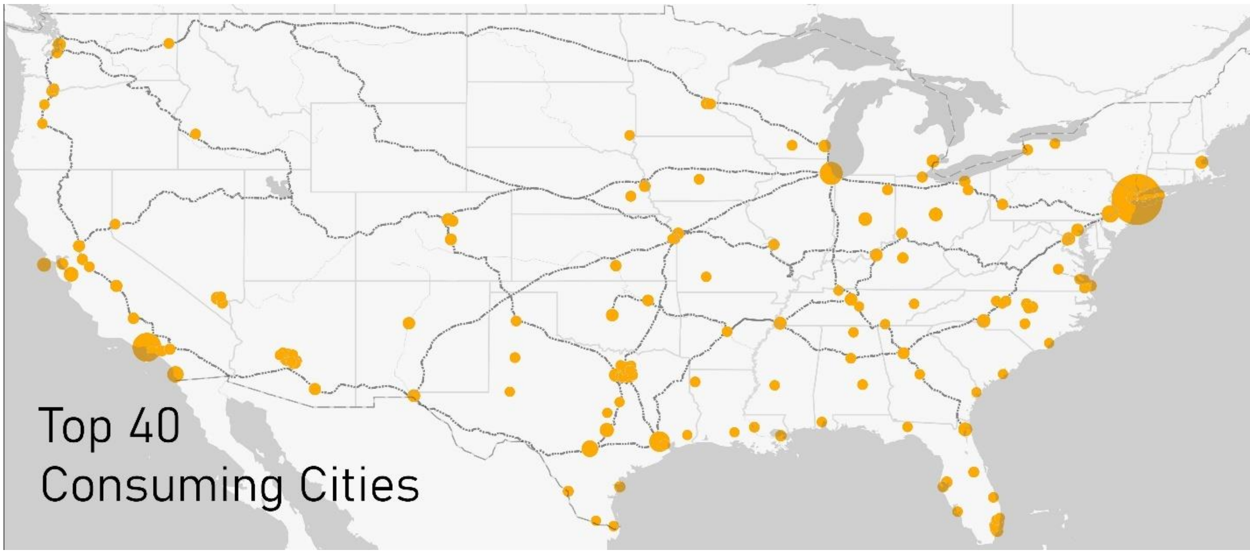


Figure 3: Map of the Top 40 U.S Cities in terms of Total Energy Consumption in Megawatt-hours. New York is the largest consumer but not so in terms of per capita. Most high consumption cities are distributed along Class - I Rail Corridors.

Transmission

How do transmission systems work from a systems perspective?

This paper concerns itself with the third crucial component of energy systems planning which is transmission. Transmission refers to the connective element that transfers electrical energy from its point of origin to its destination i.e., power plant to destination. Electricity generated at plants is converted to High-Voltage at step-up transformer substations since transmission at higher voltages reduces losses on the transmission lines due to heat dissipation. As it nears the destination the voltage is stepped down at another sub-station and using a local distributive system it is transported to homes and offices. The diagram below illustrates the typical transmission setup of a power grid.

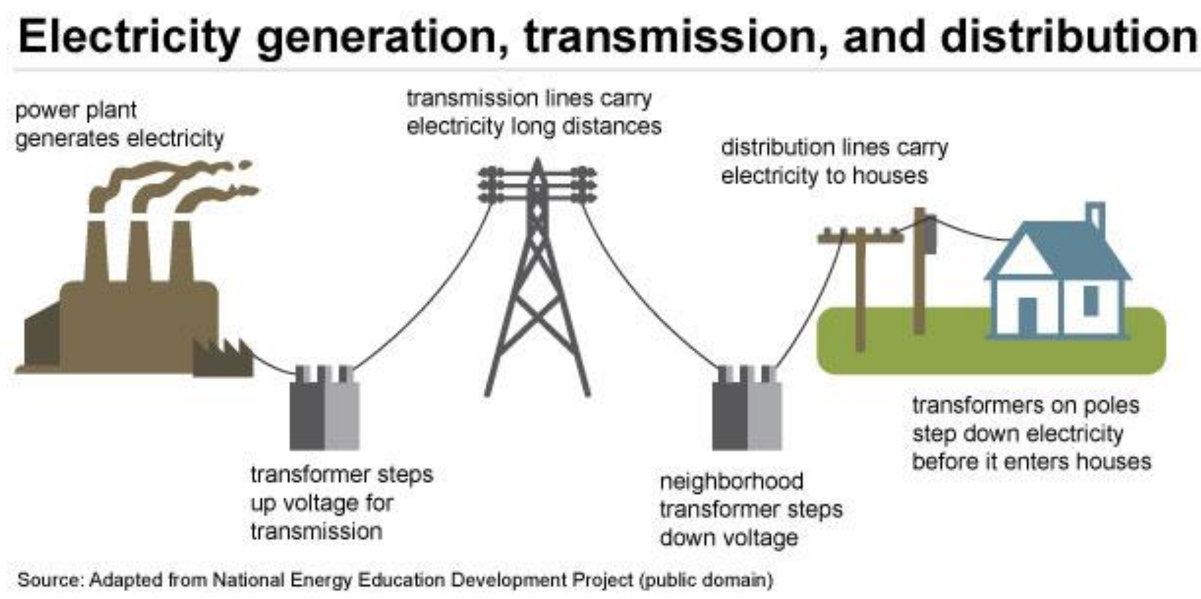


Figure 4: The Transmission Grid Explained. [Source: Energy Information Administration]

For instance, we see below the transmission lines that service the area of Metro Atlanta [Figure 5]. Power is generated at non -urban locations and services several substations which distribute energy to the urban and suburban populations and services.

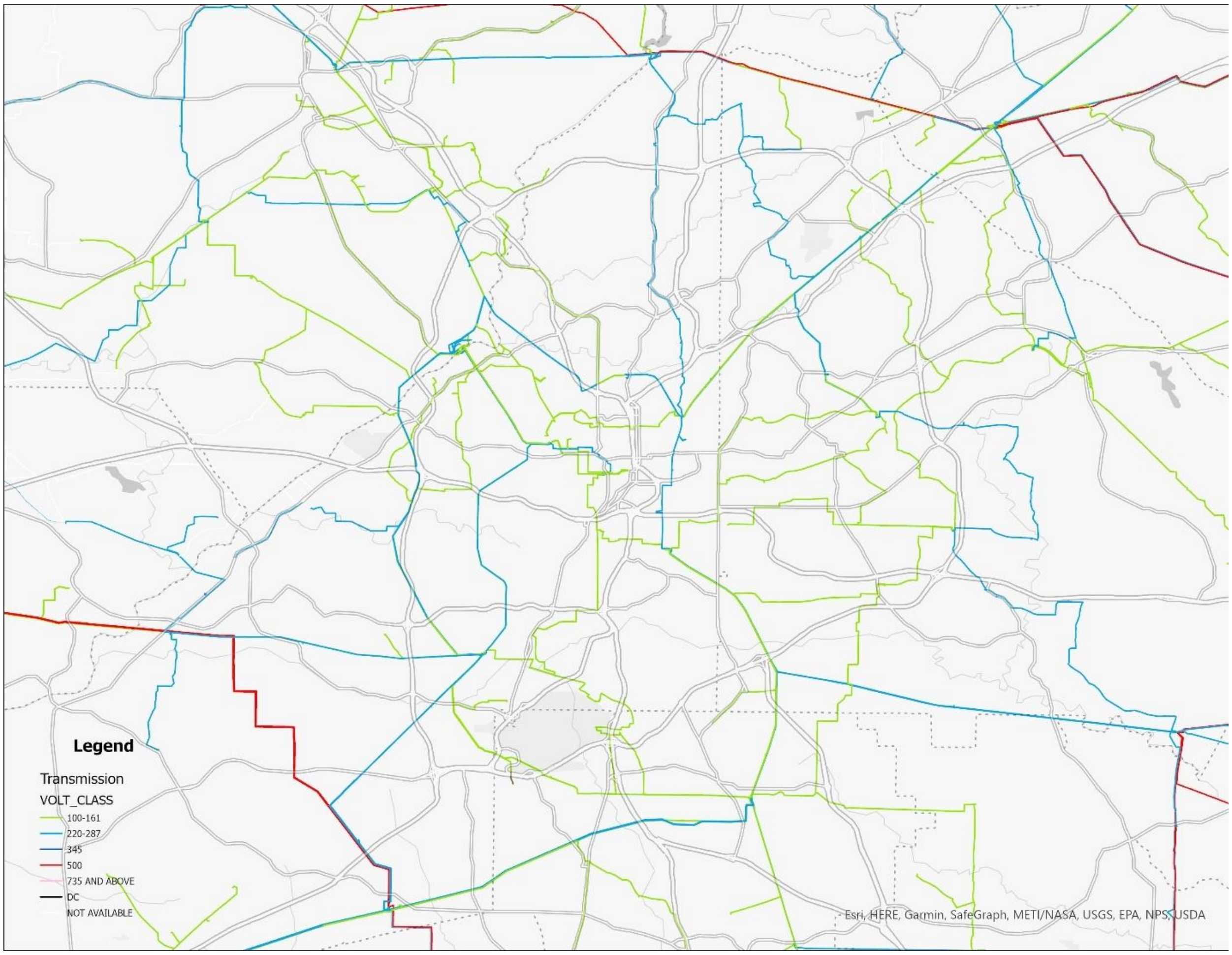


Figure 5: Transmission Layout in the Metro Atlanta region. As the interiors of the city approaches, the Voltage Class is steadily stepped down.

We find a good depiction of how the transmission grid works. 500 kV Volt Class lines transfer energy from plants to the outskirts of the Metro region. 220 -287 kV Volt Class lines bring this energy into the area with 100 -161 kV Volt Class lines further distributing it within the inner regions. Distribution lines (not shown in [Figure 5]) carry these to the inner neighborhoods.

There are currently XXX Miles of Transmission [Figure 6]. The American Transmission grid has several classes based on the amount of electricity that is being carried [Nardelli et al., 2014]. These are 100 – 160, 220 – 290, 345, 500, 735 & Above, DC, Under 100. There are two kinds of renewable energy sources – distributed scale and utility scale. The former cannot work with High Voltage Transmission lines and is operated at the Medium Voltage / Low Voltage scale. With regards to transmission challenges, renewable energy sources are not subject to parameters set by operators but rather nature. At utility scale, they require substantial land and need to be transferred from locations inconvenient to the grid [Zahedi, 2011]. These are the gaps that we seek to quantify and identify. Additionally, several papers discuss the issue with interrupted power reserves due to variability and argue that Distributed Power Grids and Micro Grids as better alternatives [Kaijuka, 2007]. The potential for mapping GIS based Mini Grids using an example in Sub Saharan Africa where Central Transmission is not possible is illustrated [Moner-Girona, 2018]. These act as sources which are close to the distribution network as opposed to the transmission network and therefore closer to the system load (Cities, Consumers). It is argued that this may be better since electricity bills include cost of inefficient transmission grid. United States Department of Energy Grid 2030 Vision Plan is a very useful framework document to study these alternatives. Transmission routing is based on multiple methods all of which are oriented towards reducing the cost - the Least Cost Path Algorithm, Multicriteria decision making and the Analytic Hierarchic process by assigning weights to different criteria [Quinones-Varela et al., 2007; Tarife et al., 2020]. The Grid Access and Planning Method is an interesting method that may add value to how RE-DE grids may be connected to central networks [Carvallo et al., 2019]. The

Analytic Hierarchic Process is used in multiple studies [Lazarou et al., 2021; Uyan et al., 2013; Gerbo et al., 2020]. It is seen as the most useful multi criteria decision making framework for reasons not highlighted. It is also used in a GIS base planning support system (PSS) for utility providers in Scotland utilized topographic, land use, environmental information, and power network infrastructure data [Quinones-Varela et al., 2007]. All these were considered to create measures of resistance. Routes were created such that the Least Cost Path followed the path of least resistance. The GIS PSS also utilizes a power flow study for optimization of losses and other system characteristics, but an important takeaway is that this does not affect the spatial routing which is the focus and limit of the study [Stram, 2016]. An additional task is the identification of energy usage patterns in each state followed by interstate transfer patterns. The EIA and SEDS database are useful resources, and their use has been validated in multiple studies [Arderne et al., 2020; Zahedi, 2011].

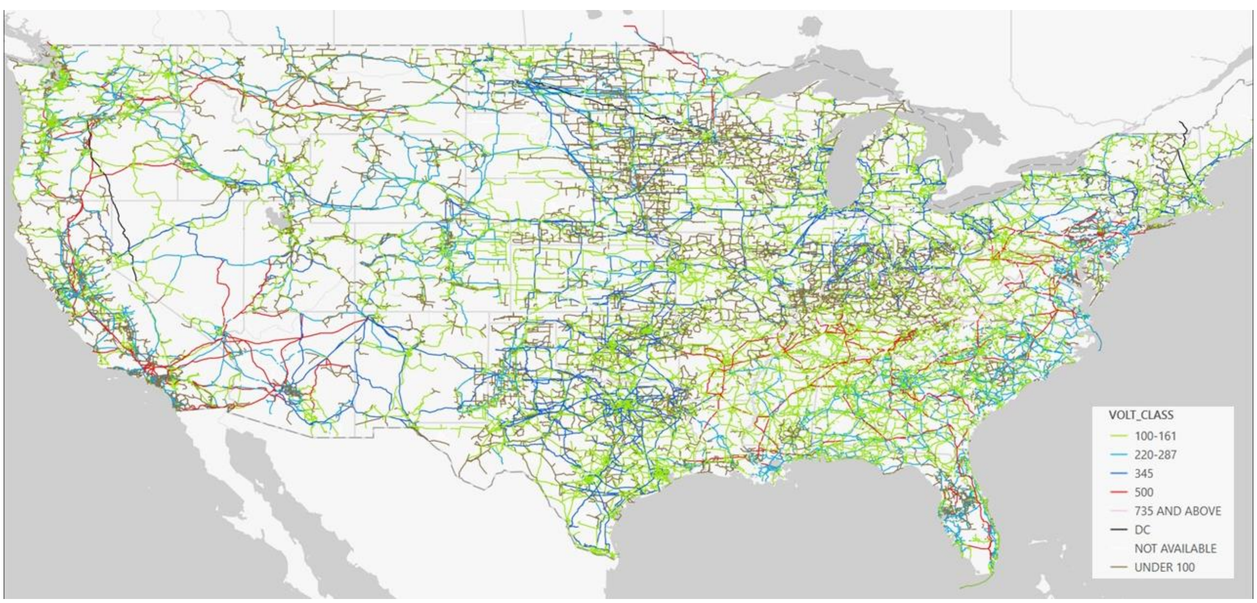


Figure 6: The American Transmission Grid. High Voltage AC Transmission beyond 500kV is concentrated to the West and Eastern regions. We need additional high voltage capacity from the Central US where most of the RE potential is.

Problems regarding Transmission for Renewable Energy (RE) Grid Expansion

There are several problems associated the expansion of renewable energy sources in addition to the additional transmission capacity that is required to expand the grid. The problems are chiefly economic, regulatory, infrastructural, social and geographic. While this paper concerns itself only with latter perspective a brief overview of the other aspects is provided here since they present themselves in the choices being made for geographic decision – making and suitability analysis.

The major barrier to the Green Economy in the US lies in the infrastructural challenge posed by the nation's transmission grid. As renewable capacity increases, the limited transmission capacity bottlenecks its expansion and feasibility. The US will need to upgrade its current transmission which are plagued by old infrastructure that cannot handle intermittent voltage fluctuations and needs to add three times the current capacity due to increased demand as electric vehicles increase in popularity by 2045 [Phillips, 2023]. An additional barrier is the process that is used to plan transmission which is through feasibility studies of individual proposals and its impact on transmission. Experts argue that in the RE era, a large capacity shared transmission that individual transmission can link to is a more feasible alternative that will accelerate the transition to the green economy. The Federal Energy Regulatory Commission has proposed that potential high energy renewable energy ones be proposed against which such transmission lines can be planned [FERC Report, 2021]. These are proposed long term solutions.

While the social acceptance of renewable energy sources such as solar energy farms have been found to be generally positive across nations [Pinto et al., 2021]. Siting on private lands has been found to be an issue as property owners and residents do not want these farms near places of habitat citing aesthetic, cultural, habitat loss, property value reduction and loss of arable land as reasons. This is mainly a problem in rural America and several successful attempts have been made to block projects in Texas, Kansas and Maine [Groom, 2022].

Utility-Scale Solar Farms require large amounts of area. For instance, The Solar Start farm in the Los Angeles desert has the highest capacity at 579 MW but is spread over 3000 acres of area. The same amount of energy can be produced by a natural gas plant in about 100 acres.

Regulatory issues abound as well as more than 100 rural localities alone in 2022 have enacted administrative barriers to the siting of solar farms in their jurisdictions [NREL, 2022]. These barriers also extend to transmission. Research has shown that internationally, barriers to transmission facility planning share a similar defense of local interests such as in the Franconian region of Germany [Neukirch, 2020]. Historically, these protests have been channeled majorly by the fact that transmission lines are seen as a blot on the landscape and additionally they present difficulties in land acquisition since they cross privately owned lands across miles of rural landscape. This is exacerbated by the fact that while RE farms require polygonal geometries for establishment, transmission requires linear geometries which are not typical of administrative and legal boundaries. Few artificial linear elements exist except freeway systems and railroads while natural linear elements are essentially only restricted to rivers and streams. The CU transmission project controversy of Western Minnesota in the 1970s [Hansen, 2021] and the recent Western Wisconsin protests against the Hickory

Creek Line of the American Transmission Company are representative [Groom, 2022]. The 145-Mile New England Clean Energy Connect transmission project is the latest fatality in Maine as voters rejected the project.

A technological issue with transmission capacity expansion lies in the suitability of traditional AC power lines for RE transmission. AC power lines have a high distance decay in terms of power loss compared to DC transmission [Liang et al., 2020]. As discussed above, RE zones lie outside of traditional power plant locations, leading to Ac transmission having high energy dissipation and loss. A feasible alternative is to use HVDC transmission lines which have lower power loss.

High-voltage direct current transmission (HVDC - T) is touted as a feasible alternative to alternating current when it comes to the expansion of transmission for renewable energy systems. As discussed above, distance of transmission and the dissipation of generated energy during transmission are issues when it comes to utility-scale renewables expansion. Additionally, from a technology perspective, the variable rate of loading and production concerned with renewables poses an infrastructural threat to AC networks which need more stable and continuous energy sources. HVDC-T has no such issues. It is suitable for RE because –

- It can transmit bulk power from remote power sources to load centers efficiently without requiring intermediate taps.
- They provide feasible alternatives to increase the capacity of existing lines when new construction is quite expensive.

- It has been cited as the most efficient method to integrate RE sources to the grid.
- HVDC-T is cheaper than AC for the same power transmission capability with cost of AC steeply increasing as the distance of transmission increases.

  [Gavrilovic, 2023; Power, 2018; Roberts, 2023; Utility Dive, 2023; “Creating a National HVDC Transmission Network - Federation of American Scientists”, 2023].

Railroads as a Feasible Alternative

The American Railroads were the backbone of the US Economy with it being the primary mode of passenger and freight transportation for long distances in the early 20th century. Overtime and with the introduction of the Interstate highway system, its importance declined and currently federal funding for railways are very low compared to the Federal Highway Administration [Sacks, 2016]. Most of the railway tracks currently are used for freight transportation. As railways became outmoded, many companies merged to survive and formed the current organizations that form the rail structure of the US. The seven largest operators which as CSXT, BNSF, Union Pacific, Canadian National, Canadian Pacific and Norfolk Southern are categorized as Class I Railroads with the highest valuations and track ownership [Figure 7]. CPR & CN have been omitted from the map below as they ply their lines majorly in the Canadian jurisdiction with only one major line extending to the port of New Orleans. This is not to say that they are not important as many experts have argued that the future Renewable Grid should be a North American consolidation [Albert, 2004]. There are around 55 Class II railroads which are defined as either having 350 Miles of rail track ownership or a specific valuation of business [Sidhu, Charney & Due, 1977]. These are regional railroads and critical to the health of state economies [Figure 8: Convex Hulls as minimum bounding geometries representing the extents of Class II railroads which number over 55 privately owned entities.].

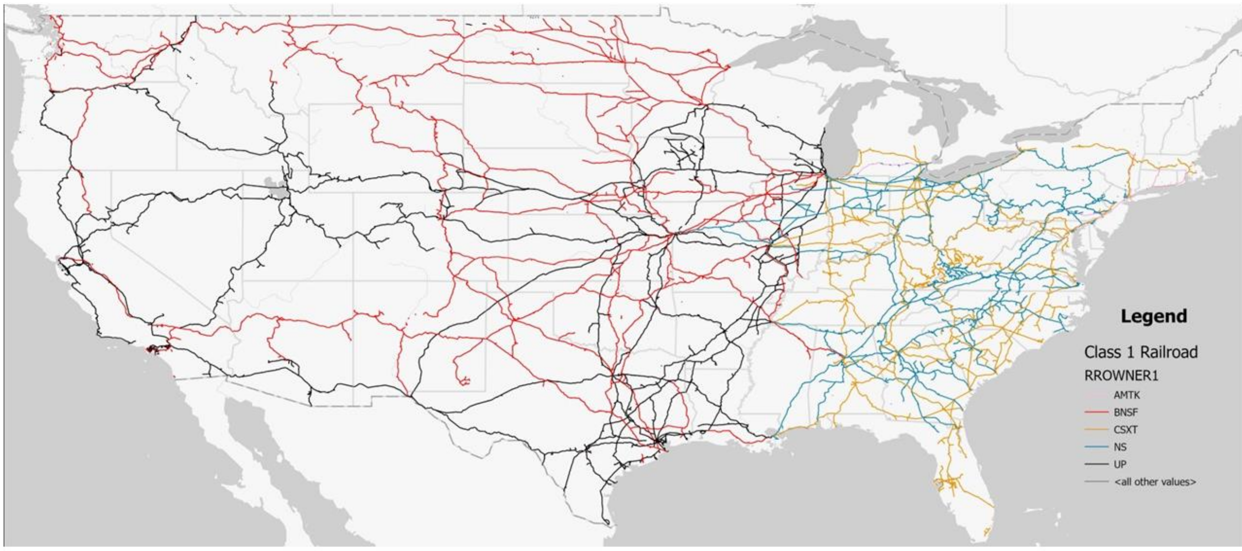


Figure 7: Map of Class I Railroads in the US symbolized by Ownership. Union Pacific & Burlington Northern Santa Fe owned by Berkshire Hathaway are the most important railroads in terms of energy transmission from the West to the East.

Amongst the Class II Railroads, the companies PVTX, USG and AMTK have mileage ownership greater than 350 Miles but are not regional. While Amtrak is passenger rail, the other two are connecting railroads providing crucial connections between different companies and therefore their geometries are dispersed. The other Class II companies are nearly 55 in number. Their convex hull geometries are mapped below [Figure 8]. Details regarding each of these are presented in Appendix B.

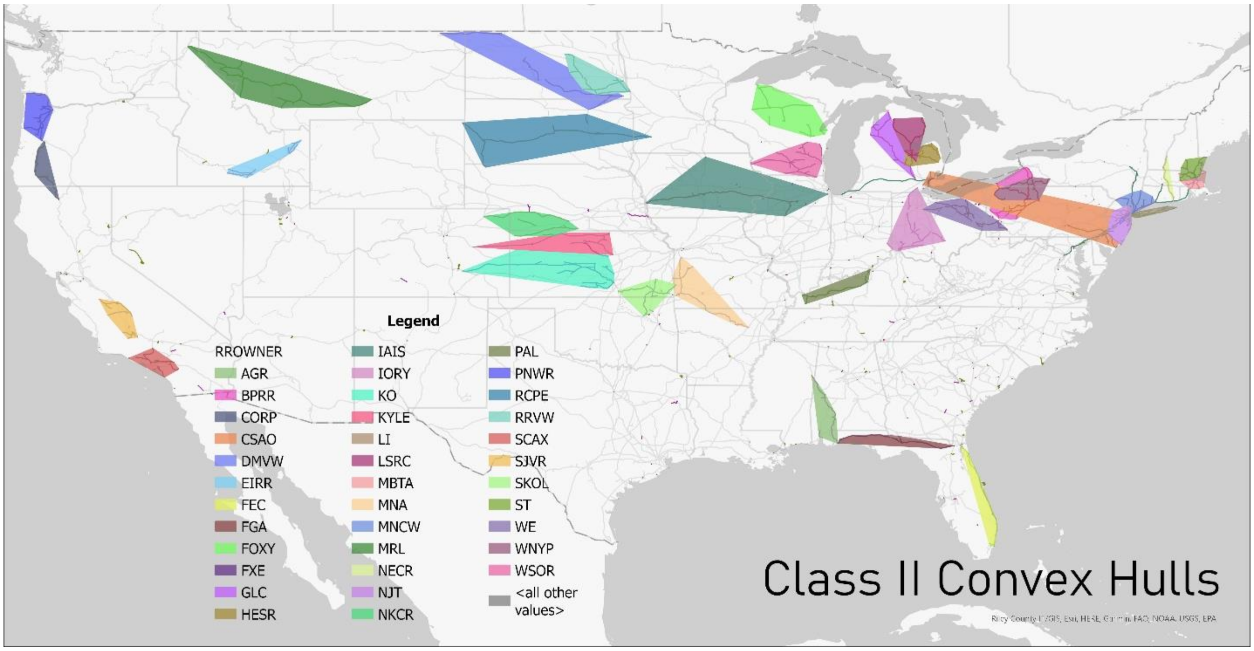


Figure 8: Convex Hulls as minimum bounding geometries representing the extents of Class II railroads which number over 55 privately owned entities.

The Federal Railroad Right of Way Act of 1875 grants railroads 200 Foot right of way easements to major railroads. This is sufficient width amongst large diameter pressurized and insulated transmission pipes to be laid underground. While overground transmission may pose electromagnetic field problems to the functioning of the rail system. Underground transmission does not pose the same risks since the ground serves as a dampening element. Rail Right-Of-Ways are considered private property under U.S Law [Federal Railroad Rights of Way, 2023].

Siting is the major barrier to transmission development currently. Calls for a railroad oriented HVDC transmission have been made by several groups such as the Federation of American Scientists have called it crucial that calls for an underground HVDC transmission system next to railroads is a much better option than putting together a jumble of privately owned property mosaics. It only requires negotiation with seven

American companies and does not add visual pollution unlike the existing stock [Tenzer, 2016]. Railroads and highways are seen as the enablers of a future US high-voltage corridor grid. Direct Connect Development is a utilities company that has secured a 350 – Mile corridor between Mason City, Iowa and Plano, Illinois for the SOO Green HVDC Link which is a 2.1Billion Dollar project. It will carry 2.1 Gigawatt of power from wind farms to the interconnected grid in the Midwest and connect the MISO and PJM regional energy markets. This has been built primarily along the rail lines of Canadian Pacific Railway. The company argues that Siting and Permitting are the biggest problems and supersede cost as a concern by a huge margin [“How Transmission along Railroads and Highways Could Break Open Clean…”, 2023]. The American Jobs Plan proposes a Grid Deployment Authority that can leverage ‘existing rights of way in transmission expansion”. The National Renewable Energy Laboratory’s “Interconnection Seams Study” mirrors the claims made by several consulting organizations [Bloom, 2020; Brinkman, 2020]. This project undertakes a similar study with different parameters [“Creating a National HVDC Transmission Network - Federation of American Scientists”, 2023].

Devolving the Problem Statement

This project is concerned with identifying a set of railroad corridors and their feasibility in having High Voltage Direct Current Transmission Lines laid along their right of way. A series of categorical objectives need to be established based on which quantitative measures are to be developed. These are listed as characteristics that are important for the success of the transmission line.

- **Supply Capacity** – How many sources of Renewable Energy Zones can the rail corridor connect to assuming every zone is connected to the nearest corridor? This also looks at High Priority zones or areas where there is an overlap of different categories of potential utility scale farm areas.
- **Demand Capacity** – How many clustered demand points i.e., towns and cities can the rail corridor serve and satisfy? Demand points outside of the direct vicinity of the rail corridor are not considered for this analysis as it will require an analysis of the transmission network in whole which is beyond the scope of this paper.
- **Distributive Capacity** – How many existing transmission lines can the rail corridor connect to? This looks at an intersection of the high voltage alternating current infrastructure already in place.
- How many solar farms can it connect to? This looks at the individual farm count as described in the NREL Solar Supply Curves.
- **Replacement Capacity** – How many fossil fuel power plants can this corridor replace? How many megatons of carbon dioxide equivalent greenhouse gas emissions can it mitigate? This is analyzed utilizing the current energy profile of the cities on the corridor.

- **Administrative Capacity** – How many Electric Planning Areas does the corridor pass through? How many States does it pass through? While this can be an administrative impediment in establishing the HVDC line, it can also serve as an opportunity to quickly integrate disparate geographies within the service area of the transmission line. Since we are looking at the utility of the line post establishment, it is best to take an increased number of state and planning areas participation as an attractive measure.

All the measures listed above are derived from available and validated data sources listed in the forthcoming section. These are then further processed to derive necessary comparisons.

Data

Since the analysis considers the three-dimensional nature of transmission considering supply, demand and connectivity; many datasets are utilized in the process. Several of these datasets have been modified to suitable formats prior to which this section highlights the structure of the native data format. The following data sources were utilized to analyze the feasibility and potential for railroad line right of ways to be used as potential sites for siting of High Voltage Direct Transmission Lines [Table 1]

DATASET	TYPE	GOVERNING AUTHORITY	YEAR
Solar Supply Curves Limited Access	geoJSON	National Renewable Energy Laboratory	2022
National Transit Atlas Database - Rail lines	geoJSON	Federal Transit Administration	2021
National Transit Atlas Database - Rail nodes	geoJSON	Federal Transit Administration	2021
City & County Profile	CSV File	National Renewable Energy Laboratory	2016
USGS DEM 30M	30M Raster	United States Geological Survey	2021
USGS Hydrology Layer	Polygon Vector	United States Geological Survey	2021
USGS Protected Forest Layer	Polygon Vector	United States Geological Survey	2021
National Land Cover Dataset	30M Raster	United States Geological Survey	2019
EGRID Plant Database	Excel File	Energy Information Administration	2021
Transmission Lines Dataset	geoJSON	Department of Homeland Security	2021

Table 1: List of validated data sources. These are further processed to derive measures for the analysis.

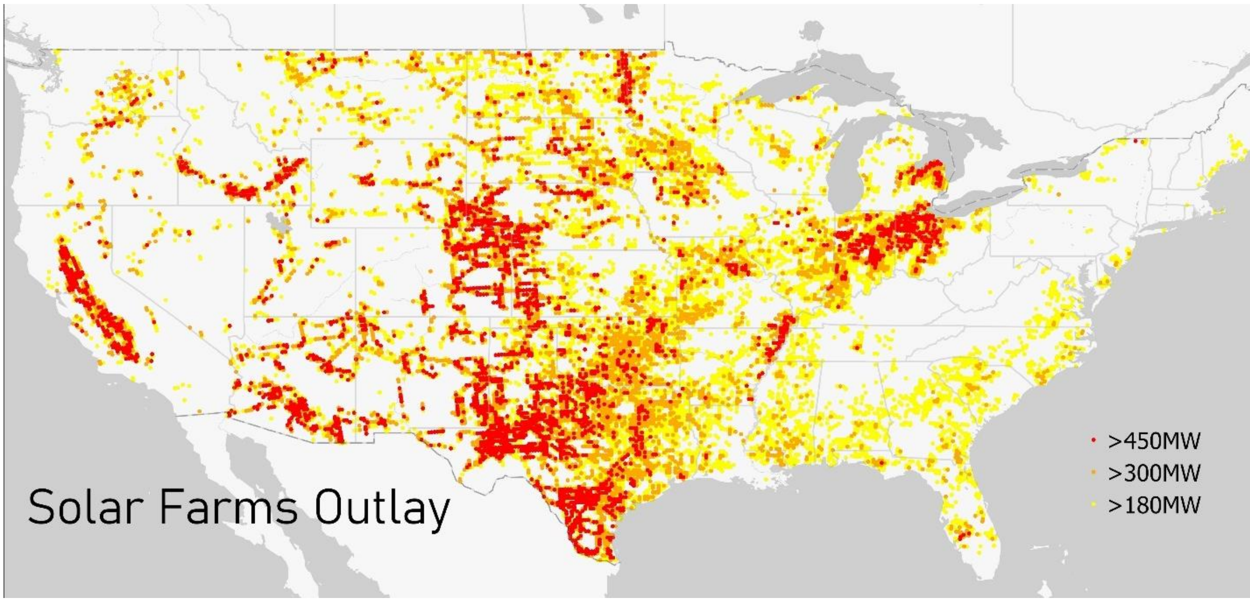


Figure 9: Solar Farms based on applied exclusions in the contiguous US. They are symbolized by Nameplate Capacity in Megawatts.

The map above showcases the high-capacity solar farms that have been mapped from the NREL supply curves [Figure 9]Figure 9: Solar Farms based on applied exclusions in the contiguous US. They are symbolized by Nameplate Capacity in Megawatts.. Compare it to the Wind Farm map outlay from the same source [Figure 11]. For lower capacities of a maximum of 100 MW wind farms have lower geographic distribution mostly to the east of the Rocky Mountains. On the other hand, Solar Farms have a greater potential for decentralization.

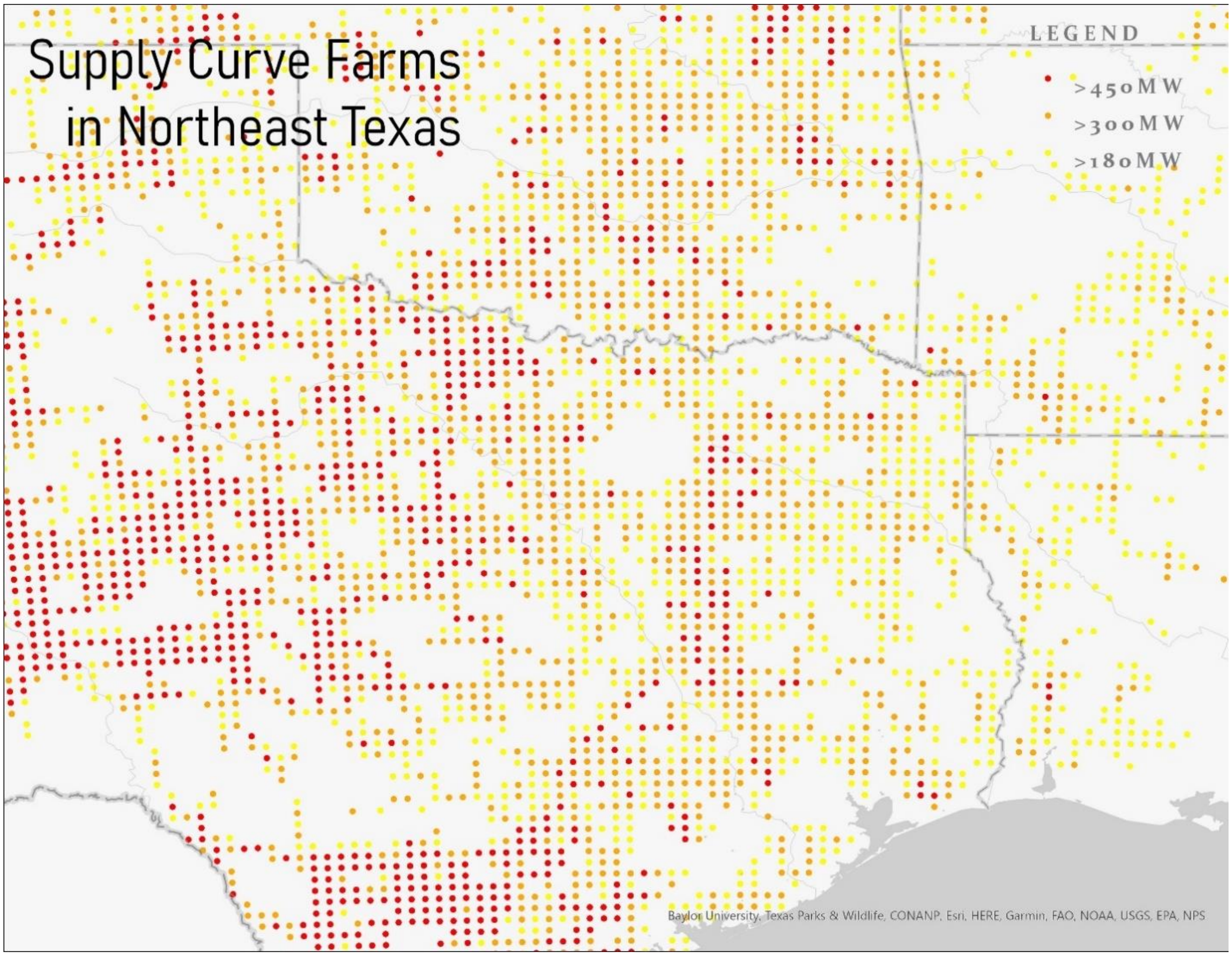


Figure 10: NREL Supply Curve Points in the North-East of Texas which has the highest capacity in total.

The figure above shows the outlay of the NREL supply point curves in Texas [Figure 10]. Farms are centered to a single point geometry and distributed with areas, sizes and capacities outlined in the attributes layer.

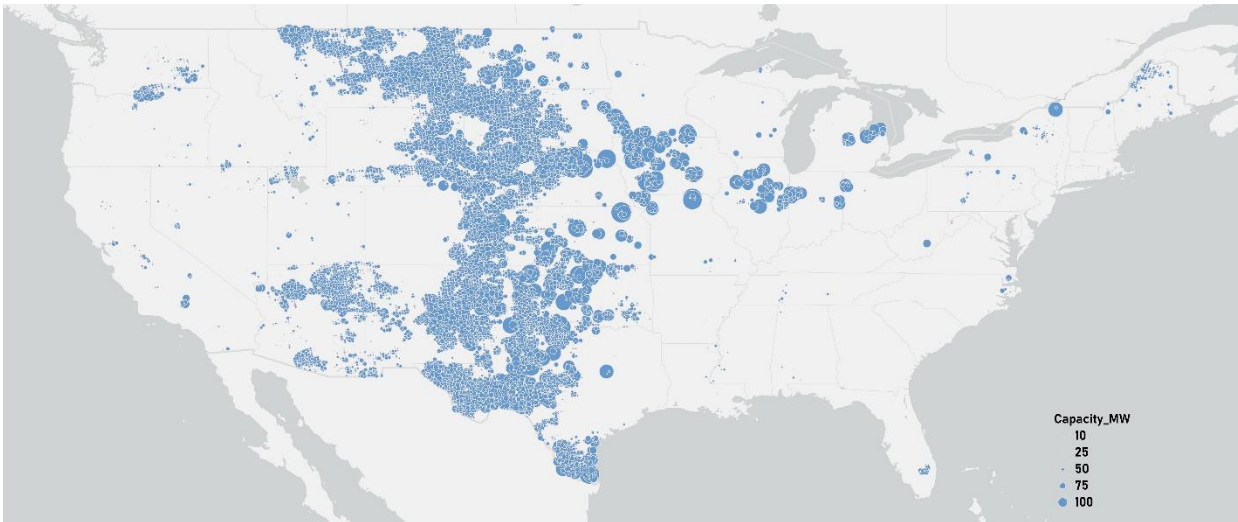


Figure 11: Wind Farms with nameplate capacity over 10MW.

Additionally, several assumptions are undertaken at each step of the methodology since insufficient literature exists in several domains. The transmission lines dataset has been procured by the Homeland Foundation Level Infrastructure Dataset as it is a matter of national security. Additionally, the rest of the raster layers from the USGS was converted to vectors for computation.

Methods

Selection of Data Points

There are several rail lines with nodes denoting geometric vertices and stations. It is not within the scope of this project to identify the feasibility of each edge as that would be a micro-consideration during deployment. Instead, we attempt to focus on high impact corridors which are anchored by cities with high consumption on either.

City Name	Population	Total_MWh	GHG_Total	City_Name	Population	Total_MWh	GHG_Total
New York city	8461961	42480133.76	34518533.8	Columbus city	837038	7653234.662	10817057.42
Philadelphia city	1559938	30083416.78	42056662.22	Seattle city	668849	7168072.288	5562763.665
Houston city	2240582	30083416.78	42056662.22	Atlanta city	456378	6893186.911	8087296.995
Los Angeles city	3918872	23635432.56	28755318.14	Tulsa city	399906	6707355.313	7505965.008
Chicago city	2714017	18879520.96	25551575.57	San Diego city	1374812	6227377.619	10608811.68
San Antonio city	1439358	16535298.7	19692698.89	Portland city	620589	5767690.409	5872486.962
Dallas city	1278433	16366036.6	21366724.89	Baltimore city	621000	5641413.581	6181095.511
Phoenix city	1555324	16014728.11	16135930.96	El Paso city	678058	5627215.453	7530983.789
Memphis city	655857	9835956.777	11965870.75	Kansas City	471767	5299512.448	8269453.606
Nashville-Davidson	643771	9835956.777	11965870.75	Chattanooga city	175462	4993132.945	4757104.174
San Francisco city	850282	9340807.931	12301533.65	Omaha city	443072	4662143.436	5665887.515
Jacksonville city	856616	9340807.931	12301533.65	Shreveport city	198571	4653479.389	5552577.418
Austin city	907779	9340807.931	12301533.65	San Jose city	1009363	4567200.882	6332379.901
Fort Worth city	815930	8818317.365	12169743.09	Honolulu County	986999	4567200.882	6332379.901
Oklahoma City city	620015	8404050.775	11462539.74	Hempstead town	768708	4520105.269	4236041.905
Charlotte city	808834	8247164.176	8459043.565	Miami city	432622	4342764.106	3744471.276
Denver city	663303	7709620.645	5044095.716	Louisville - Jefferson	611573	4295888.355	6171138.716
Washington city	659009	7709620.645	5044095.716	Detroit city	683443	4286521.939	9024815.091
Indianapolis city	846674	7653234.662	10817057.42	Tampa city	361477	4133705.66	4619716.597

Table 2: Top 40 Cities with highest Energy Demand. Selected cities which are on Class I railroads are highlighted in green.

Several of these cities even though high on consumption are not incident or connected by Class- I railroads and are connected by Class II regional railroads. To reduce the complexity of the study network, only cities with junctions or nodes served by class I railroads are selected. A further filter of geographical distance is applied to only select cities which are in different regions in order to increase the length of the corridor and consequently its capture potential. Two large cities anchored by short rail span will be insufficient to adequately reflect the scope of this analysis with reduced geographical threshold. In the instance below we can see how the corridor anchored by Memphis and Nashville has only two clusters in proximity. The Supply to Demand Ratio is only 0.06 [Figure 12].

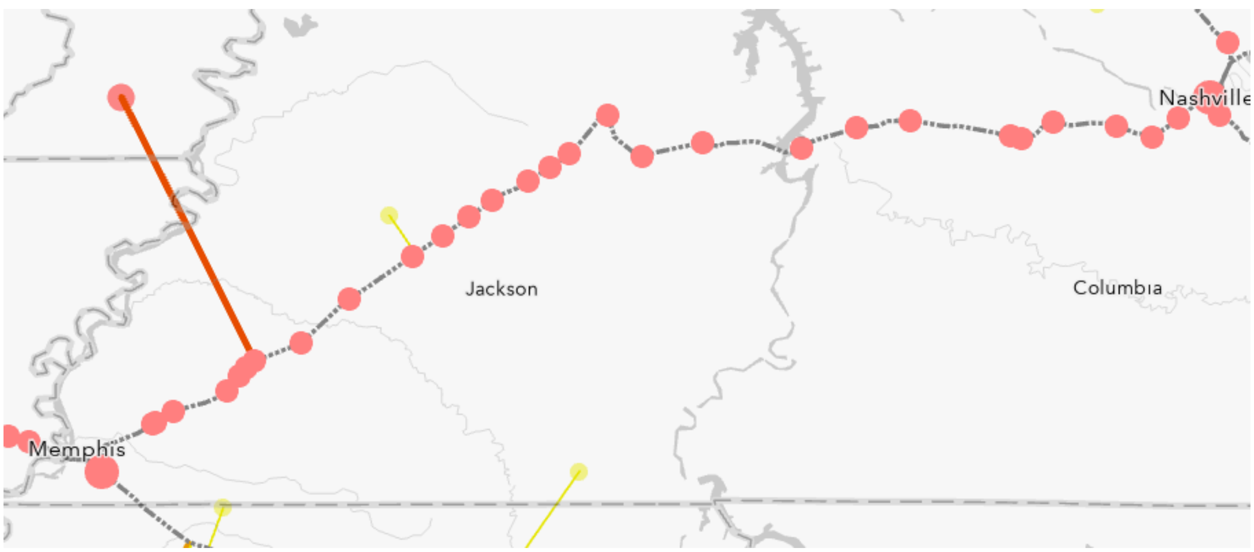


Figure 12: Rail Length between Memphis & Nashville. Supply to Demand Ratio is very low at 0.06.

We arrive at 17 Rail Corridors a shown below [Figure 13]. These are derived by creating a network for analysis. The corridors are selected by running the shortest paths between two cities in order to minimize the cost of length of the transmission.

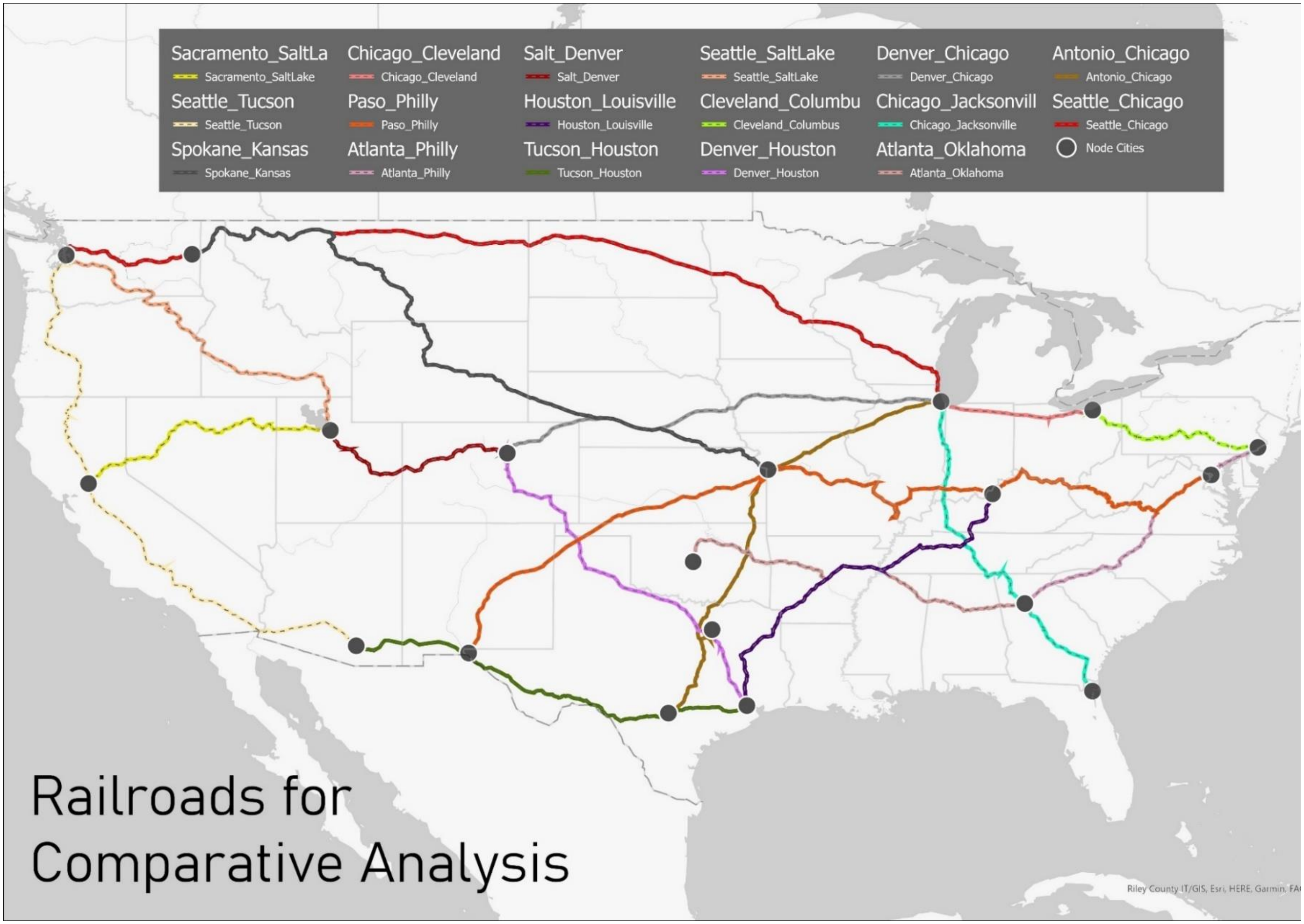


Figure 13: Seventeen Rail Corridors selected for final analysis.

Post the identification of anchor nodes, the cities on the line and within a 10-mile buffer are considered for demand calculations. An overlay analysis is conducted to separate our demand sample. A better method would be to identify the transmission overlays and the concurrent connections to the transmission but without information on the directed network, the methodology will prove to be difficult to arrive at conclusive results. As a result, a simple geographic overlay is considered to define our demand sample.

To identify the replacement capacity of a line to mitigate energy produced through conventional fossil fuel plants we select a subsection of fossil fuel powered plants further devolved to represent only those within a 60-mile buffer. This 60-mile buffer is derived from the average distance to transmission exhibited by all the utility scale farms we will select in the next section. For any plant within this buffer, it will make more sense from the perspective of renewable transition to have its transmission connected either to a destination or to the HVDC line [Figure 14]. Many of the plants in the Midwest have a good city to plant replacement ratio.

The geometry of the rail lines is extremely complicated. In order to make it easier for analysis, they were simplified to reduce pseudo nodes and simultaneously reduce the complexity of intersections with multiple lines into single nodes. This was done using the sfnetworks tidygraph R package. The Douglas-Peucker Algorithm was utilized to simplify the lines. It is a n iterative algorithm that splits a line segment, analyzes the geometry and recreates the nodes. A sample of the simplification for the Kansas City, Kansas area are showed below [Figure 16]. The number of nodes and lines are reduced from 254,319 and 263202 to 17,332 and 19456 respectively.

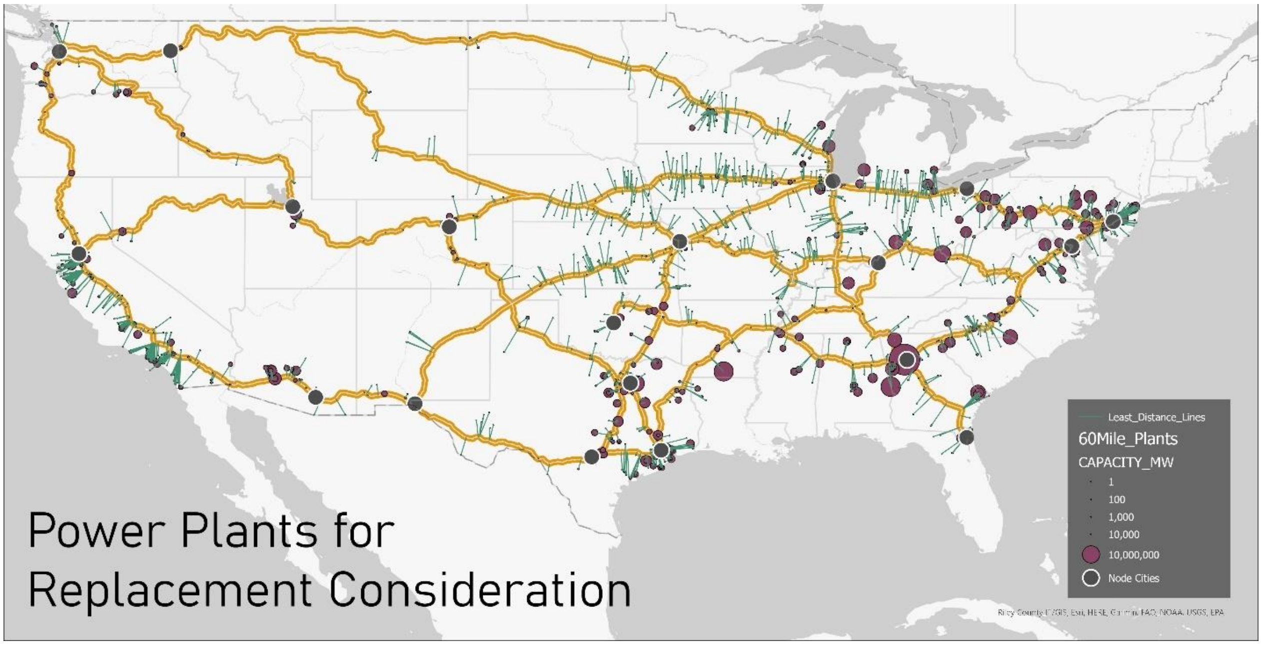


Figure 14: Power plants within a 60 - mile buffer of the selected rail corridors.

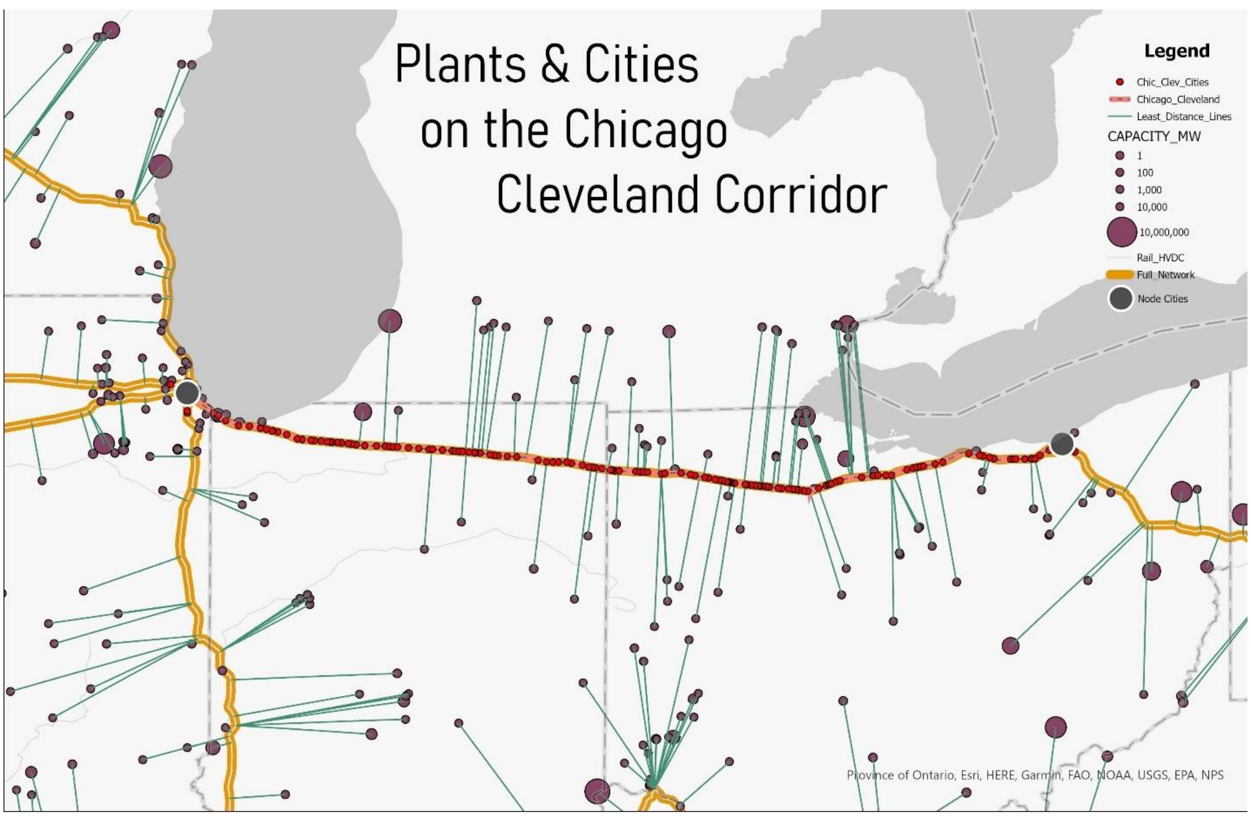
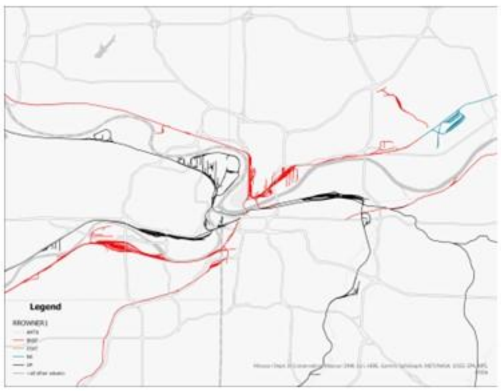
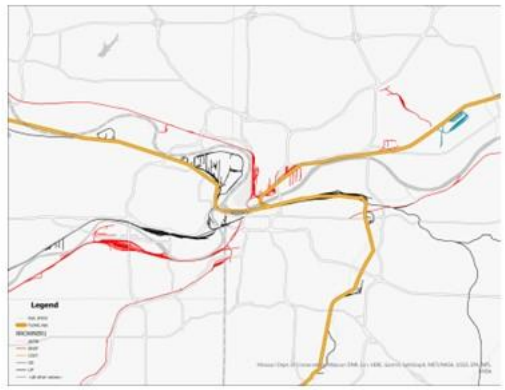


Figure 15: Mapping the Cities and the Power Plants that are mapped to the Chicago - Cleveland Corridor.

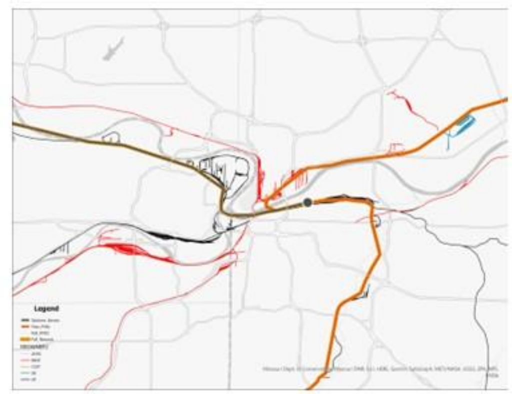
Topology Correction of Rail Corridors



In Kansas City, Union Pacific, Burlington North & Santa Fe, Norfolk Southern Railways meet. They have complex geometries with several ancillary nodes which are not required.



The Network is selected by smoothing Pseudo-Nodes, removing duplicate edges and selecting the shortest paths between cities.



The Kansas City, KA node is shown along with the El-Paso to Philadelphia Route and the Spokane to Kansas City Route.

Figure 16: Douglass - Peucker Algorithm applied to the Class I railroad geometry to simplify the network for running analysis.

Raster Analysis

While the NREL Solar Supply Curves take note of exclusions, the dataset was tested with the different raster datasets that were collected previously [Table 1]. It was found that several exclusionary datasets overlapped with areas indicated as potential sites for solar farms [Figure 17: Exclusions where Solar Farms cannot be developed. These are based on practical difficulties that have been captured in the literature.. I arrived at the conclusion that the Solar Supply Curves needed to be further narrowed down in order to ascertain a more conservative estimate of solar capacity. This process was undertaken by constructing a logical diagram. Datasets were divided into exclusions and penalties. Exclusions consisted of: -

Water features with a 1-mile buffer - This is done in order to mitigate any potential watershed flooding and other hydro-geological features.

Urban areas with a 2-mile buffer - Reports show that there is widespread concern of corruption of landscapes and fear of new technology such as utility-scale farms. Additionally, the cost of land in the periphery of urban and suburban areas would be prohibitive for utility-scale farm development [Yenneti, 2016].

Protected Forests – Several national protected forest areas and reserves exist especially in the southern US and the Sierra Nevada range. No development can be undertaken in these areas.

Tribal and Indigenous Reservations – These are federally protected lands with indigenous control of the decision-making process. These semi-autonomous regions have different political structures and may not be fully compatible with large-scale capital investment.

Therefore, these are occluded. Additionally, it is found that only a few of the major tribal sub-divisions have feasible utility-scale potential.

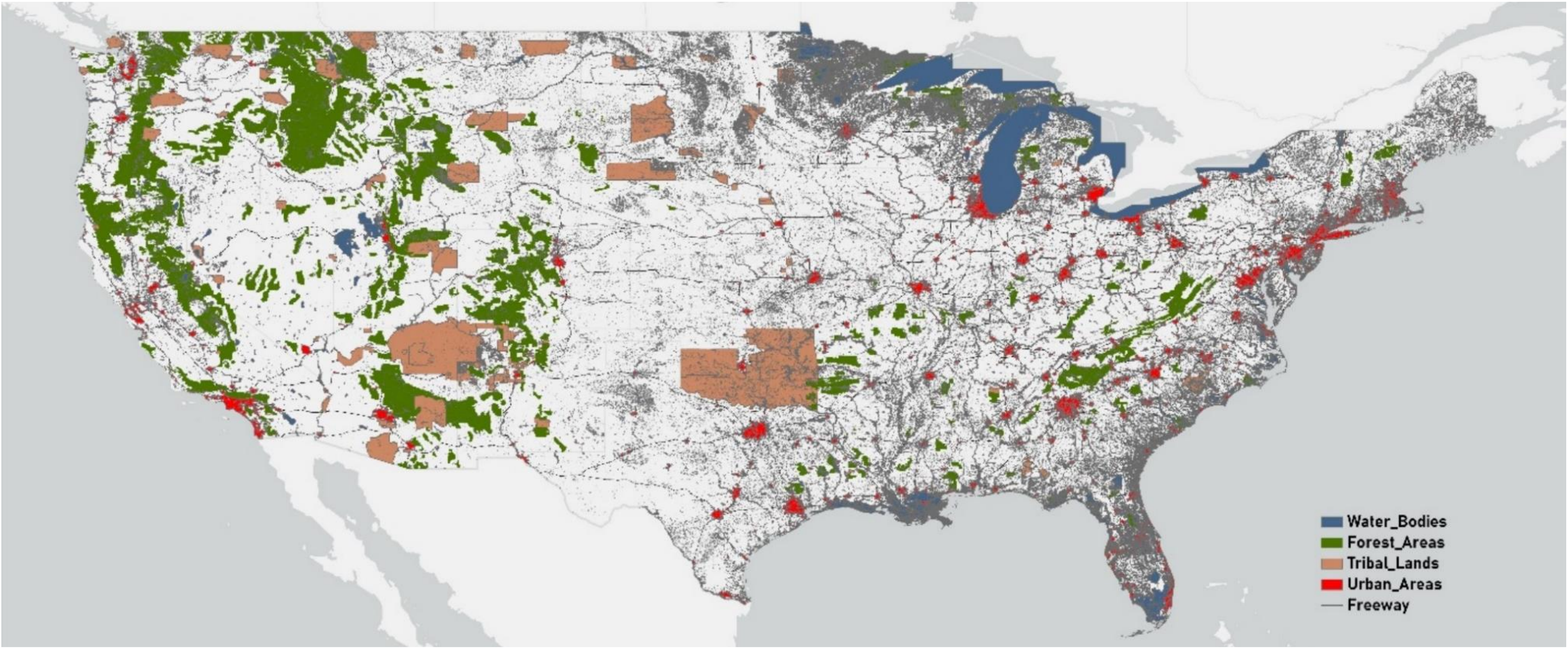


Figure 17: Exclusions where Solar Farms cannot be developed. These are based on practical difficulties that have been captured in the literature.

The image shows all the exclusions overlaid [Figure 17]. They form a significant chunk of the contiguous land area of the US especially where solar potential is abundant.

Penalties consist of largely a geospatial translation of popular movements. The conversion of non-protected forest land continues to be a divisive issue with many local jurisdictions expressing concern. Additionally, conversion of cropland is also contested since the loss of arable land is a serious concern amongst rural communities as discussed in the overview. Farms sited in Forestland or on Cropland are not excluded as that would prove unfeasible in terms of transitioning to a net-zero economy. Instead, a 20% deduction in terms of Capacity of Solar Energy produced by a farm is levied. No literature exists as this refers to a quantitative translation of a social barrier and is additionally a reasonable phenomenon and cannot be standardized across regions. Barrier to development in one out of every parcel is assumed for this problem.

The diagram below showcases a logical construct of each process undertaken [Figure 18]. Solar Points which overlap with any of the exclusions are clipped and excluded. For points overlapping with forests or cropland, field containing the Nameplate Capacity in Megawatt-hour is subjected to a 20% reduction.

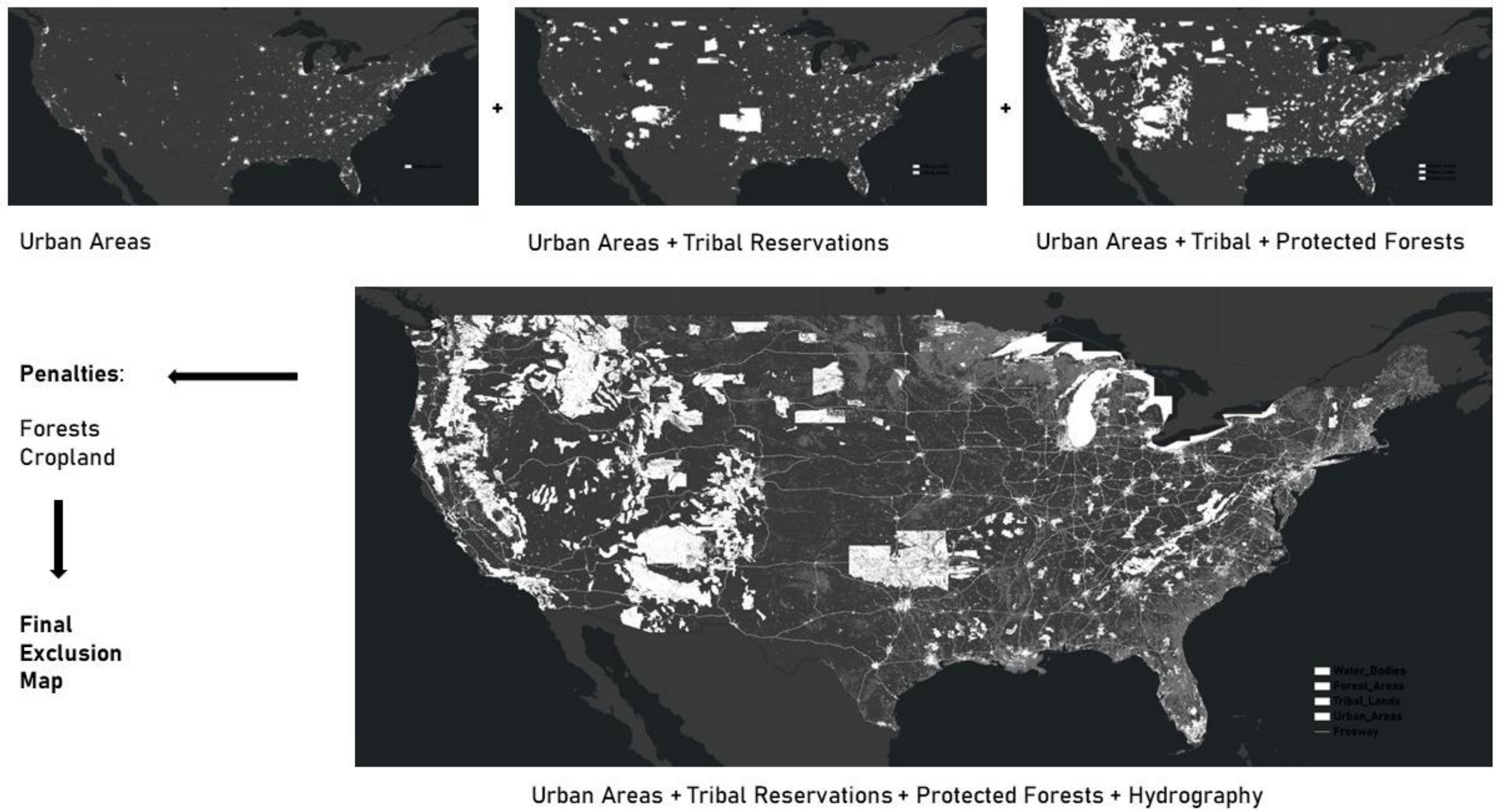


Figure 18: A series of maps showcase exclusions overlaid one on top of another to clearly mark areas that can be allowed for development.

At this stage the data required for further analysis and the identification of supply clusters is ready.

Energy Calculations

With the various point geometries assigned to each of our selected rail corridors, we have several data points with which to develop our measures for analysis. As described in the Data section, the NREL supply curves provide information on how much energy can be produced and which are the area's most feasible for farm development. Each point is a spatial representation of a potential polygonal geometry farm. The supply curve refers to the potential of each point.

The Actual Capacity of each supply point is calculated using the Capacity Factor and the Nameplate Capacity of each entity. Unlike conventional power plants, solar power plants present a unique challenge in terms of Annual Energy Output. The geography of our study area covers the contagious USA which has several different climate zones as described by the Department of Energy [Kim & Kim, 2018]. These impact the sunshine hours available. An integral metric of the feasibility of a solar farm is the average annual sunshine hours. While it is impossible to predict in advance cloudy days, it is possible to understand what the projected number of sunshine hours per year is from years of weather data [Stanhill, 2005]. The average number of sunshine hours for each state is provided below [Table 3].

State	% Sun	Total Hours	Clear Days	State	% Sun	Total Hours	Clear Days	State	% Sun	Total Hours	Clear Days
Alabama	58	2641	99	Kentucky	56	2514	93	Ohio	50	2183	72
North Dakota	59	2738	93	Louisiana	57	2649	101	Oklahoma	68	3089	139
Arizona	85	3806	193	Maine	57	2513	101	Oregon	48	2341	68
Arkansas	61	2771	123	Maryland	57	2582	105	Pennsylvania	58	2614	87
California	68	3055	146	Massachusetts	58	2634	98	Rhode Island	58	2606	98
Colorado	71	3204	136	Michigan	51	2392	71	South Carolina	64	2826	115
Connecticut	56	2585	82	Minnesota	58	2711	95	South Dakota	63	2947	104
Delaware	48	2145	97	Mississippi	61	2720	111	Tennessee	56	2510	102
Florida	66	2927	101	Missouri	60	2690	115	Texas	61	2850	135
Georgia	66	2986	112	Montana	59	2698	82	Utah	66	3029	125
North Carolina	60	2651	109	Nebraska	61	2762	117	Vermont	49	2295	58
Idaho	64	2993	120	Nevada	79	3646	158	Virginia	63	2829	100
Illinois	56	2567	95	New Hampshire	54	2519	90	Washington	47	2170	58
Indiana	55	2440	88	New Jersey	56	2499	94	West Virginia	63	2829	60
Iowa	59	2691	105	New Mexico	76	3415	167	Wisconsin	54	2428	89
Kansas	65	2922	128	New York	46	2120	63	Wyoming	68	3073	114

Table 3: Average number of Sunshine hours in each stat. Cloudy days on average from the last forty years have been averaged. Source: Weather.com.

For each of our supply point geometries, we calculate the total annual capacity [Equation 1: Calculations for Solar Capacity for Individual Farms.

$$ActualCapacity \ = \ CapacityFactor * Nameplate\ Capacity * Annual\ Sunshine\ Hours$$

Equation 1: Calculations for Solar Capacity for Individual Farms.

For instance, for a projected NREL supply point solar farm near El Paso Texas which has 2800 Annual Sunshine Hours, the actual capacity is 260 MWh though it has a nameplate capacity of 600 MW. The Capacity Factor is 0.4. The mapping of the Capacity Factors is clearly outlined in the methodology for the NREL data source.

Supply is variably distributed as expected. As shown in the map below [Figure 19], the states of Texas, New Mexico have the highest supply of points with potentials upward of 180 MW. Name Plate Capacity of each supply point which is less than 180 MW is removed since it would not be useful in terms of actual capacity for utility scale development. Texas therefore seems to be one of the most powerful states in terms of energy for renewable and conventional fossil fuel sources.

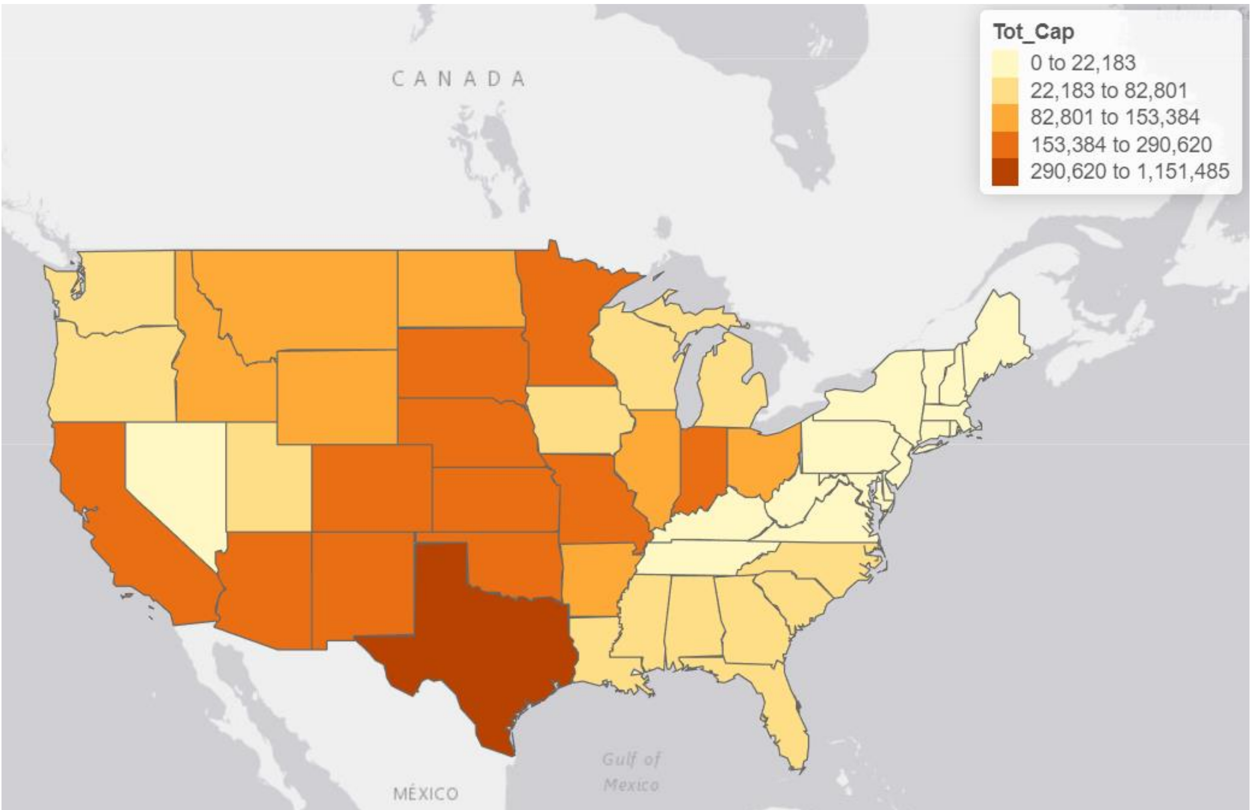


Figure 19: Total Solar Capacity in each state of the US. Texas & New Mexico have the highest capacities. Surprisingly the States of Indiana and Ohio have a lot of capacity as well due to the low slope average of 5% being an asset for large scale farm development.

The NREL 2016 City and County Profile as described above in the data section provides a large amount of data that we utilize in the preparation of our demand side measures. The total greenhouse gas emissions, percentage of consumption by sector, per capita and per household unit measures are derived. The following series of formulas describe all the measures that are calculated [

$$TGHG_i = \sum_i [GHG(RE)_i + GHG(CE)_i + GHG(IE)_i + [(ING_i + CNG_i + RNG_i) * EF_{natural\ gas} + GHG(P)_i * EF_{petrol} + GHG(D)_i * EF_{diesel}$$

$$i = City1,\ City2,\ City3 \ldots.\ k$$

$$where\ TGHG = Total\ Greenhouse\ Gas\ Emissions\ in\ Mega\ Tons\ of\ Carbon\ Dioxide\ Equivalent,$$

$$GHG(RE)_i = Total\ Greenhouse\ Gas\ Emissions\ in\ Mega\ Tons\ of\ Carbon\ Dioxide\ Equivalent\ from\ Residential\ Electricty\ Consumption,$$

$$GHG(CE)_i = Total\ Greenhouse\ Gas\ Emissions\ in\ Mega\ Tons\ of\ Carbon\ Dioxide\ Equivalent\ from\ Commercial\ Electricty\ Consumption,$$

$$GHG(IE)_i = Total\ Greenhouse\ Gas\ Emissions\ in\ Mega\ Tons\ of\ Carbon\ Dioxide\ Equivalent\ from\ Industrial\ Electricty\ Consumption,$$

$$ING = Industrial\ Natural\ Gas\ Consumption\ in\ Trillion\ Cubic\ Feet,$$

$$CNG = Commercial\ Natural\ Gas\ Consumption\ in\ Trillion\ Cubic\ Feet,$$

$$RNG = Residential\ Natural\ Gas\ Consumption\ in\ Trillion\ Cubic\ Feet,$$

$$Emission\ Factors;\ (EF_{natural\ gas} = 0.054981\ ,\ EF_{petrol} = 0.010795,\ EF_{diesel} = 0.012655,)$$

Equation 2: Total Greenhouse Gas Emissions in Megatons of Carbon dioxide Equivalent for a city.

$$TCFuels_i = \sum_i \left[ELP_i * 0.0366 + ELD_i * 0.0407 + \left[(ING_i + CNG_i + RNG_i) * 0.00029 * 10^{-12} \right] \right],$$

$$i = City1,\ City2,\ City3 \ldots.\ k$$

$$where\ TC = Total\ Consumption\ of\ Fuels,$$

$$ELP = Electricity\ in\ MWh\ of\ utilized\ Petrol,$$

$$ELD = Electricity\ in\ MWh\ of\ utilized\ Diesel,$$

$$ING = Industrial\ Natural\ Gas\ Consumption\ in\ Trillion\ Cubic\ Feet\ converted\ to\ Electricity\ in\ MWh,$$

$$CNG = Commercial\ Natural\ Gas\ Consumption\ in\ Trillion\ Cubic\ Feet\ converted\ to\ Electricity\ in\ MWh,$$

$$RNG = Residential\ Natural\ Gas\ Consumption\ in\ Trillion\ Cubic\ Feet\ converted\ to\ Electricity\ in\ MWh,$$

Equation 3: Total Consumption of a city annually in Megawatt-hours for Natural Gas, Petroleum and Diesel.

$$TC_i = \sum_i (RE_i + CE_i + IE_i),\ i = City1,\ City2,\ City3 \ldots\ k$$
$$\begin{aligned} \text{where } TC &= Total\ Consumption\ pre\ Transport\ Electrification\ , \\ RE &= Residential\ Sector\ Consumption\ in\ MWh, \\ CE &= Commercial\ Sector\ Consumption\ in\ MWh, \\ IE &= Industrial\ Sector\ Consumption\ in\ MWh; \end{aligned}$$

Equation 4: Total Consumption of a city annually in Electricity Megawatt-hours from Residential, Commercial and Industrial consumption.

$$Total\ Consumption\ (MWh) = \sum_i (TCFuels_i + TC_i),$$
$$i = City1,\ City2,\ City3 \ldots\ k,$$
$$\text{where } TCFuels_i = Total\ Consumption\ of\ Fuels,$$
$$\text{where } TC_i = Total\ Consumption,$$

Equation 5: Total Consumption in Megawatt-hours including fuels and electricity annually.

Cluster Analysis

Currently we have all our geometries in single point shapefiles. For the purpose of our analysis, conserving this format would be counterproductive as we would like to understand where the regions with highest potential for utility scale solar farms exist and how they correspond with our rail corridors. This is so because this project is oriented towards understanding which transmission line maximum projects can be connected to as opposed to individual siting and identification for a prospective developer. This is based upon the premise that most utility farms will be in feasible areas where clustering provides the benefit of making long distance energy transmission financially feasible.

The **DBSCAN Cluster Methodology** is used for our analysis and creation of clusters. THE DBSCAN Methodology is a density-based clustering method that assumes that some points in space are more closely situated than other points. As such, it is a methodology that is best suited when we wanted to identify high density clusters in contrast to regions of low density. We use a cluster tolerance of 5 points to ensure that we have a minimum capacity of at least 100MW. The latter metric is arrived at based on the calculation of actual capacity of farms based on the capacity factor and nameplate capacity calculations. For farms with a 180 MW rating, a cluster of five farms is the smallest grouping that provides a 100 MW. It is important to note that here we are not describing a utility-based farm as being 100 MW in capacity at a minimum which is not the right value since most utility scale farms have 5 MW capacities on average [Slusarewicz & Cohen, 2018]. Instead, we make the argument that a 100MW capacity improves the ability for multiple privately owned farms to be clustered together. Using this tolerance, we generate cluster maps for each of our 180 – 300 MW, 300 – 450 MW and 450 Plus MW categories [Figure 21]. One cluster pertaining to the entire State of Texas was removed since it constitutes an unfeasible scenario of utility development.

The clusters generated need to be converted to polygon vectors for analysis. These polygons need to correspond to an area that roughly captures the area represented by each of these points. A spatial join methodology is used to isolate the Solar Supply Points associated with each cluster and assign them their respective Cluster ID. Once this has been achieved, we need to create polygons such that each polygon covers the entirety of the points in the cluster while simultaneously ensuring that a straight line drawn between any pairs of points does not cross the boundary of the polygon. The Convex Hull is the geometric representation of this logic. Convex Hulls are generated for each of the clusters. The total energy capacity in each cluster is calculated by the summation of the actual annual capacities of each of the points within the clusters determined by a spatial join [Equation 6: Total Solar Energy produced in Megawatt-hours annually for any of the three cluster categories.

$$Total\ Cluster\ Capacity\ =\ \sum_{i}(CapacityFactor * Nameplate\ Capacity * Annual\ Sunshine\ Hours),$$

$$i = City1, City2 \ldots k$$

Equation 6: Total Solar Energy produced in Megawatt-hours annually for any of the three cluster categories.

Here, total cluster capacity refers to one corridor. The same mathematical definition follows for the power plants mapped to a corridor as well. A representation of the actual convex hull polygon representations of each cluster is shown below. Additionally, each of the clusters have varying capacities since they cover different amounts of areas. The distribution is also visualized for greater detail. Of note, are the several high priority zones that abound near the Chicago to Cleveland Corridor. A HVDC line [SOO – Link] already exists in the region to carry Iowa wind power to the Great Lakes region Metro Areas as described in literature section [Figure 20]

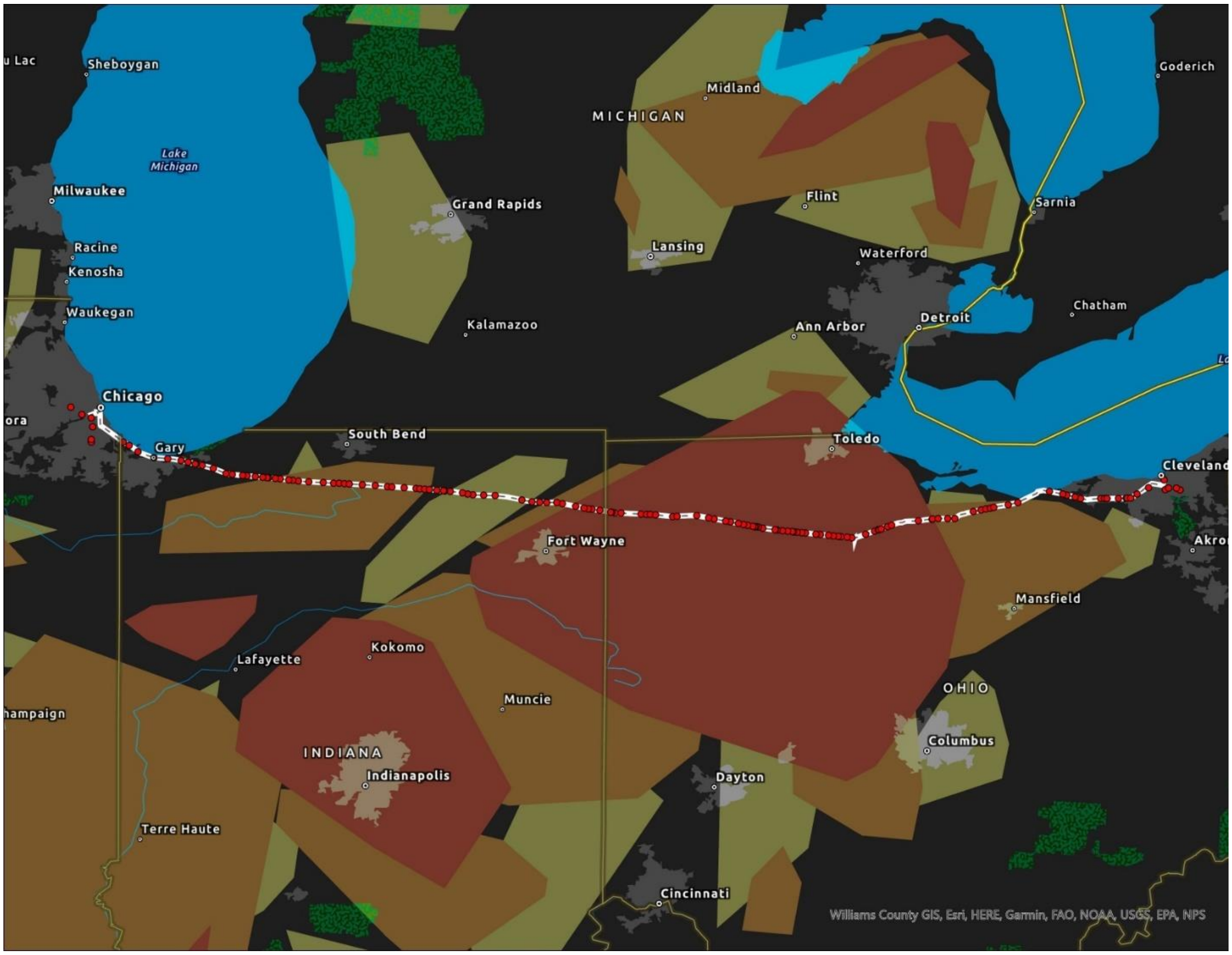


Figure 20: Clusters near the Chicago - Cleveland Corridor with Cities on the Corridor mapped. Note the large 450 MW Nameplate Cluster with Fort Wayne, Toledo and Columbus as anchors.

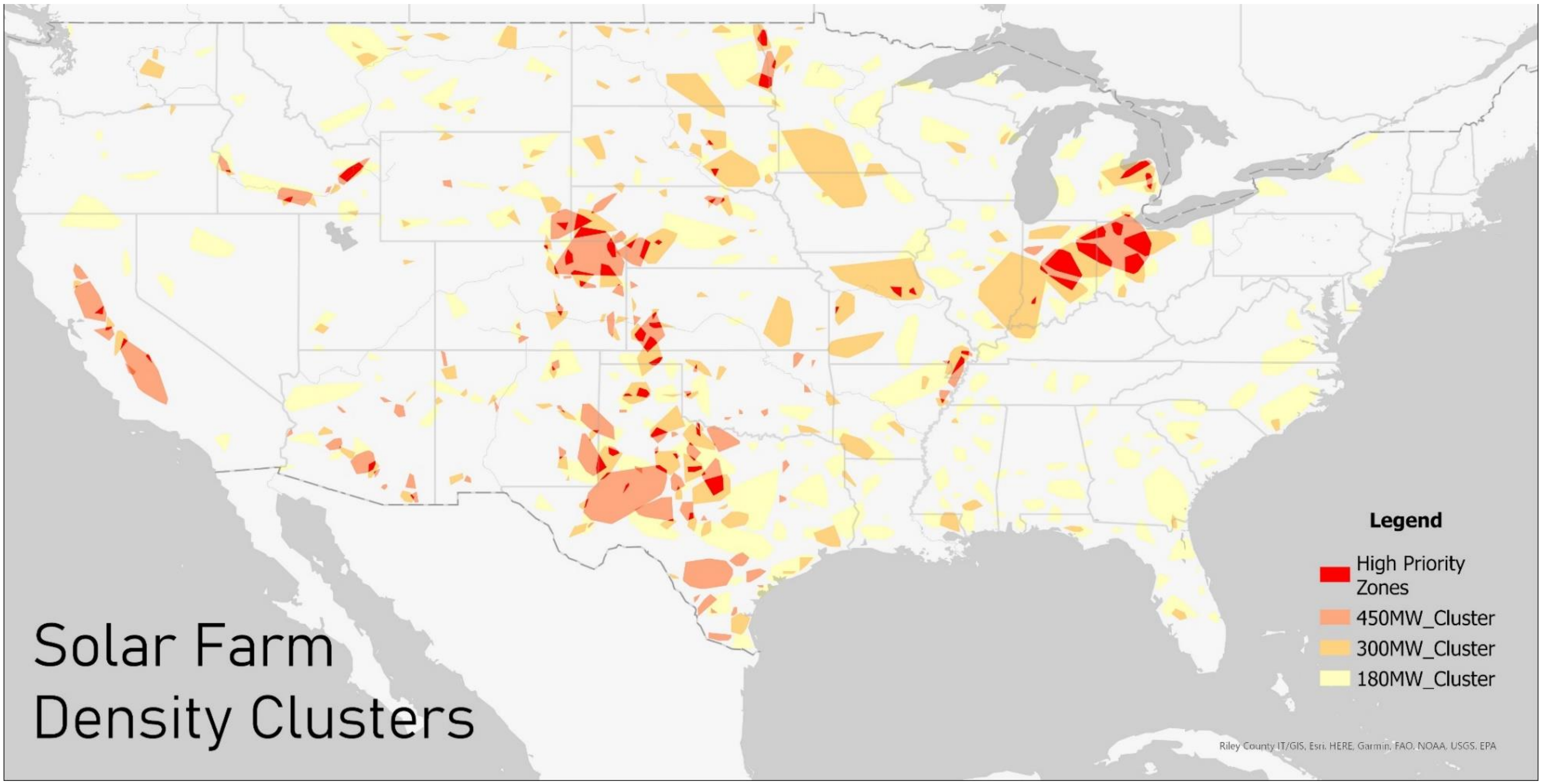


Figure 21: Solar Farm Clusters in all categories across the USA.

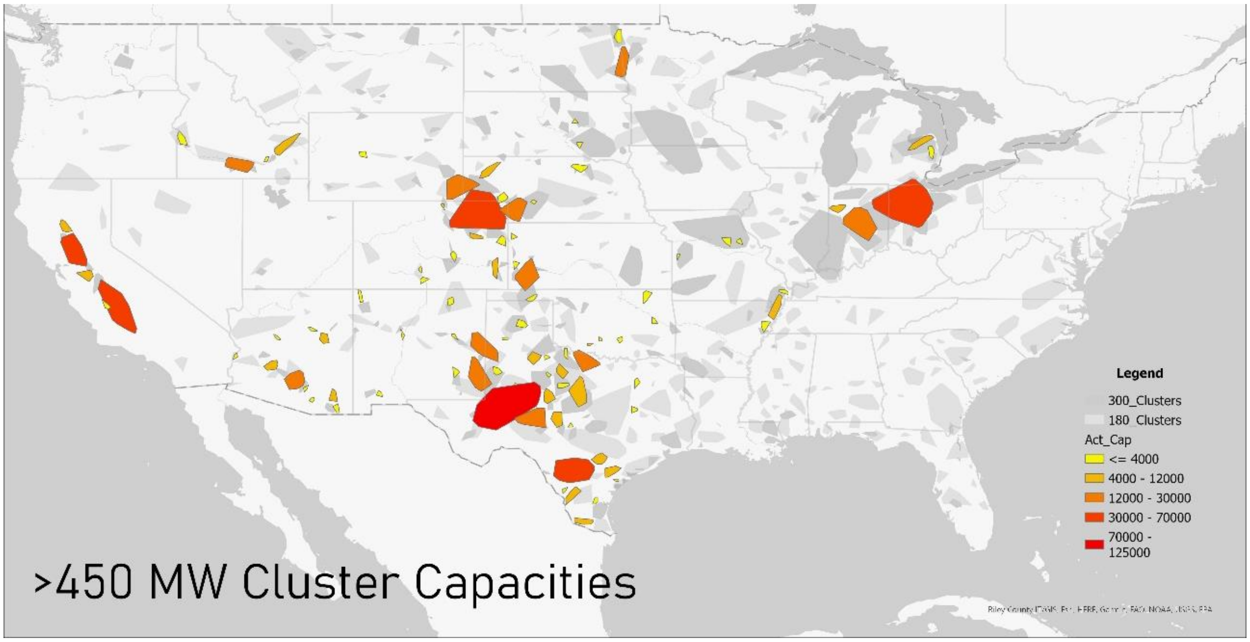


Figure 22: 450 MW Clusters. These are the areas with the highest concentration of big utility scale farm development.

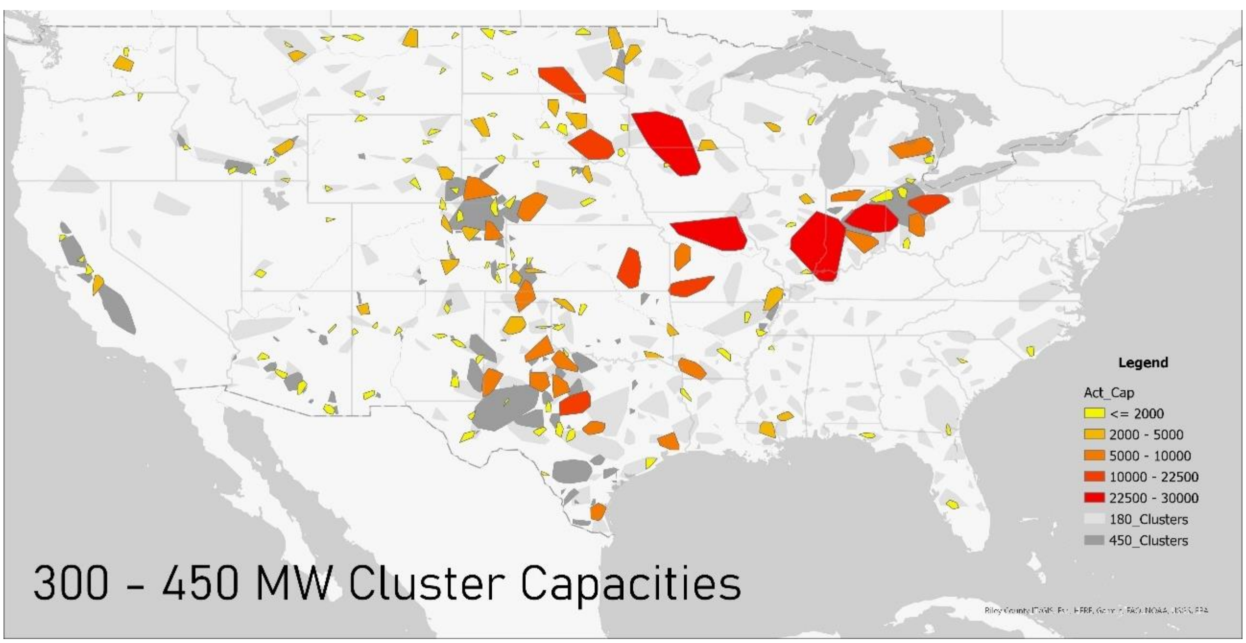


Figure 23: 300 - 450 MW Nameplate Capacity Farm Clusters. Note how the largest clusters with greatest capacities are in the Midwest region as opposed to the Southern US.

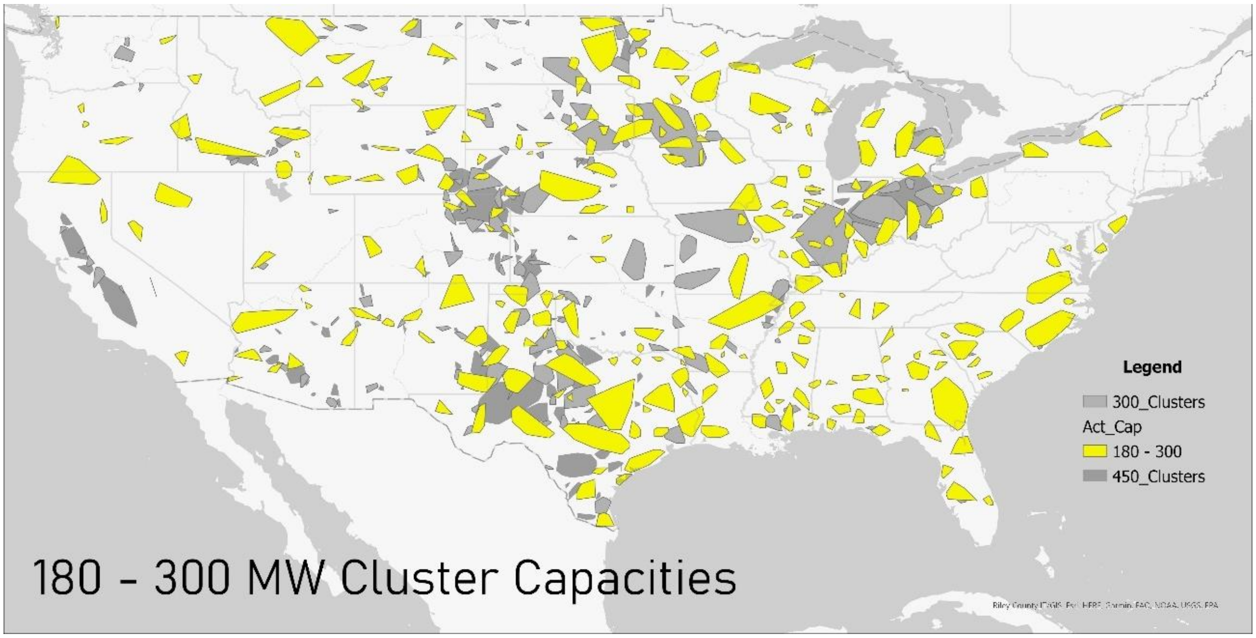


Figure 24: 180 - 300 MW Nameplate Capacity farms. There are clusters also in the Eastern US which promotes the opportunity for Community Farms.

Another important aspect of understanding the geographic outlay of potential farm areas is to identify the areas with equal access to the different energy categories. This can be identified by creating a spatial shapefile of overlaps. These spaces signify the ability for a potential rail line corridor to connect to multiple areas with a single transmission extension. These have been marked as High Priority Zones. **There are 99 High Priority Zones.**

Proximity Analysis

Now that we have generated clusters, these clusters need to be assigned to their nearest rail corridors under consideration. We utilize clusters as opposed to individual supply curve points, as it gives a decision maker easier ability to identify zones of interest. Note that the end user of this document is not the private developer but the federal authority such as the National Energy Regions Commission.

The centroid of each cluster amongst all three categories is generated. The centroids are used as the proxy point geometries for assigning the nearest rail corridor to each cluster [Figure 25]. This is based on the nearest neighbor analysis with centroids as the input geometries and the rail polylines as the target geometry. Each centroid is then assigned to its nearest rail polyline [Figure 26]. This provides the understanding of how many potential farm locations could be accessed by a particular corridor. We find that the distribution of different clusters varies amongst the corridors.

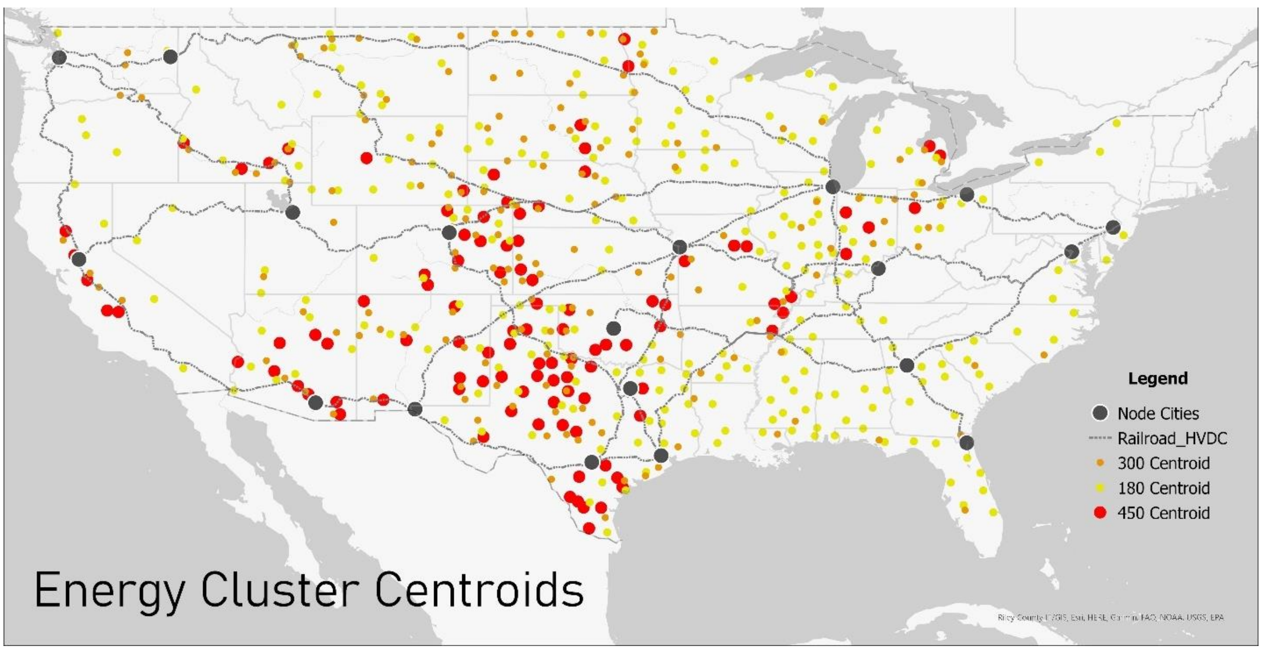


Figure 25: Energy Cluster Centroids for each of the zones.

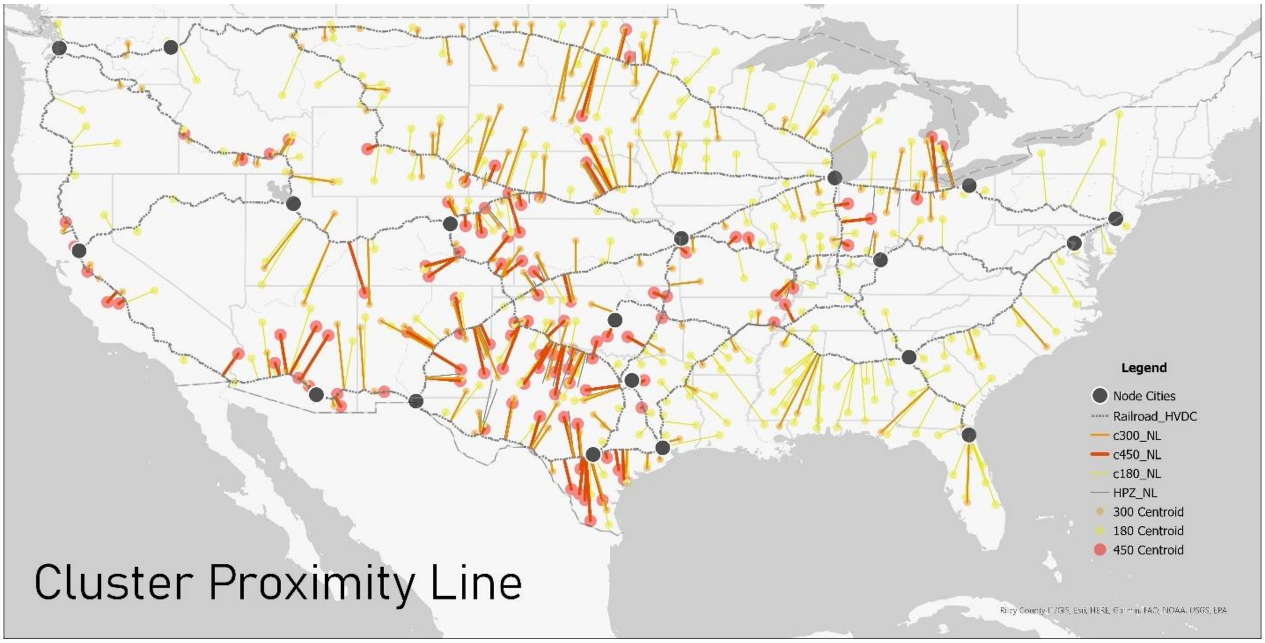


Figure 26: Energy cluster Centroids mapped to their rail corridor based on proximity. Each centroid is assigned to one corridor.

We also need to find the replacement capacity of the corridor i.e., the amount of energy produced by fossil fuel powered plants that could be potentially replaced by HVDC transmission along this railway line. A proximity nearest neighbor analysis is utilized to assign power plants to their corresponding nearest rail line. We find that most of the plants are in the Northeast region in concurrence with the idea that in energy generation strategies where fuel can be moved, plants locate themselves near population centers to restrict transmission losses [Figure 27].

CORRIDOR	NF180MW	NF300MW	NF450MW
Sacramento_SaltLakeCity	11	0	0
Seattle_Tucson	53	29	191
Seattle_KansasCity	232	103	55
Chicago_Cleveland	77	163	147
ElPaso_WashingtonDC	320	184	126
Atlanta_Philadelphia	131	5	0
SaltLakeCity_Denver	9	12	3
Houston_Louisville	265	52	20
Tucson_Houston	96	60	409
Seattle_SaltLakeCity	47	18	45
Cleveland_Philadelphia	32	0	0
Denver_Houston	133	113	107
Denver_Chicago	154	227	147
Chicago_Jacksonville	236	140	59
Atlanta_Oklahoma	176	26	1
SanAntonio_Chicago	203	194	34
Seattle_Chicago	287	160	27
Mean	144.82	87.41	80.65
Standard Deviation	97.04	75.38	101.33

Table 4:Number of Farms in each city.

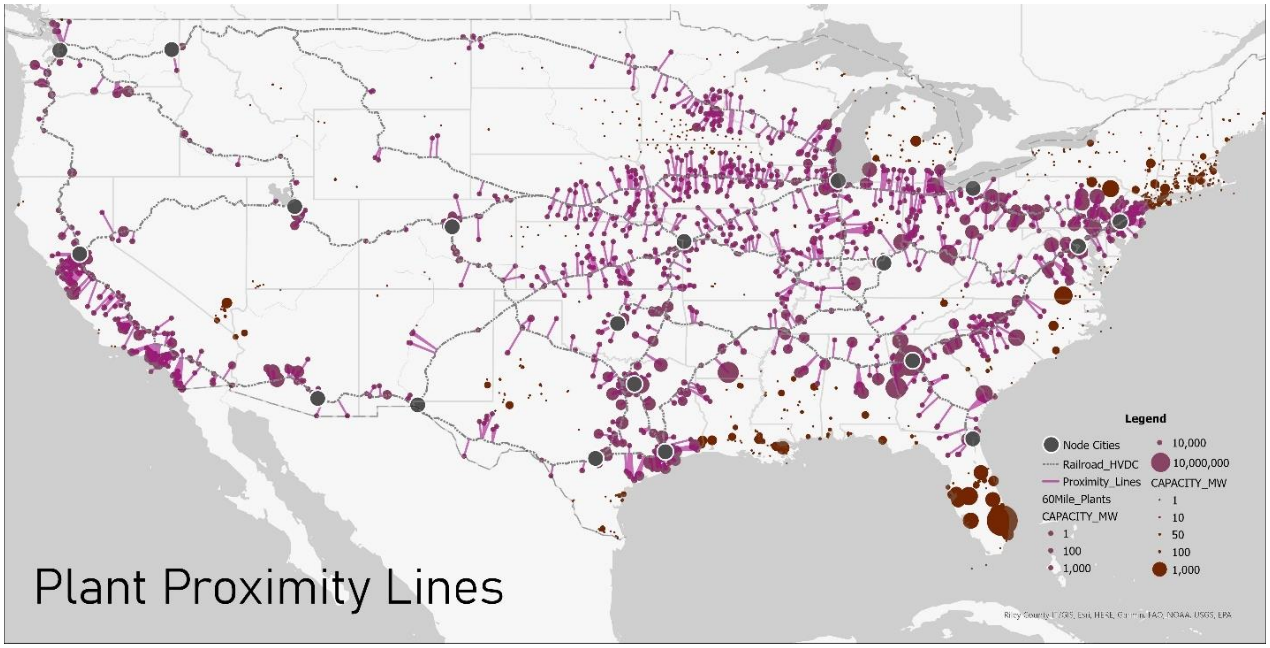


Figure 27: Conventional fuel power plants mapped to their corridor of nearest proximity. Their nameplate capacity summation is required to calculate the total replacement potential that a corridor has in terms of replacing conventional fuels.

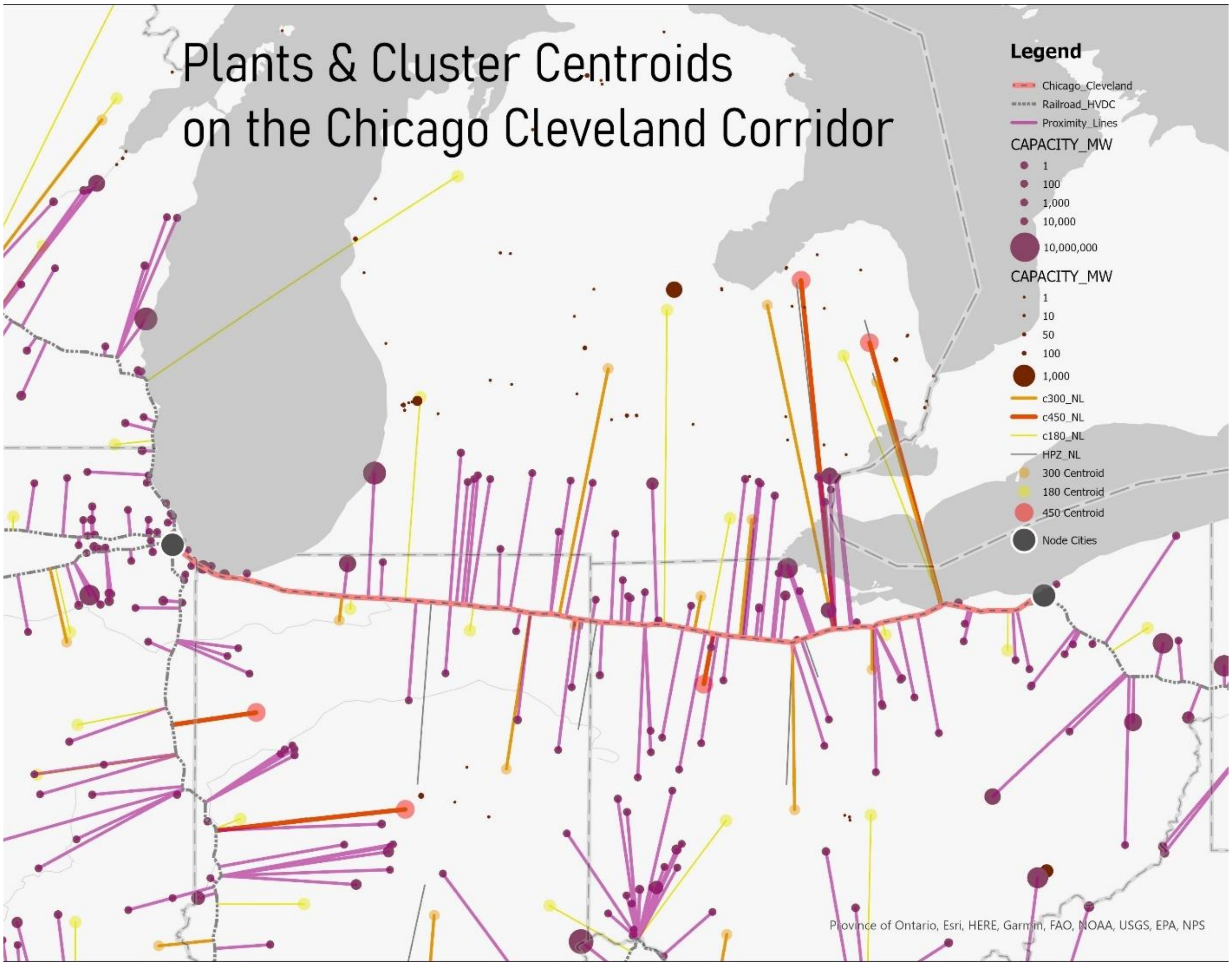


Figure 28: Chicago - Cleveland Corridor with the proximity lines mapped.

A closer look at the Chicago- Cleveland Corridor is shown above. All the proximity lines are mapped with their origins [Figure 28].

Intersections Analysis

The distributive capacity of a corridor is determined based on how many HVAC lines intersect with it in the Voltage Class range of 330 – 760 Kilovolts. This provides the opportunity for future expansion to consider existing transmission lines. We find that there is an even distribution [Figure 29]. A segregated analysis of each can be found in Appendix A Sheet 2 for each corridor.

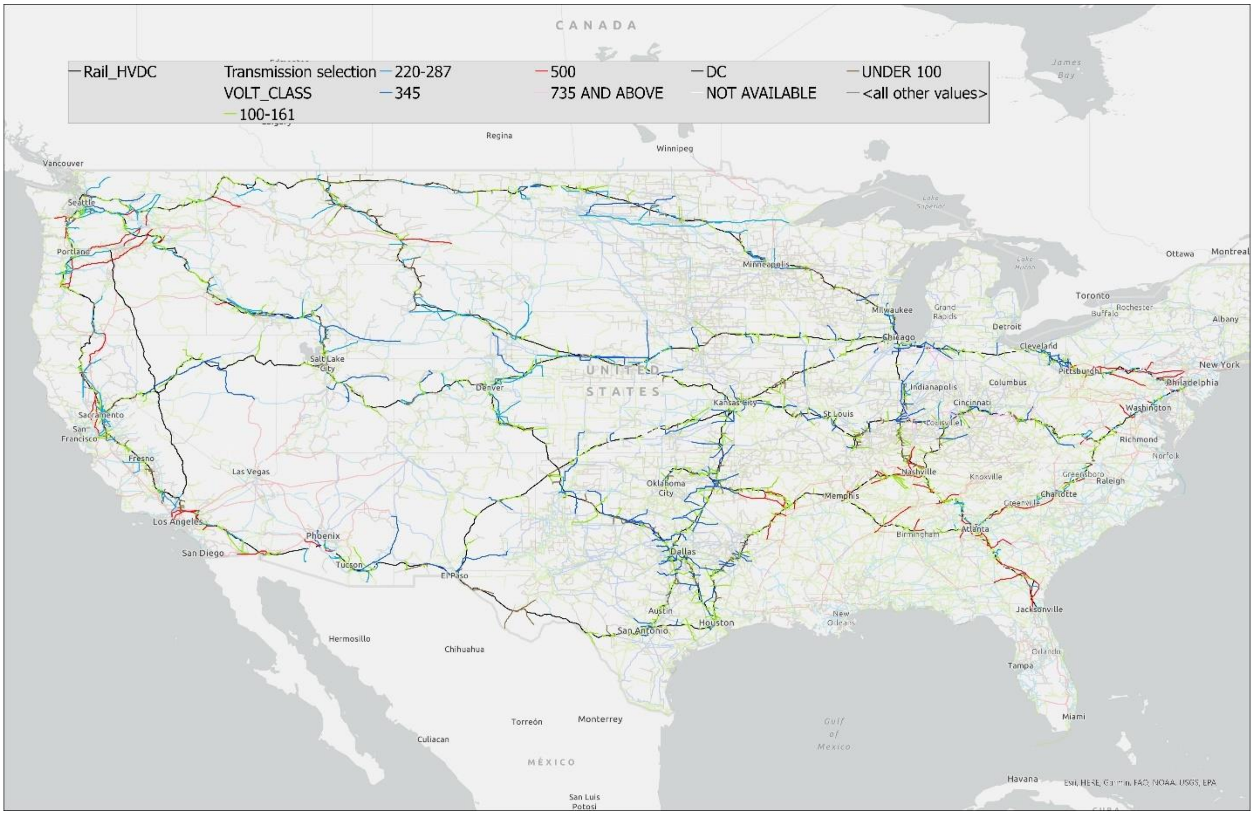


Figure 29: Existing High Voltage AC Transmission Lines intersecting with Rail Corridors.

While the previous intersection focused online geometries, we also need to identify the electrical transmission areas that a particular corridor traverses along with the states which all have a say in how the transmission line is built and administered. This requires a spatial overlap segmentation of the polygon geometries. The figures below showcase the states the States that the El Paso - Philadelphia rail corridor passes through [Figure 30,Figure 31].

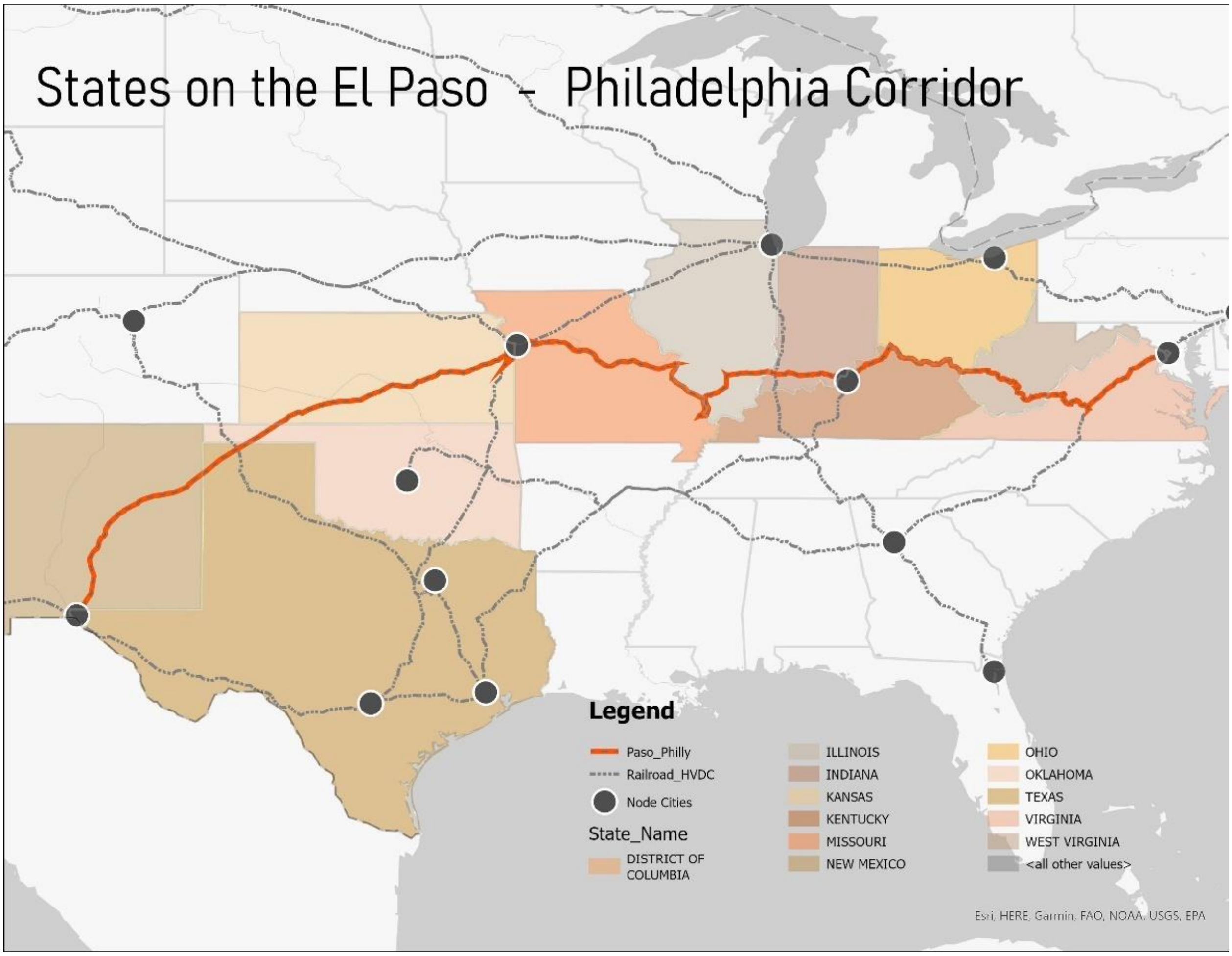


Figure 30: States that intersect with the El Paso - Philadelphia Corridor.

Figure 31: Electric Transmission Planning Areas that intersect with the El Paso - Philadelphia Corridor. Each of these Planning Areas have different regulations and coordination between them is currently a challenge.

Comparative Analysis

This stage of the process concerns itself with a summation of the various metrics associated with each corridor. The measures that can be best used to quantify the ability and potential of a railroad corridor to serve as efficient infrastructure has been delineated in the problem statement section. First, the supply and demand capacities are amalgamated to present a S/D Ratio which represents the total capacity of the corridor in terms of energy generation and consumption [Table 5].

Rail Corridor	States	Demand (Th- MWh)	Supply (Th-MWh)	Supply/Demand Ratio
Sacramento_SaltLakeCity	California_Utah	6097083.1	2305465.4	0.4
Seattle_Tucson	Washington_Arizona	266585612.0	410354559.0	1.5
Seattle_KansasCity	Washington_Kansas	19439933.4	232194337.4	11.9
Chicago_Cleveland	Illinois_Ohio	73643005.6	311346140.7	4.2
ElPaso_WashingtonDC	Texas_DC	189031839.5	403163143.7	2.1
Atlanta_Philadelphia	Georgia_Pennsylvania	291252603.6	10602019.1	0.0
SaltLakeCity_Denver	Utah_Colorado	40165253.6	20652219.6	0.5
Houston_Louisville	Texas_Kentucky	98932967.0	94981815.5	1.0
Tucson_Houston	Arizona_Texas	139468439.6	786459229.6	5.6
Seattle_SaltLakeCity	Washington_Utah	33347048.5	104249296.4	3.1
Cleveland_Philadelphia	Ohio_Pennsylvania	148462634.1	2350455.6	0.0
Denver_Houston	Colorado_Texas	122133211.6	320080081.7	2.6
Denver_Chicago	Colorado_Illinois	78555282.8	481561343.4	6.1
Chicago_Jacksonville	Illinois_Florida	165021751.4	229071425.5	1.4
Atlanta_Oklahoma	Georgia_Oklahoma	111313025.5	41010566.7	0.4
SanAntonio_Chicago	Texas_Illinois	171454546.6	283612542.4	1.7
Seattle_Chicago	Washington_Illinois	110888665.1	215701540.5	1.9

Table 5: List of Node Cities for selected Rial Corridors and their total supply capacities and demand needs mapped.

We have now completed the preprocessing that is required to arrive at the statistics for each corridor. In order to compare each corridor, each of these measures must be assigned credible weights that mimic their importance in planning the energy system. These weights are based on the literature reviewed and the relative importance of each measure outlined in the problem definition section. The assigned weights are outlined below [

Table 6].

Measure	Type	Weight	Unit / Unit Type
Intersections	Distributive	0.1	Count
Supply / Demand Ratio	Capacity	0.4	Ratio
Fossil-Fuel Powered Plant Capacity	Replacement	0.1	Megawatt Hours
No. of Farms	Distributive	0.1	Count
Total Greenhouse Gas Emissions	Replacement	0.1	Megatons of Carbon dioxide Equivalent
Number of Electric Transmission Planning Areas	Administrative	0.1	Count
Number of States	Administrative	0.05	Count
High Priority Zones	Capacity	0.05	Count

Table 6: Weights assigned to each measure for comparative analysis. The type of measure is also highlighted.

Since the units of each measure vary significantly, they need to be standardized to a comparable scale. We use the standard method of creating normalized z-scores to redefine the various measures [Equation 7].

$$Z = [M_i - \mu(M)] / \sigma(M),$$
$$i = Corridor1,\ Corridor2 \ldots\ k$$
$$M = Raw\ Measure$$

Equation 7: Conversion of Raw Measures to normalized Z-Scores.

The z -scores lie between the values of -1 to +1 with the mean at 0. They provide the comparison of the corridors with respect to the mean. Our interest lies in identifying the best outcomes in a manner that is comprehensible to the lay audience and therefore a scale of 0 to 100 is identified. Linear Transformation is undertaken to arrive at these values [Equation 8]. Post transformation, the assigned weights to each variable are applied to calculate a final standardized score [Equation 9].

$$T(Z_i) = [[Z_i - Min(Z)]*100] / [Max(Z) - Min(Z)]$$
$$i = Corridor1,\ Corridor2 \ldots\ k$$
$$Z = Normalized\ Z - Score$$

Equation 8: Linear Transformation of the derived Z-Scores for easier comprehension.

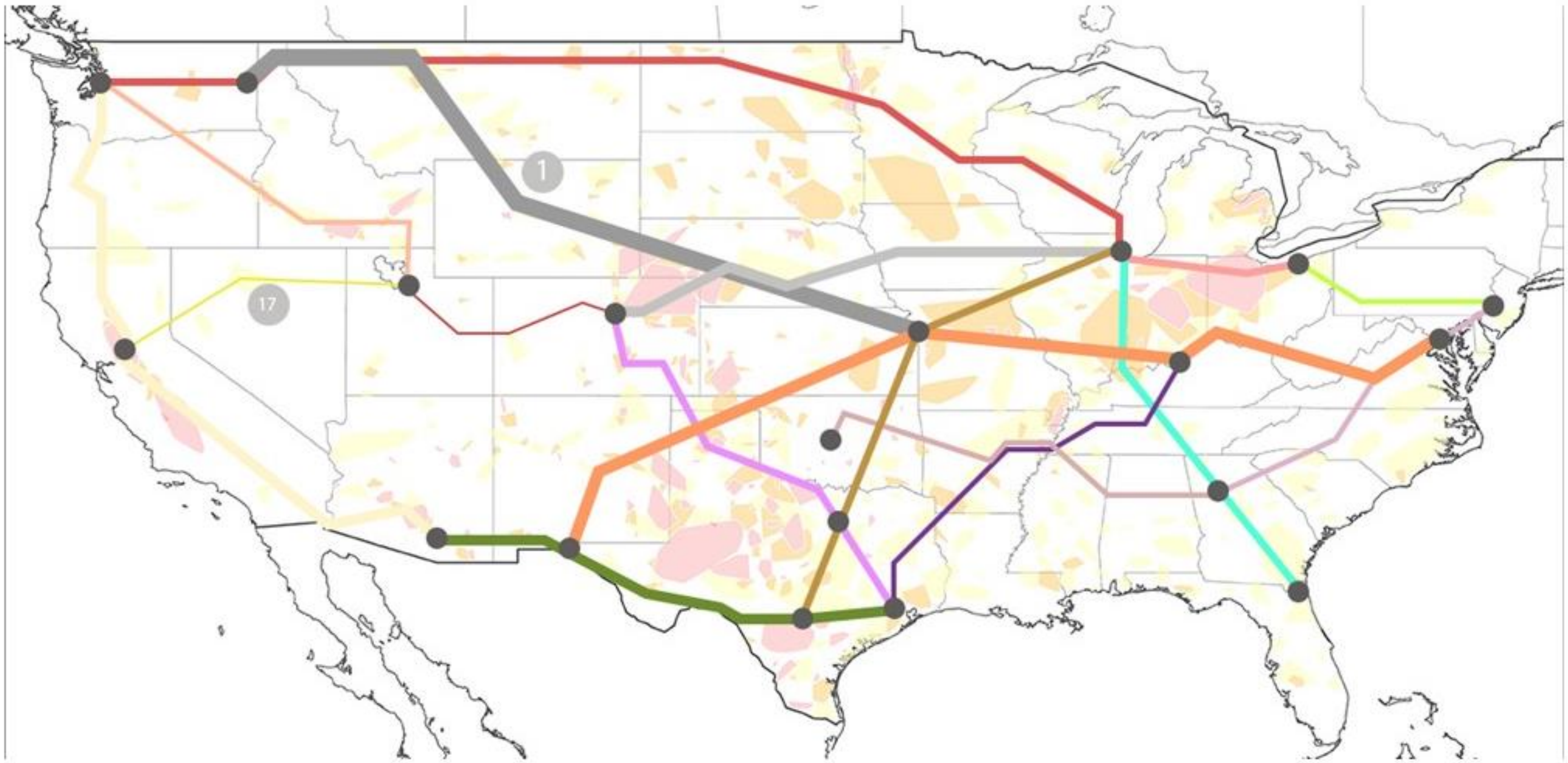
$$T(Z_i)_{Final} = T(A_i)*0.1 + T(B_i)*0.1 + T(Ci)*0.1 + T(D_i)*0.1 + T(E_i)*0.05 + T(F_i)*0.05 + T(G_i)*0.1 + T(H_i)*0.4$$
$$i = Corridor1,\ Corridor2 \ldots k$$
$$A = Number\ of\ Intersections,\ B = Replacement\ Capacity,\ C = Number\ of\ Farms,$$
$$D = Total\ Greenhouse\ Gas\ Emissions,\ E = Number\ of\ States,\ F = Number\ of\ High\ Priority\ Zones,$$
$$G = Number\ of\ Electric\ Transmission\ Planning\ Areas,\ H = Supply\ to\ Demand\ Ratio$$
$$*\ All\ Values\ (A\ to\ H)\ have\ been\ normalized\ and\ linearly\ transformed\ to\ a\ value\ between\ 0\ to\ 100$$

Equation 9: Summation of final transformed scores of each measure for comparison.

Results & Discussion

Relative importance of each corridor as a potential long range HVDC transmission line are captured with scores rated on a 0 – 100 linear transformed scale [Figure 32]. Please note that this score is a linear transformation of a standardized metric in order to improve its readability for drawing conclusions. The actual standardized values are more apt for statistical analysis.

The comparative analysis undertaken on our 18-corridor sample has definitive and conclusive results. A summary of all the different metrics that we have developed through geospatial analysis of the solar raster datasets and profiles developed by the NREL is presented in tables [Table 7, Table 8].



Corridor	Score	Corridor	Score	Corridor	Score	Corridor	Score
Sacramento_SaltLakeCity	0	SanAntonio_Chicago	59.38	Atlanta_Philadelphia	37.39	ElPaso_WashingtonDC	90.24
SaltLakeCity_Denver	0.48	Seattle_Chicago	60.85	Houston_Louisville	41.53	Chicago_Jacksonville	57.46
Cleveland_Philadelphia	17.29	Seattle_Tucson	69.70	Chicago_Cleveland	51.65	Denver_Houston	55.53
Seattle_SaltLakeCity	30.24	Denver_Chicago	71.69	Atlanta_Oklahoma	35.54	Tucson_Houston	73.74
Seattle_KansasCity	100						

Figure 32: Final Visualization of each Rail Corridor based on assigned scores on a linear transformed scale.

CORRIDOR	STANDARDIZED WEIGHTED SCORE	RESCALED	RESCALED SU/DE RATIO
Sacramento_SaltLakeCity	-0.99	0.00	3.04
SaltLakeCity_Denver	-0.98	0.48	4.18
Cleveland_Philadelphia	-0.65	17.29	0.00
Seattle_SaltLakeCity	-0.39	30.24	26.08
Atlanta_Oklahoma	-0.29	35.54	2.96
Atlanta_Philadelphia	-0.25	37.39	0.17
Houston_Louisville	-0.17	41.53	7.92
Chicago_Cleveland	0.03	51.65	35.31
Denver_Houston	0.11	55.53	21.84
Chicago_Jacksonville	0.14	57.46	11.50
SanAntonio_Chicago	0.18	59.38	13.73
Seattle_Chicago	0.21	60.85	16.17
Seattle_Tucson	0.39	69.70	12.77
Denver_Chicago	0.43	71.69	51.26
Tucson_Houston	0.47	73.74	47.14
ElPaso_WashingtonDC	0.79	90.24	17.75
Seattle_KansasCity	0.98	100.00	100.00

Table 7: Weighted and Transformed Scores for each Corridor.

The Seattle Kansas City Route is the most optimal railroad for HVDC Transmission line development. This position is largely determined due to its extremely high Supply to Demand Ratio. The higher weightage assigned to the latter measurement assigns this route the position and is more so because of the lack of settlements along the line which is a general characteristic of the North-West of the U.S above the Great Basin geography. It scores one of the lowest in terms of number of HVAC transmission intersections with only lines above the 300 Volt Class intersecting its geometry. It has nominal access to High Priority Zones and the number of potential Solar Farms. Its longer length also allows it to intersect several Transmission Planning Areas and States improving its ability to access multiple jurisdictions. A color gradation is utilized to render the scale for each metric in order to understand how each corridor scores across each metric [Figure 32].

CORRIDOR	INT	HPZ	REP_CAP	TGHG_MTON	STATES	PAREA	SU_DE	NFARMS
Sacramento_ SaltLakeCity	-1.10	-0.88	-1.23	-1.66	-0.79	-0.44	-0.77	-1.58
SaltLakeCity_ Denver	-0.97	-0.88	-1.08	-1.18	-1.18	-1.15	-0.72	-1.51
Cleveland_ Philadelphia	0.06	-0.88	0.88	0.51	-1.18	-1.87	-0.89	-1.47
Seattle_ SaltLakeCity	-0.26	-0.28	-0.95	-1.33	-0.39	-0.67	0.17	-1.06
Atlanta_ Oklahoma	-0.58	-0.88	1.19	-0.11	0.39	0.52	-0.77	-0.58
Atlanta_ Philadelphia	-0.97	-0.88	1.20	2.00	1.18	-0.44	-0.88	-0.93
Houston_ Louisville	0.06	-0.73	0.89	-0.23	-0.39	0.28	-0.57	0.13
Chicago_ Cleveland	-0.26	0.63	-0.51	-0.28	-0.79	-1.15	0.55	0.39

Denver_ Houston	0.51	2.15	-0.47	-0.15	-0.79	0.28	0.00	0.21
Chicago_ Jacksonville	0.71	-0.58	-0.13	0.81	0.79	1.00	-0.42	0.64
SanAntonio_ Chicago	2.58	-0.73	0.21	0.58	0.39	-0.67	-0.33	0.62
Seattle_ Chicago	0.51	-0.28	-0.59	0.06	0.79	1.95	-0.23	0.84
Seattle_ Tucson	0.00	0.33	2.26	1.37	-0.39	1.95	-0.37	-0.21
Denver_ Chicago	-0.46	1.24	-0.85	-0.34	-0.39	-0.44	1.20	1.13
Tucson_ Houston	-0.52	0.48	-0.22	0.08	-0.79	0.04	1.03	1.32
ElPaso_ WashingtonDC	1.93	2.15	0.73	1.28	2.75	0.52	-0.17	1.66
Seattle_ KansasCity	-1.23	0.03	-1.31	-1.42	0.79	0.28	3.18	0.40

Table 8: Standardized Scores for each Individual Measure.

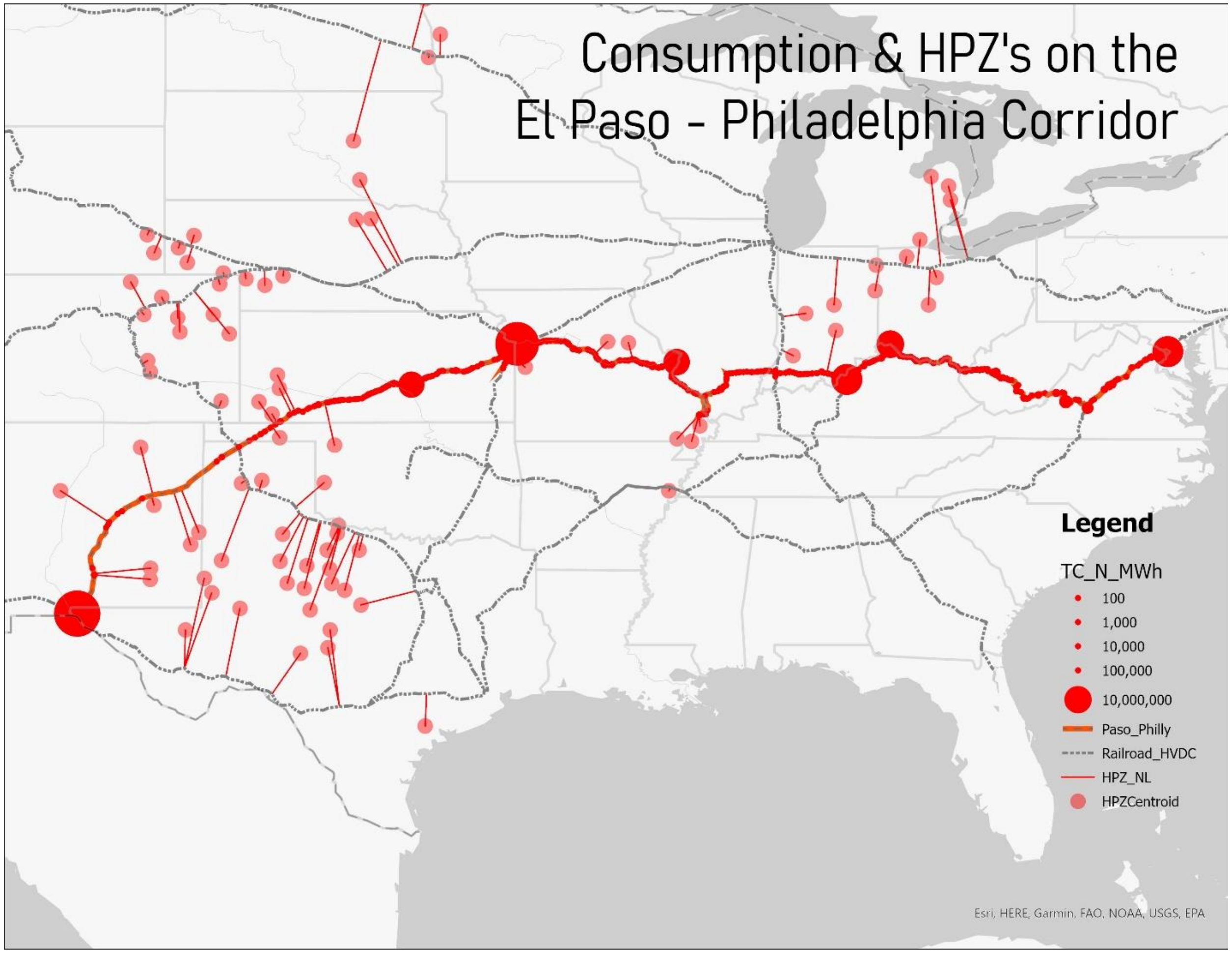


Figure 33: Consumption and High Priority Zones in the El Paso - Philadelphia Corridor.

We find that a multidimensional analysis of our corridor set yields very different results from a unidimensional quantitative analysis of supply and demand. Several corridors shift ranking significantly [Figure 34].

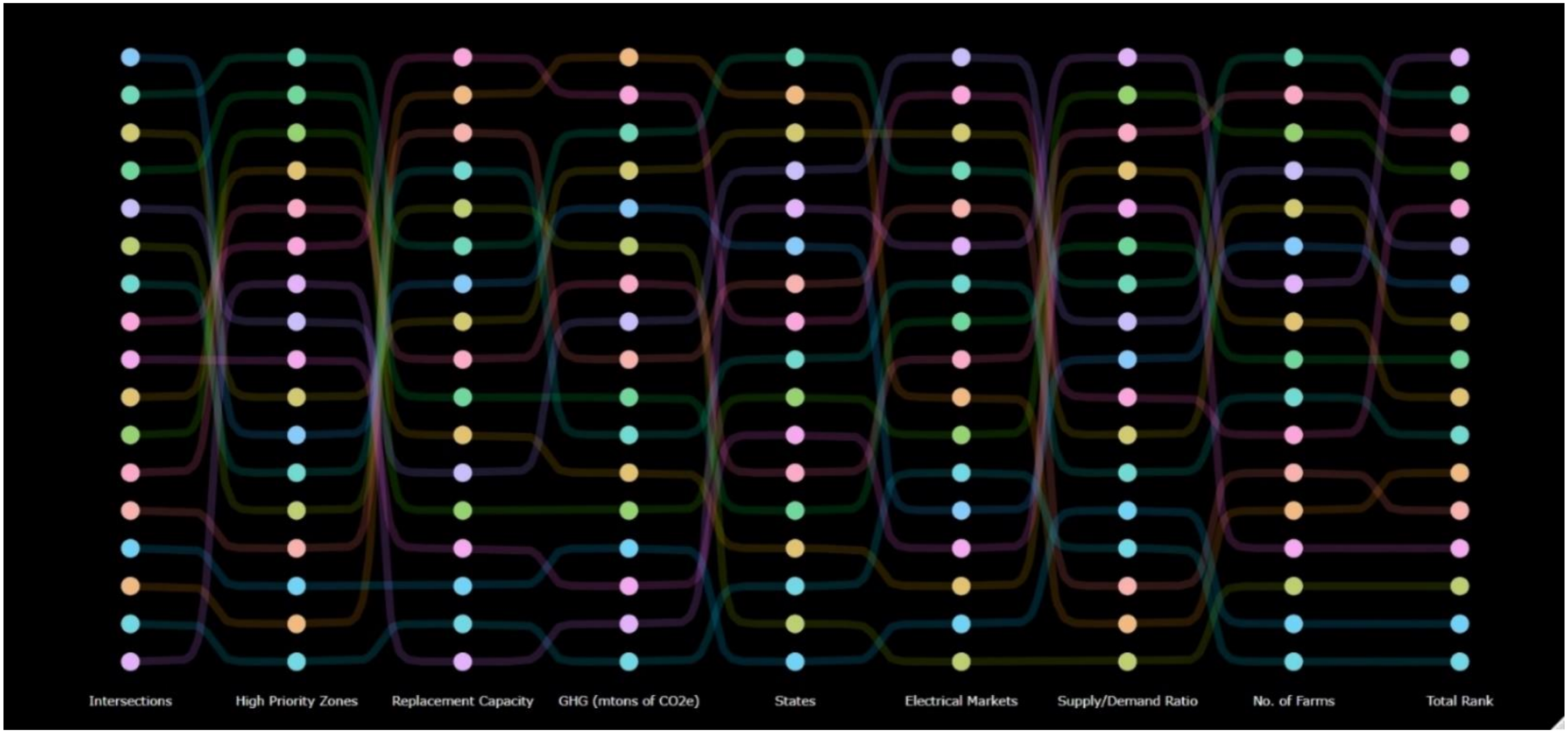


Figure 34: Bump Chart with each corridor represented in the line. Notice the high variability amongst the corridors.

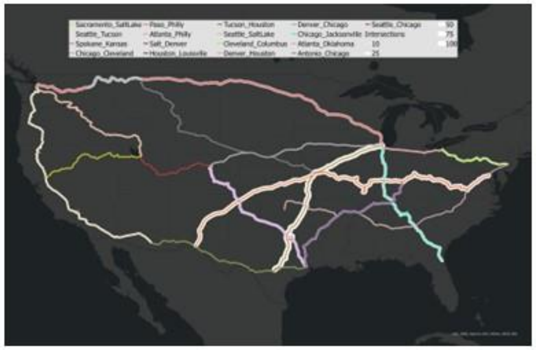
The most well-rounded Corridor is the El Paso Philadelphia DC line. It traverses several populous states and has one of the highest transmission intersections. Its El Paso origin node also ensures that it passes through Northwest Texas' high solar regions indicated by its access to 57 High Priority Zones. Additionally, it crosses several important cities with high demand along its geometry and could be the solution to the northeast renewable transition challenge discussed in the literature section. We find that it also has high replacement capacity. Confirming expert opinions on the geographic challenge to the Solar energy expansion, the most optimal routes are located with a node in the south and west of the US with Seattle and Tucson important nodes. While this can be because of the larger lengths of the regions traversed by the corridors we find that the eastern corridors score lowest in the analysis despite having comparable lengths in some corridors. The biggest consumers on this line are El – Paso TX, Kansas and Wichita Cities in Kansas, Louisville in Kentucky, Cincinnati in Ohio and Philadelphia.

Most notably the El Paso – Philadelphia corridor drops in position when only Supply and Demand Ratio is considered [Figure 33]. This is because the supply drops significantly when the corridor moves towards the Appalachian Mountains while the demand steadily rises with a higher density of settlements. This is a clear demonstration of why a multidimensional analysis needs to be undertaken as distributive capacity in terms of transmission intersection can aid in improving energy access of these areas to the more resourceful Texas area.

The Sacramento Salt Lake City Corridor although geographically important provides low utility in terms of supply and demand as its movement through the Sierra Nevada

Mountains renders low access to solar farms due to the slope factor as solar farms require slopes between 0 – 20%. Additionally, there are no major settlements outside of its end nodes. From a network point of view, this corridor is also superseded by the southern section of the Seattle-Tucson Corridor which provides access to the solar rich desert regions of the Southern U.S. Therefore, this corridor should be least prioritized as discussed in our data section. The quantitative findings provide validation to our hypothesis. Further insight into the comparative analysis is provided in the series of visualizations below [Figure 36, Figure 37, Figure 38].

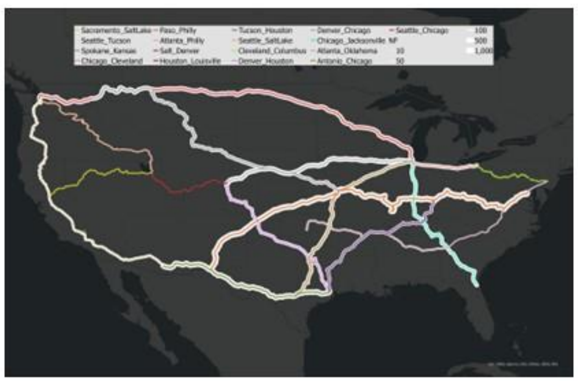
Figure 35: Color-coded Rail corridors.



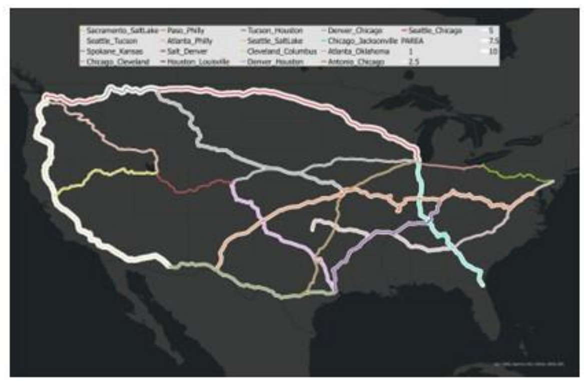
Transmission Intersections

High Priority Zones

States Intersections



Number of Farms



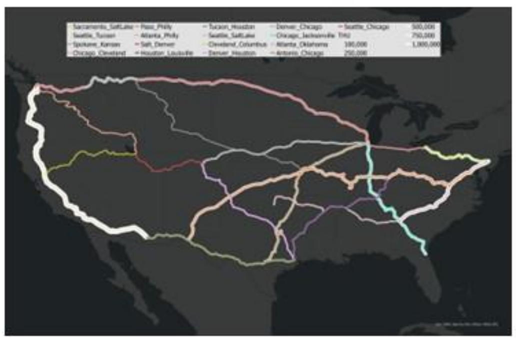
Planning Area Intersections

Figure 36: Measures visualized for each Corridor based on line weights.

Total Solar Capacity (MWh)

Total Consumption (MWh)

Supply / Demand Ratio



Total Housing Units

Total Population

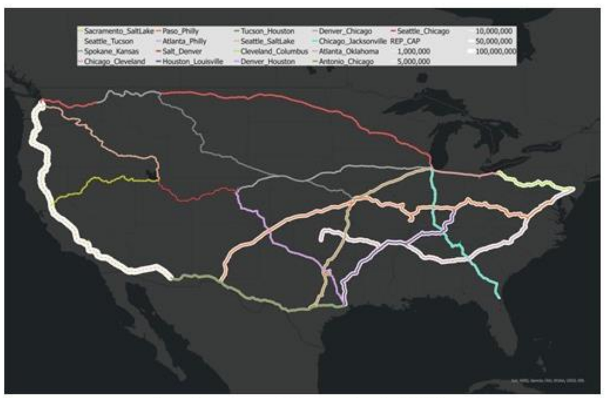
GHG – Megatons of carbondioxide equivalent

Figure 37: Measures visualized for each Corridor based on line weights.

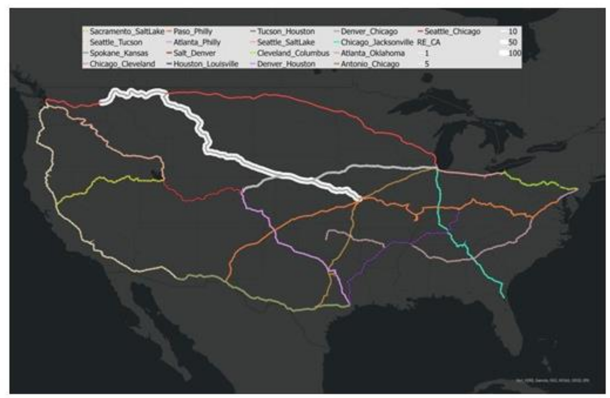
Per Capita Energy Consumption (MWh)

Per Capita Energy Consumption without including Vehicle Consumption (MWh)

Percentage Increase in Consumption with Petrol and Diesel consumption converted into electric.



Replacement Capacity in MWh



Replacement Capacity Ratio

Figure 38: Measures visualized for each Corridor based on line weights.

The large number of corridors prevents a detailed look into each within this section. Appendix A provides a detailed report of each corridor with summary information highlighted in fact sheets and the demand side information of each city on the corridor. Additionally, an interactive dashboard is created to summarize the findings for users. It showcases a distance map of each solar zone to its nearest railroad line [

Figure 39]. Appendix D provides a user guide of the interactive dashboard. Another dashboard also provides a summarization of every metric.

Figure 39: Interactive Dashboard of Supply & Near Lines based on a Kepler.Gl Visualization.

Conclusions, Limitations & Assumptions

There are several opportunities for considering Class I railroad geometries as potential opportunities in the current roadblock that the ‘Green Economy’ transition faces. Railroads offer continuous right of ways across many settlements in the spirit in which it was originally intended in the form of the Transcontinental Railroad.

Southern and Western connections in the Class I railroad system have the most potential for development in terms of supply. Cities such as Denver and Chicago have important roles to play as distribution nodes with high degree connectivity and the potential to serve as transfer links to the northeast. The southeastern US has the potential to be well served by the Texas region. The Corridors are best evaluated if subjected to the Delphi Method of expert review based on priorities. For instance, while Seattle, WA - Kansas City, KA corridor scores best, this is **largely based on its Supply/ Demand Ratio** {Which as the highest weightage - see methods further ahead} exacerbated due to very few cities on the line. It can **serve as a collecting line** that transfers energy from the Mid and Northwest to Kansas City which has a high distributive capacity. On the other hand, the **El Paso, TX - Washington DC Corridor** has a more **balanced set of metrics**. If the intention is to serve a large number of cities while increasing supply and distributive capacity, this is the best choice for transmission development. The **Denver, CO - Chicago, IL** falls under the same argument. If the intention is to achieve the same but with lower development distance the **Chicago, IL -- Cleveland, OH** Corridor is most suitable.

One of the major concerns that this project omits are the financial concerns that development of such transmission entails. In fact, transmission costs as linear line geometries are discussed in terms of cost per mile. But several dimensions exist to the problem one of which is the geospatial politics of supply and demand. The most optimal transmission corridor must also consider future expansion potential which is indicated by our multidimensional attributes. This project provides an initial outlook upon which to base future research. This project seeks to create an argument for the use of railroads as key infrastructural elements in the green transition. It is the hope of the author that increasing awareness of their integrated potential will increase funding for long range railroads in the US.

Further Considerations

The analysis shows that railroads are feasible geographical entities to distribute renewable energy across the nation and could also serve as potential new closed additions to the national grid. Further analysis should also consider the time element of energy generation, storage, the financials of development and the transfer of energy between planning areas. One major concern with using utilities in railroad right of ways is safety. Previous experience in the fiber optics industry has shown that track caving can be an issue if safety considerations are not considered.

Right of ways as well may be very based on section of the track and physical spatial constraints may present themselves. All such further considerations from an energy grid planning perspective must be considered for next steps.

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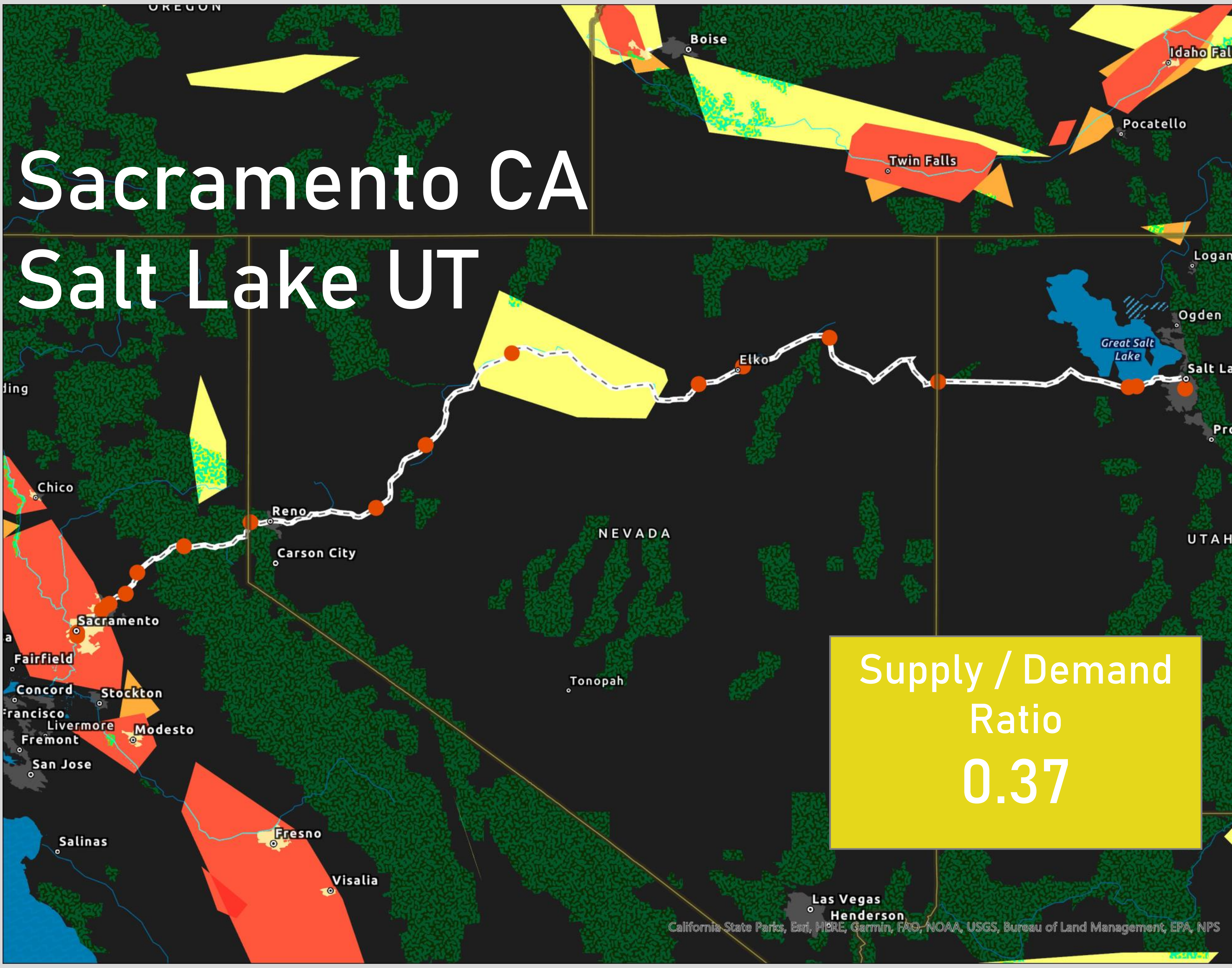
Appendix

The appendix contains a summarization of each route in the study area with all the important facts mentioned.

Sacramento CA
Salt Lake UT



Supply / Demand Ratio
0.37

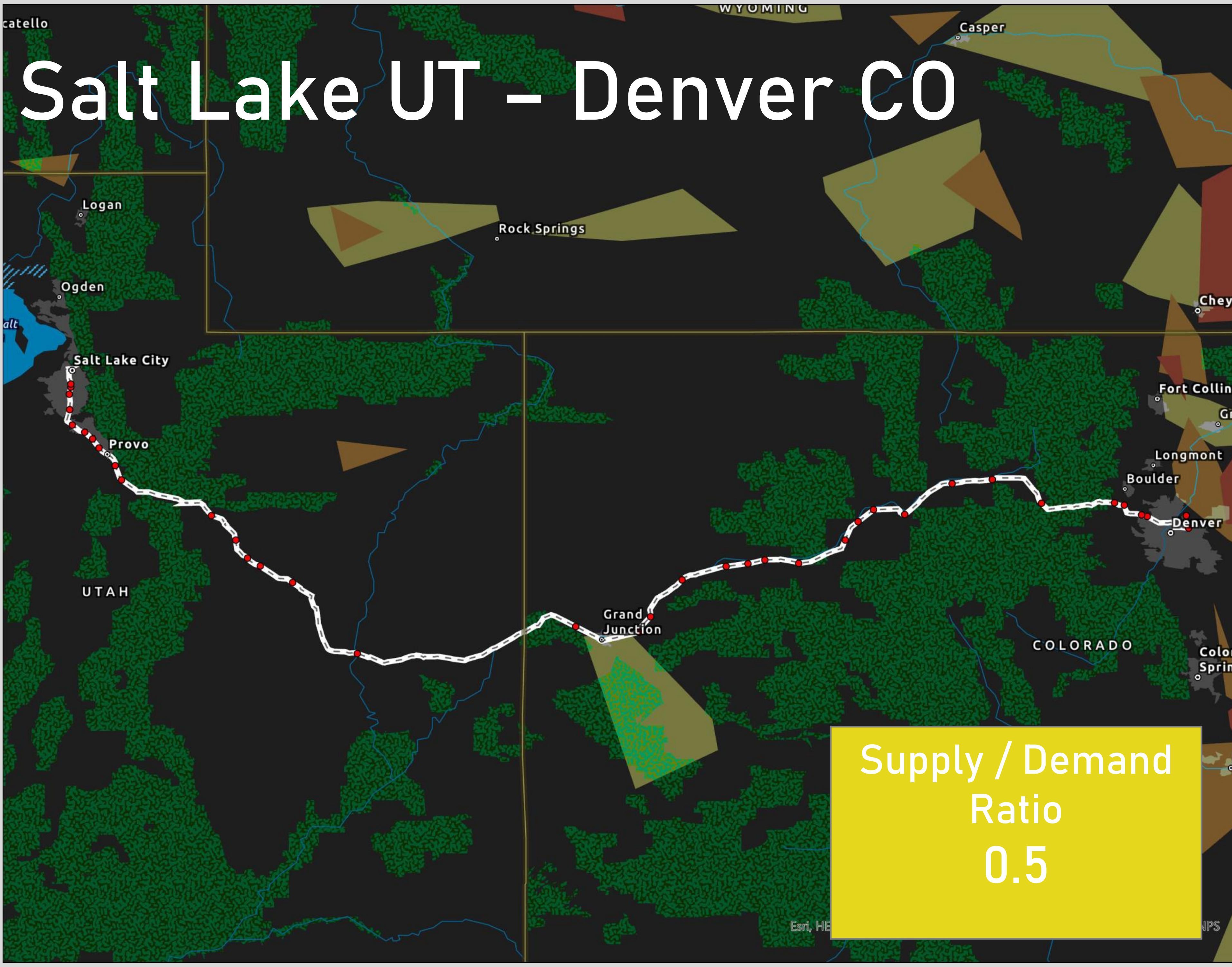
No. of Farms 11

Solar Generation (MWh)	Energy Demand (MWh)	Replacement Capacity (MWh)
2305465.3	6097083.1	6829288.8

Total Population	GHG Per Capita (mTons of Co2e)	High Priority Zones
276516	12	0

Total Consumption Per Capita (MWh)	HVAC Trans Intersections	Total Consumption Per Housing (MWh)
33	10	93

Salt Lake UT – Denver CO



Supply / Demand Ratio
0.5

No. of Farms 24

Solar Generation (MWh)	Energy Demand (MWh)	Replacement Capacity (MWh)
20652219.5	40165253.6	13307037.2

Total Population	GHG Per Capita (mTons of Co2e)	High Priority Zones
1733155	10.9	0

Total Consumption Per Capita (MWh)	HVAC Trans Intersections	Total Consumption Per Housing (MWh)
25.1	12	82.7

Seattle WA – Tucson AZ

Supply / Demand Ratio
1.5

Solar Generation (MWh)
410354559.0

Replacement Capacity (MWh)
156192855.8

Energy Demand (MWh)
266585611.9

No. of Farms
273

Total Population
12674055

GHG Per Capita (mTons of Co2e)
44.37

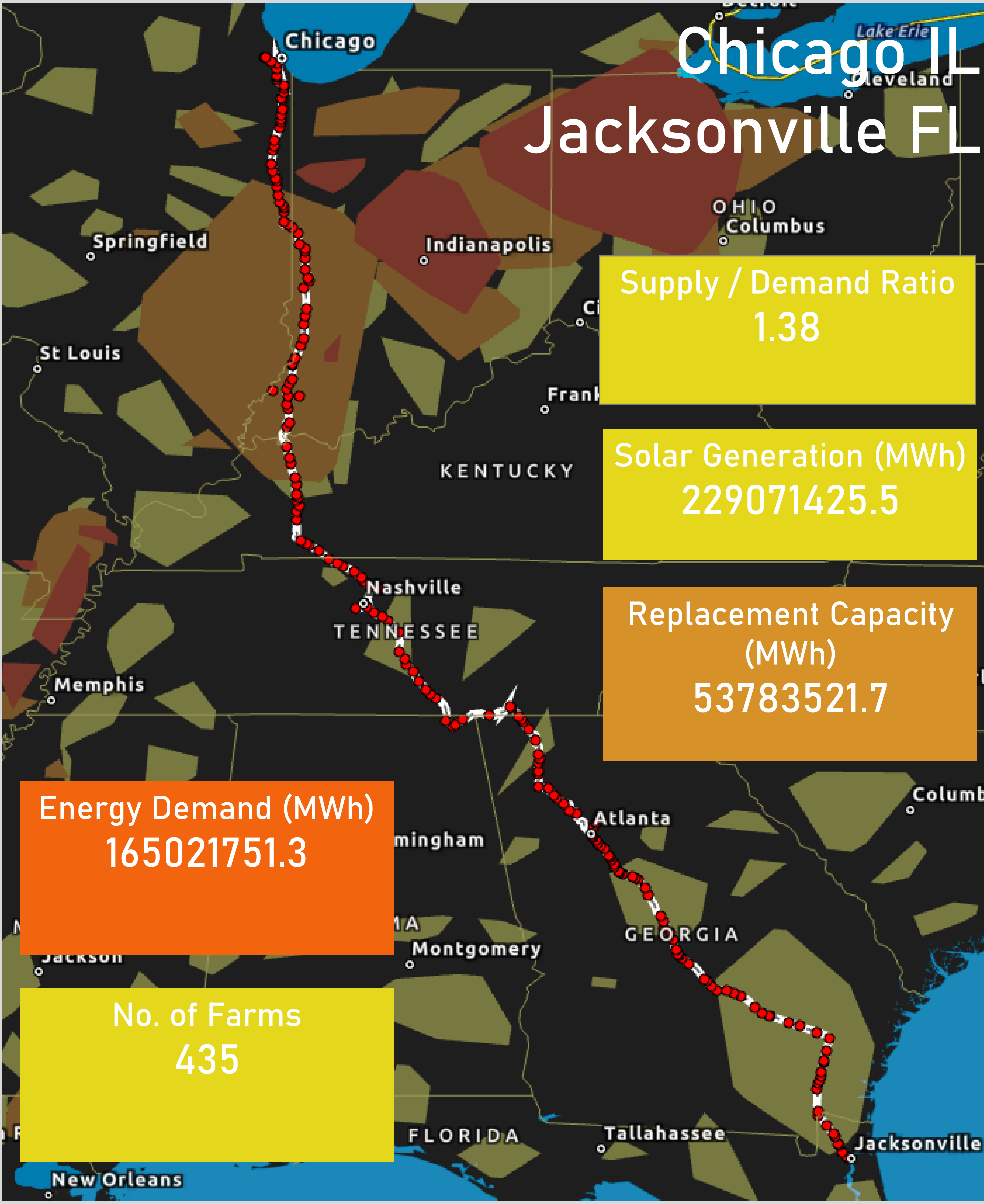
High Priority Zones
8

Total Consumption Per Capita (MWh)

HVAC Trans Intersections
27

Total Consumption Per Housing (MWh)

Chicago IL Jacksonville FL



Supply / Demand Ratio
1.38

Solar Generation (MWh)
229071425.5

Replacement Capacity (MWh)
53783521.7

Energy Demand (MWh)
165021751.3

No. of Farms
435

Total Population
5971956

GHG Per Capita (mTons of Co2e)
17.9

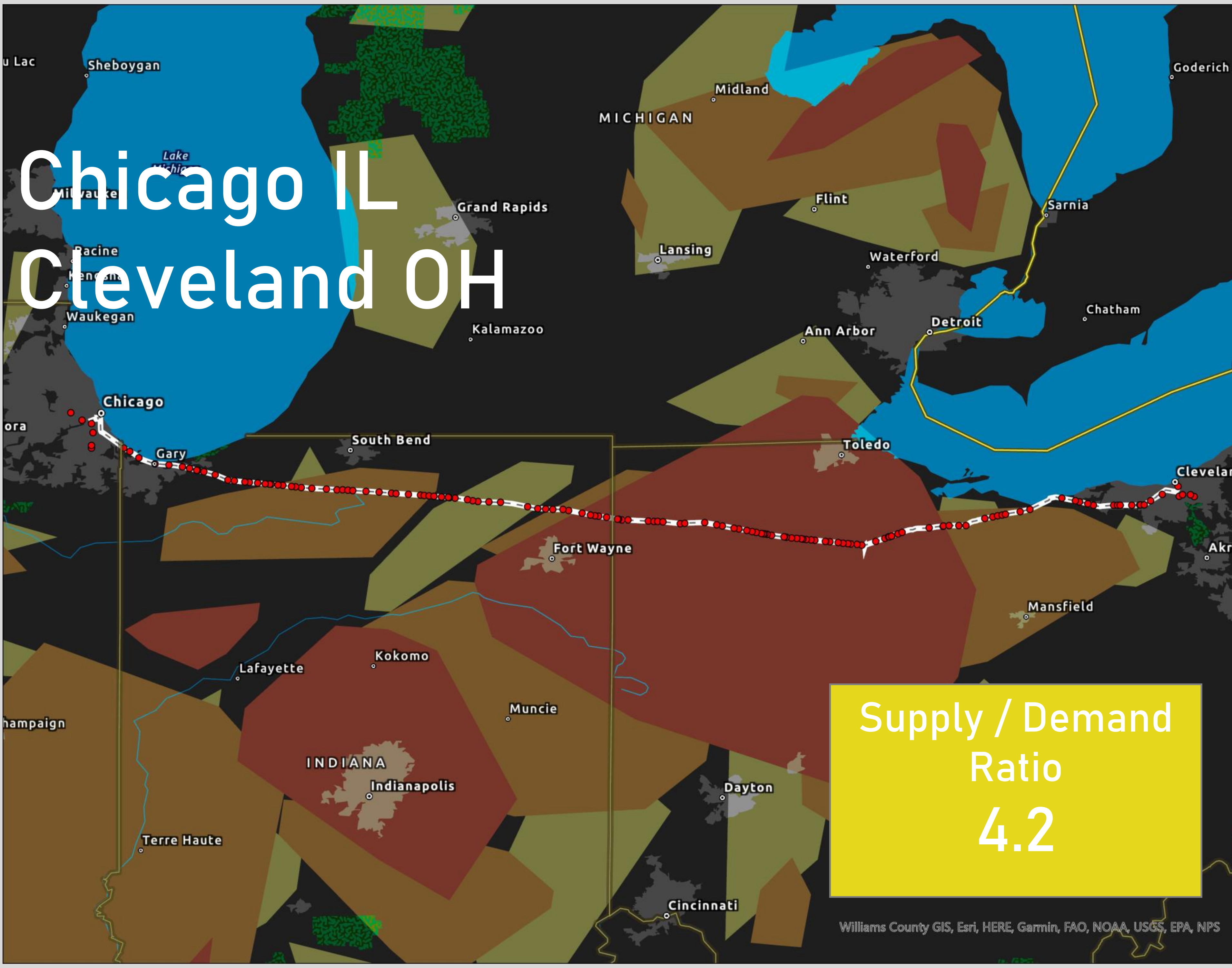
High Priority Zones
2

Total Consumption Per Capita (MWh)
39.7

HVAC Trans Intersections
38

Total Consumption Per Housing (MWh)
108.9

Chicago IL
Cleveland OH



Supply / Demand Ratio
4.2

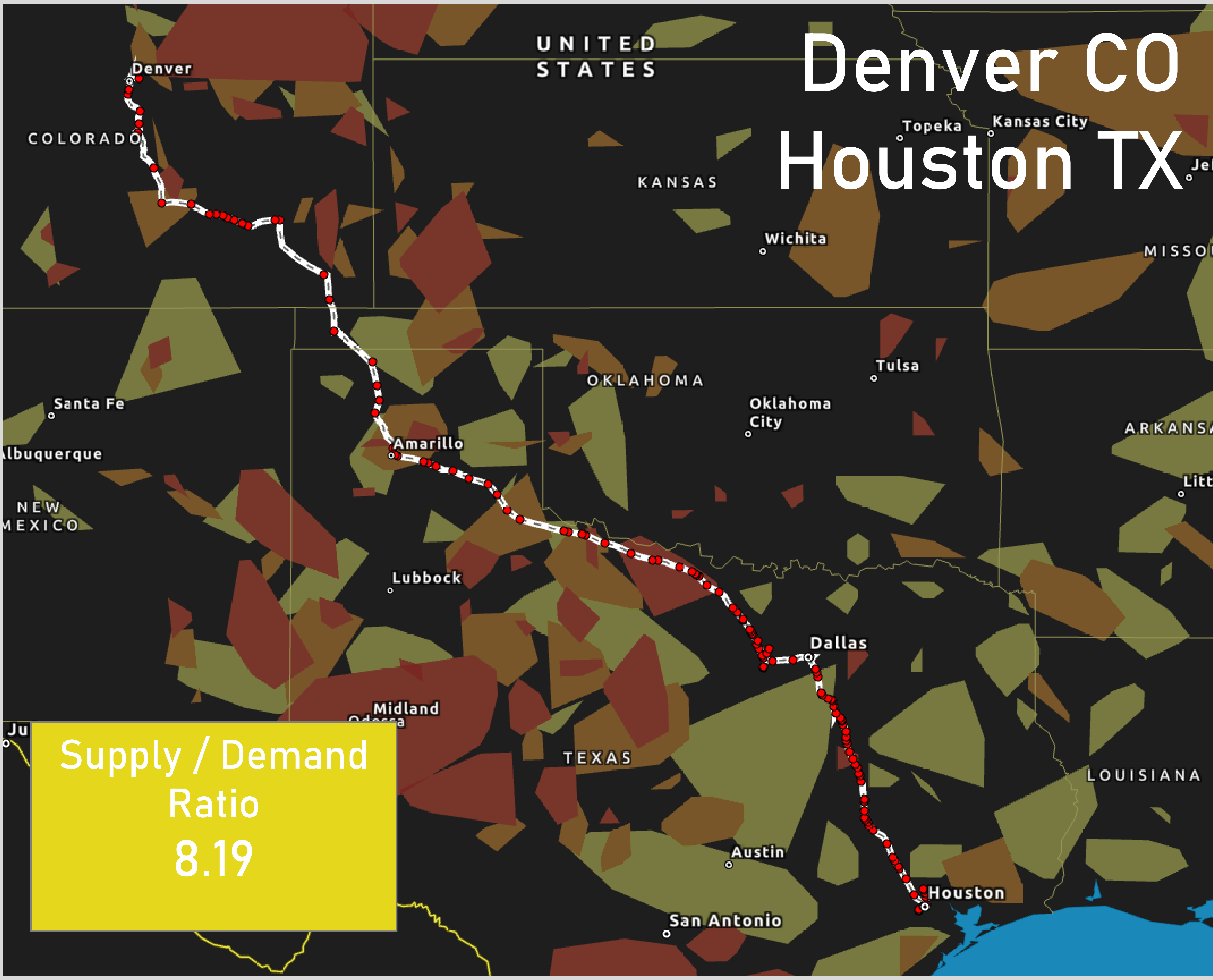
No. of Farms 387

Solar Generation (MWh)	Energy Demand (MWh)	Replacement Capacity (MWh)
311346140.6	73643005.6	37361727.3

Total Population	GHG Per Capita (mTons of Co2e)	High Priority Zones
2273396	22.7	10

Total Consumption Per Capita (MWh)	HVAC Trans Intersections	Total Consumption Per Housing (MWh)
34.3	23	83.5

Denver CO Houston TX



Supply / Demand Ratio
8.19

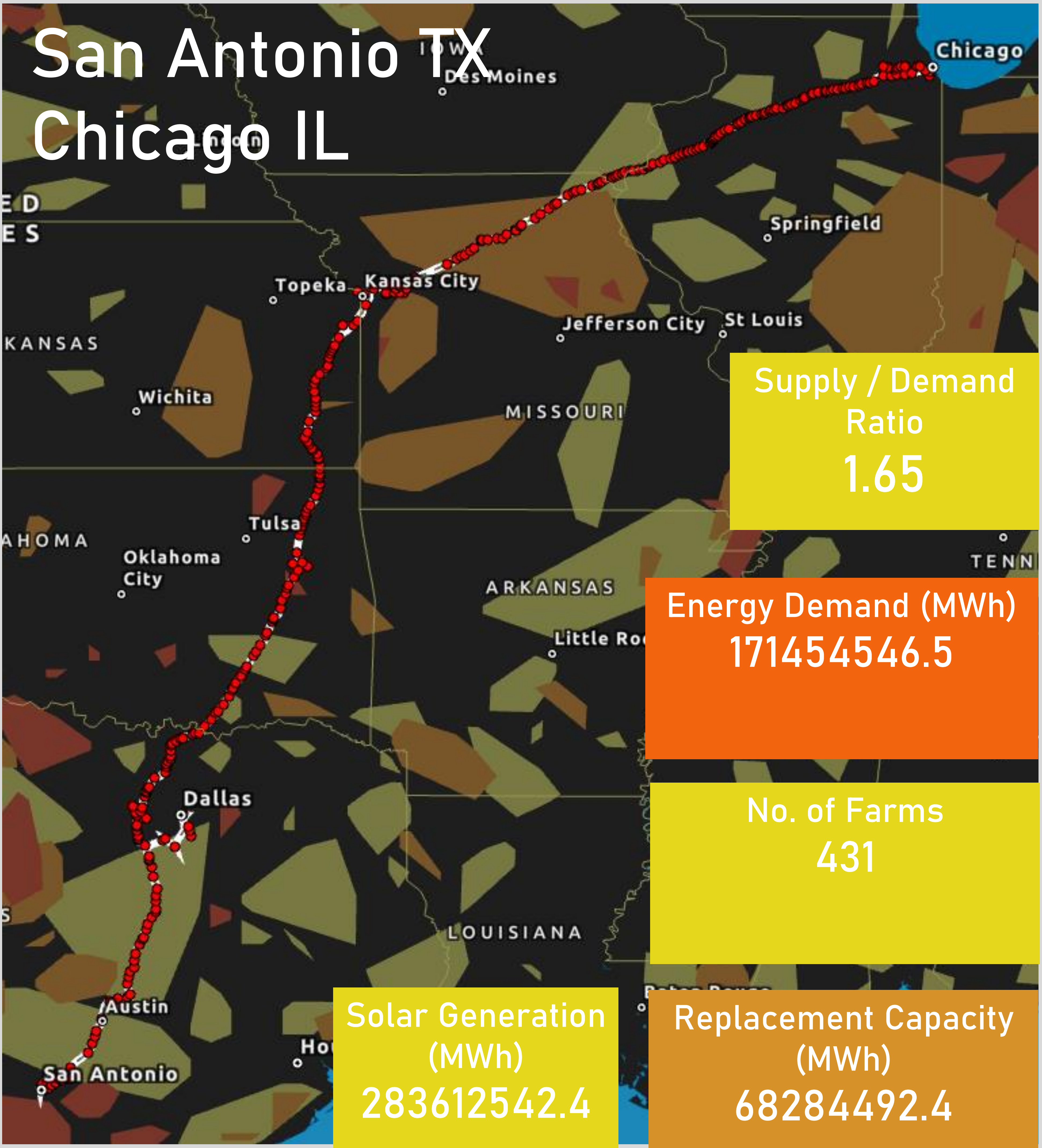
No. of Farms 353

Solar Generation (MWh)	Energy Demand (MWh)	Replacement Capacity (MWh)
320080081.6	122133211.5	39070489.4

Total Population	GHG Per Capita (mTons of Co2e)	High Priority Zones
3222009	23.5	20

Total Consumption Per Capita (MWh)	HVAC Trans Intersections	Total Consumption Per Housing (MWh)
62.6	35	159.12

San Antonio TX
Chicago IL



Supply / Demand Ratio
1.65

Energy Demand (MWh)
171454546.5

No. of Farms
431

Solar Generation (MWh)
283612542.4

Replacement Capacity (MWh)
68284492.4

Total Population
5182794

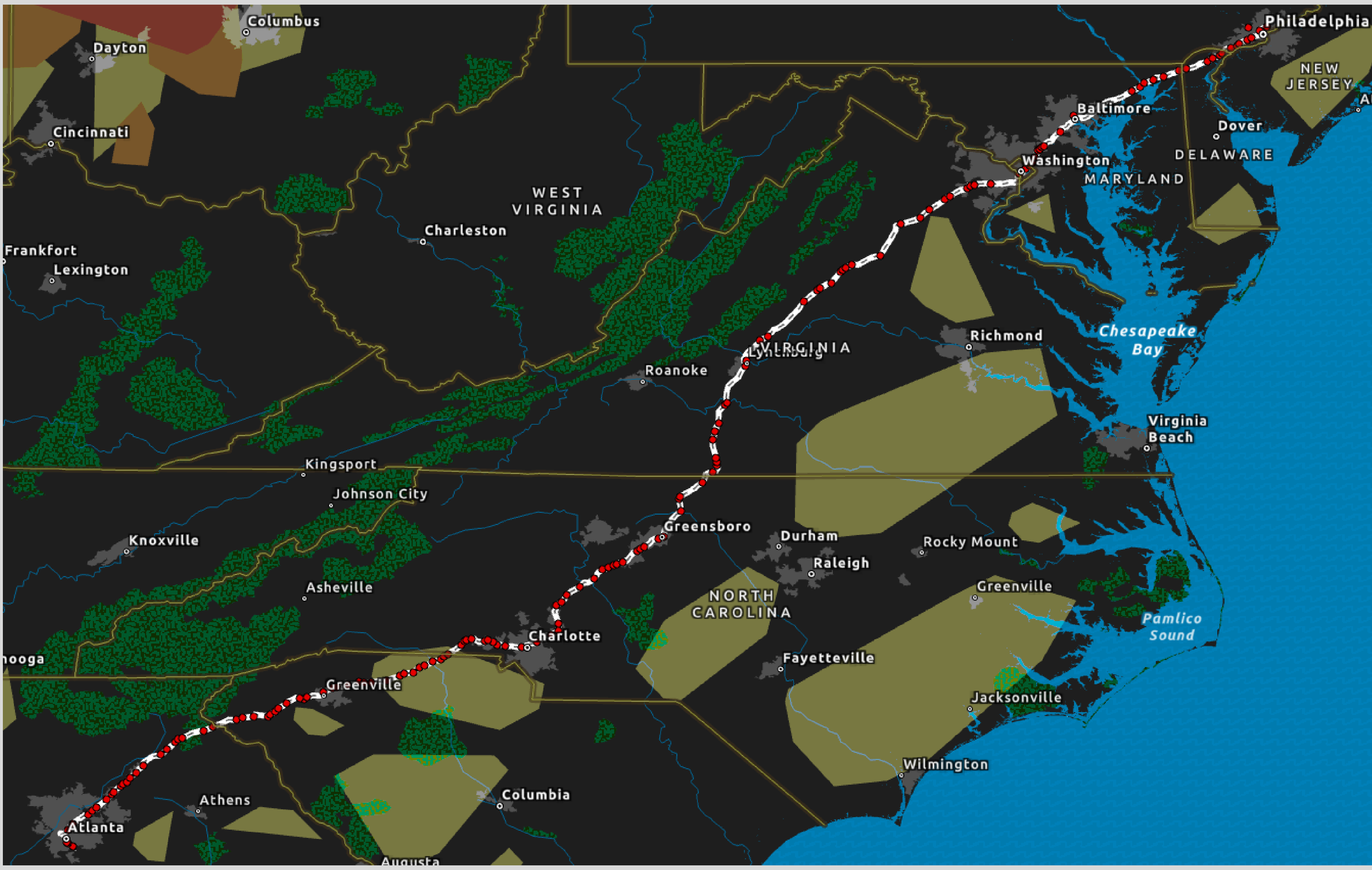
GHG Per Capita (mTons of Co2e)
17.3

High Priority Zones
1

Total Consumption Per Capita (MWh)
36.6

HVAC Trans Intersections
67

Total Consumption Per Housing (MWh)
94.4



Atlanta GA
Philadelphia PA

Supply / Demand Ratio
0.03

No. of Farms 136

Solar Generation (MWh)
10602019.0

Energy Demand (MWh)
291252603.5

Replacement Capacity (MWh)
110877601.8

Total Population
7591051

GHG Per Capita (mTons of Co2e)

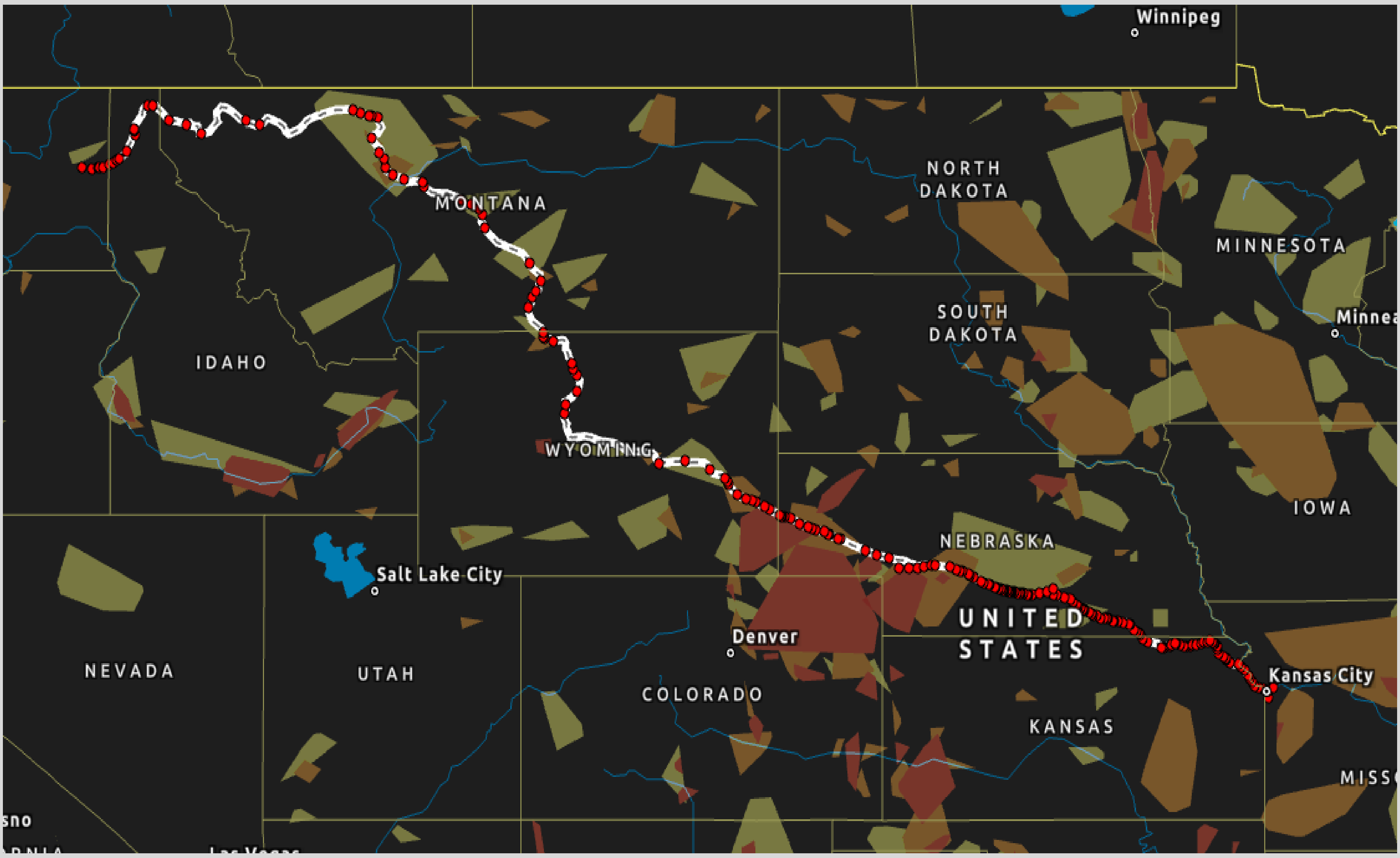
High Priority Zones
0

Total Consumption Per Capita (MWh)
51.2

HVAC Trans Intersections
12

Total Consumption Per Housing (MWh)
145.8

Spokane WA - Kansas City KA



No. of Farms **390**

Supply / Demand Ratio
11.9

Solar Generation (MWh)
232194337.4

Energy Demand (MWh)
19439933.4

Replacement Capacity (MWh)
3136654.7

Total Population
899649

GHG Per Capita (mTons of Co2e)
14.6

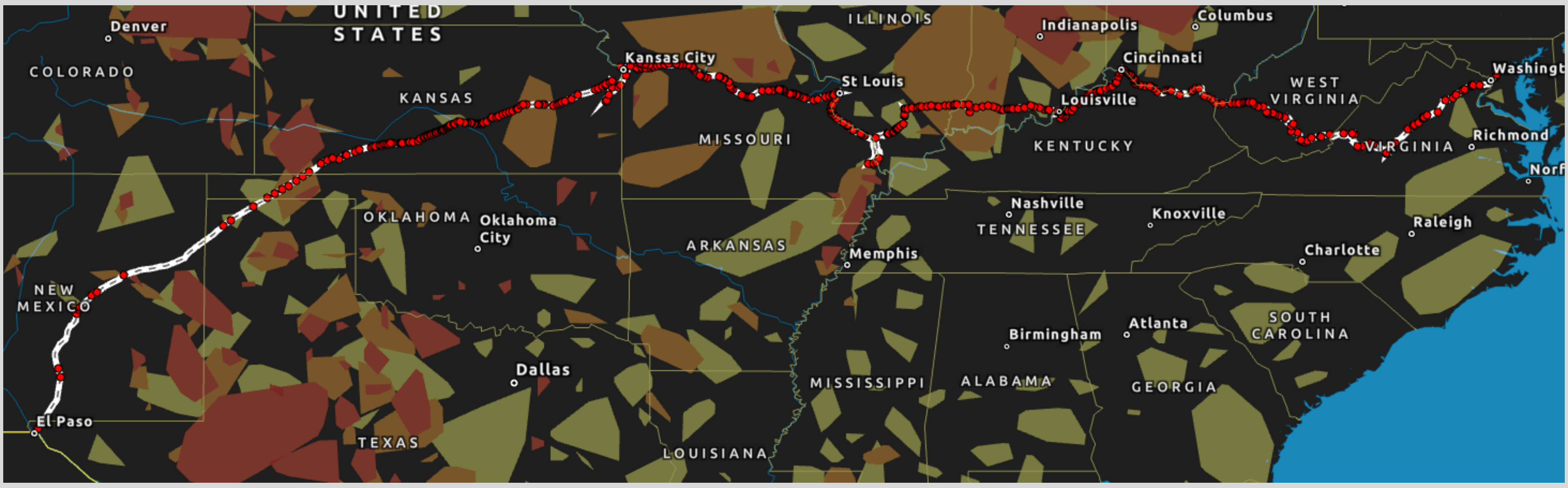
High Priority Zones
6

Total Consumption Per Capita (MWh)
28.5

HVAC Trans Intersections
8

Total Consumption Per Housing (MWh)
58.6

El Paso TX – Washington DC



No. of Farms **630**

Supply / Demand Ratio
2.13

Solar Generation (MWh)
403163143.6

Energy Demand (MWh)
189031839.4

Replacement Capacity (MWh)
90733361.4

Total Population
6053315

GHG Per Capita (mTons of Co2e)
19.8

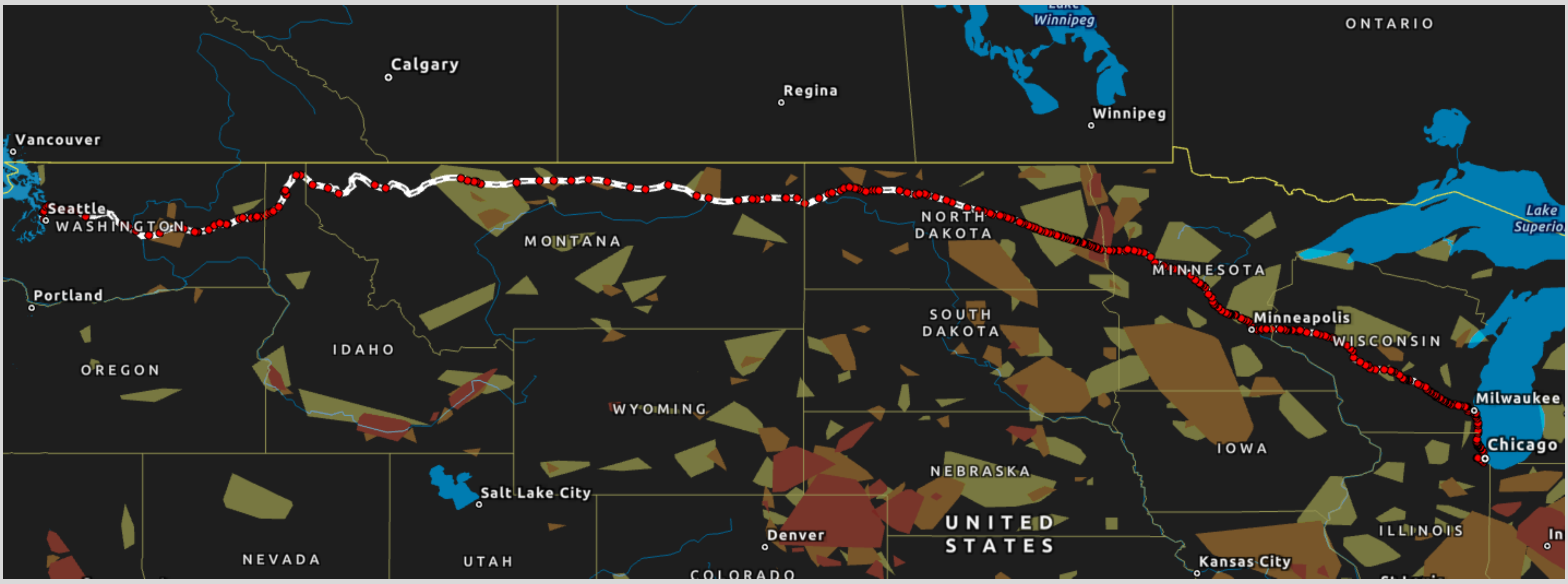
High Priority Zones
20

Total Consumption Per Capita (MWh)
38.6

HVAC Trans Intersections
57

Total Consumption Per Housing (MWh)
94.3

Seattle WA
Chicago IL



No. of Farms 474

Supply / Demand Ratio
1.94

Solar Generation (MWh)
215701540.4

Energy Demand (MWh)
110888665.0

Replacement Capacity (MWh)
34019759.4

Total Population
4766849

GHG Per Capita (mTons of Co2e)
15.3

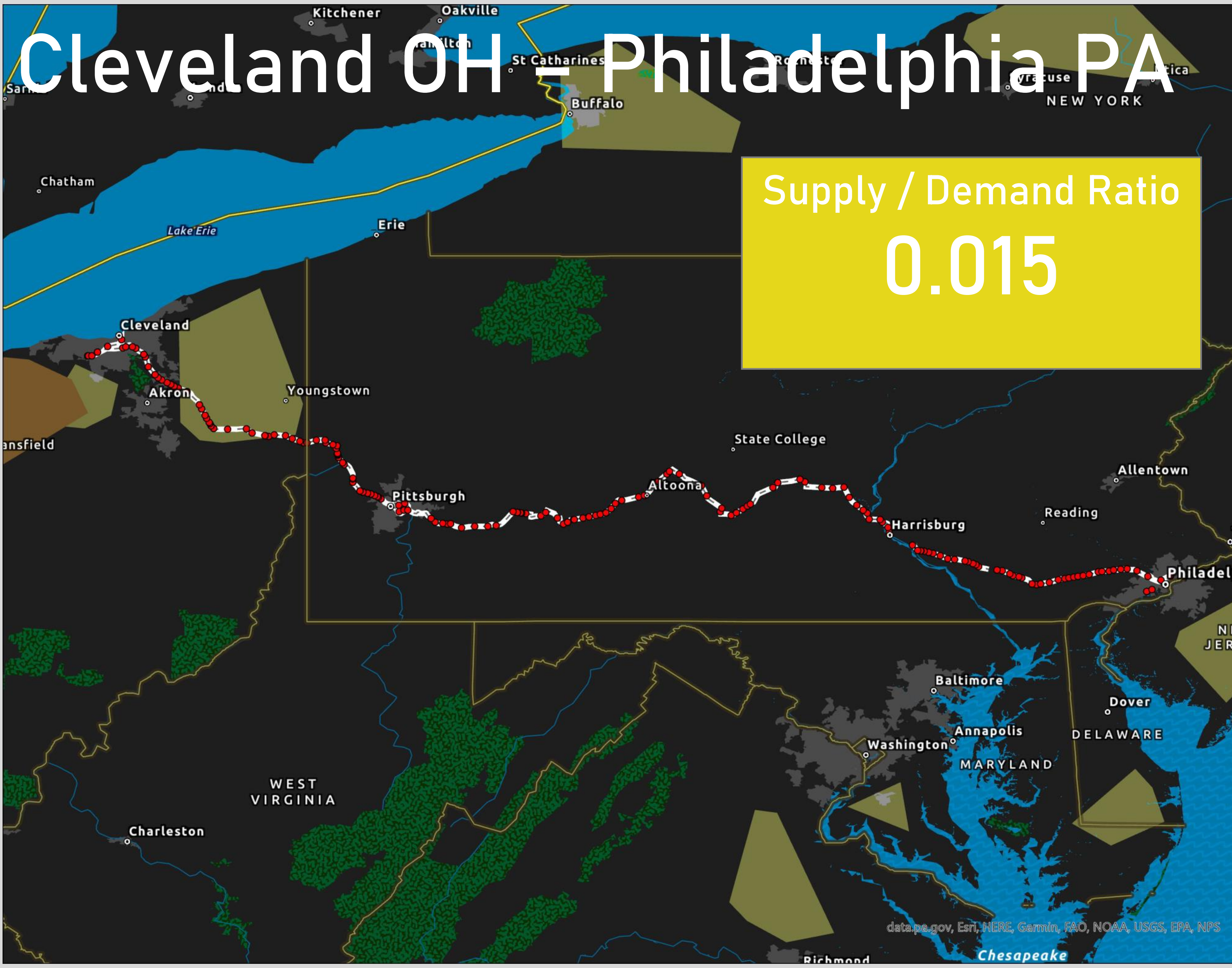
High Priority Zones
4

Total Consumption Per Capita (MWh)
28.4

HVAC Trans Intersections
35

Total Consumption Per Housing (MWh)
69.7

Cleveland OH – Philadelphia PA



Supply / Demand Ratio
0.015

No. of Farms 32

Solar Generation (MWh)	Energy Demand (MWh)	Replacement Capacity (MWh)
2350455.6	148462634.0	96995649.6

Total Population	GHG Per Capita (mTons of Co2e)	High Priority Zones
5282799	17.3	0

Total Consumption Per Capita (MWh)	HVAC Trans Intersections	Total Consumption Per Housing (MWh)
37.3	28	86.9

No. of Farms **110**

Supply / Demand Ratio
3.12

Solar Generation (MWh)
104249296.4

Energy Demand (MWh)
33347048.4

Replacement Capacity (MWh)
18707277.6

Total Population
1312157

GHG Per Capita (mTons of Co2e)
10.4

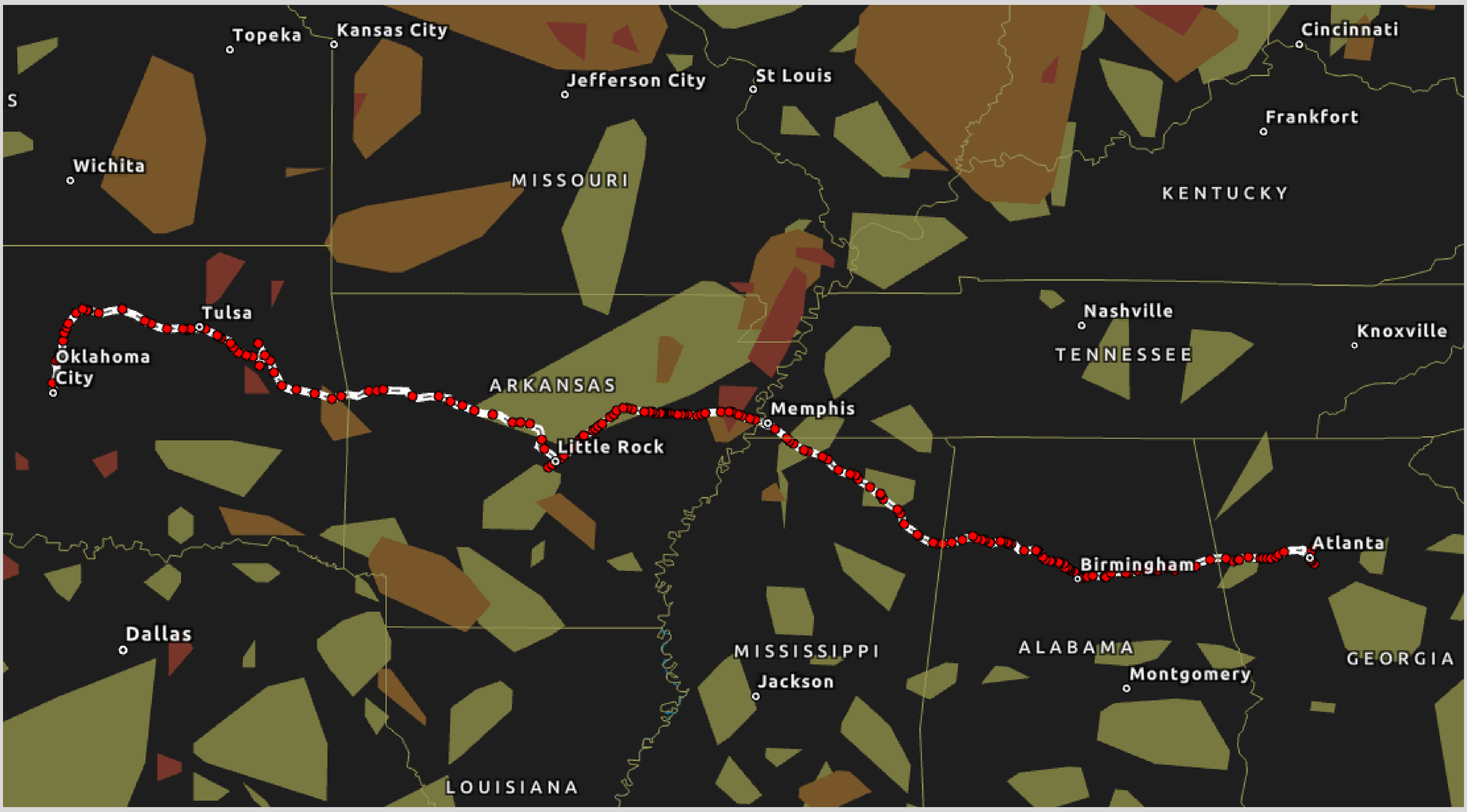
High Priority Zones
4

Total Consumption Per Capita (MWh)
27.5

HVAC Trans Intersections
23

Total Consumption Per Housing (MWh)
83.1

Atlanta GA – Oklahoma City OK



No. of Farms **203**

Supply / Demand Ratio
0.36

Solar Generation (MWh)
41010566.6

Energy Demand (MWh)
111313025.4

Replacement Capacity (MWh)
110602296.5

Total Population
2877017

GHG Per Capita (mTons of Co2e)
19.2

High Priority Zones
0

Total Consumption Per Capita (MWh)
45.8

HVAC Trans Intersections
18

Total Consumption Per Housing (MWh)
116.3

Tucson AZ – Houston TX

No. of Farms **565**

Supply / Demand Ratio
5.6

Solar Generation (MWh)
786459229.5

Energy Demand (MWh)
139468439.5

Replacement Capacity (MWh)
49812201.4

Total Population
3590701

GHG Per Capita (mTons of Co2e)
14.7

High Priority Zones
9

Total Consumption Per Capita (MWh)
36.4

HVAC Trans Intersections
19

Total Consumption Per Housing (MWh)
104.0

Denver CO – Chicago IL

No. of Farms **528**

Supply / Demand Ratio
6.13

Solar Generation (MWh)
481561343.4

Energy Demand (MWh)
78555282.8

Replacement Capacity (MWh)
22958721.7

Total Population
3350220

GHG Per Capita (mTons of Co2e)

High Priority Zones
14

Total Consumption Per Capita (MWh)
21.5

HVAC Trans Intersections
20

Total Consumption Per Housing (MWh)
55.9