U.S. Energy Parks

Co-locating e-fuel production with wind and solar

Benjamin Preneta, EER Summer Research Fellow

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Abbreviation Definitions

Abbreviation	Meaning	Notes
ADP	Annual Decarbonization Perspective	Report from Evolved Energy Research with coupled capacity expansion and demand models. See sources.
CAPEX	Capital Expenditures	Upfront capital costs for projects.
CF	Capacity Factor	The ratio of energy/output produced in a considered period to the maximum production with continuous power for the same period.
CPA	Candidate Project Area	Pre-defined area capable of having solar or wind farms installed.
FOM	Fixed Operation and Maintenance	Annual costs for operation and maintenance kept at fixed rate as opposed to variable year on year.
LCOE	Levelized Cost of Energy	Present value of total cost of building and operating energy facility. Derived by dividing total lifetime costs by energy produced.
LCOF	Levelized Cost of Fuel	Derived using same standard procedures commonly used for LCOE.
NLCD	National Land Cover Database	US Geological Survey map system characterizing land cover type and change in the US.
STS	Socio-Techno Suitability	Scoring system that measures social and economic opportunities alongside rail re-use. See Brownfield section.

Green Ammonia: A Potential High-Value Product

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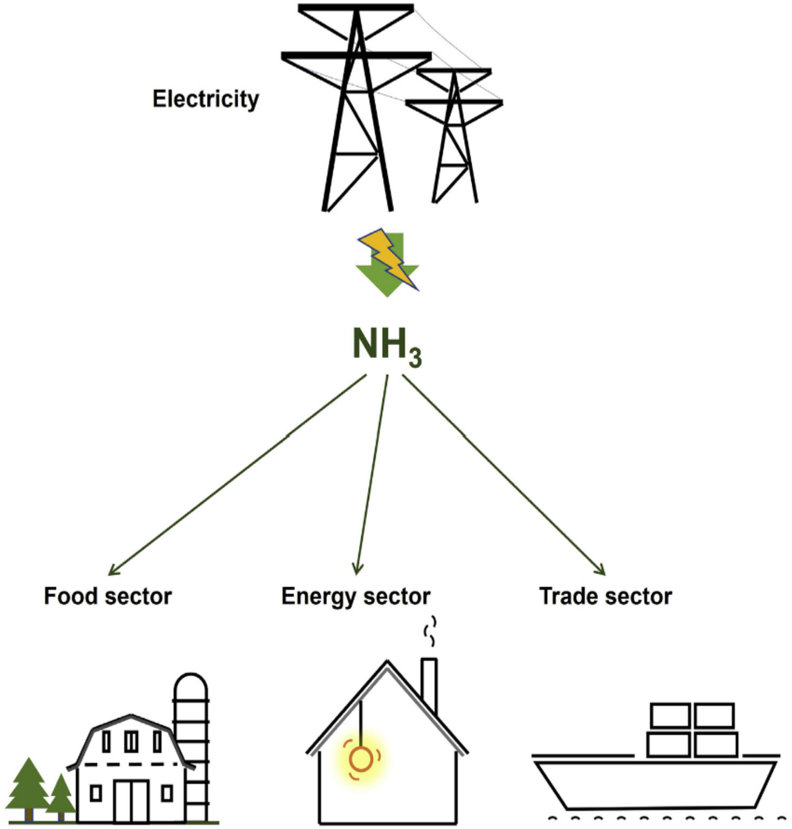
- Ammonia (NH_3) is a critical component of agricultural fertilizer and is an easy-to-transport, relatively dense store of energy.
- Around 3/4 of all NH_3 is used for fertilizer products with most of the remainder used in industry.
- Ammonia is one of the most emissions-intensive industrial products; globally 70% of ammonia uses natural gas and the remaining 30% uses gasified coal.[1]
- **There is a persistent domestic and export market for NH_3. Greening its production will greatly reduce agriculture-based emissions as well as provide a growing supply of easily transportable fuel and feedstock made from renewable energy.**

[1] IEA (2021), *Ammonia Technology Roadmap*, IEA, Paris https://www.iea.org/reports/ammonia-technology-roadmap, License: CC BY 4.0



Jain, M., Muthalathu, R., & Wu, X. Y. (2022). Electrified ammonia production as a commodity and energy storage medium to connect the food, energy, and trade sectors. *IScience*, *25*(8).

Objectives and Research Questions

- What factors affect the suitability for co-location of renewable energy and green ammonia production?
- Which factors favor the siting of energy parks at current thermal generation facilities and which favor creating new sites at highest quality renewable locations?
- What effects do economic opportunity, just transition, and social factors have on siting?
- How can the potential of hard-to-develop areas of high resource quality be unlocked by off-grid energy parks?
- How can targeted co-location potentially reduce the need for new transmission infrastructure?

Configuration Basics: Brownfield

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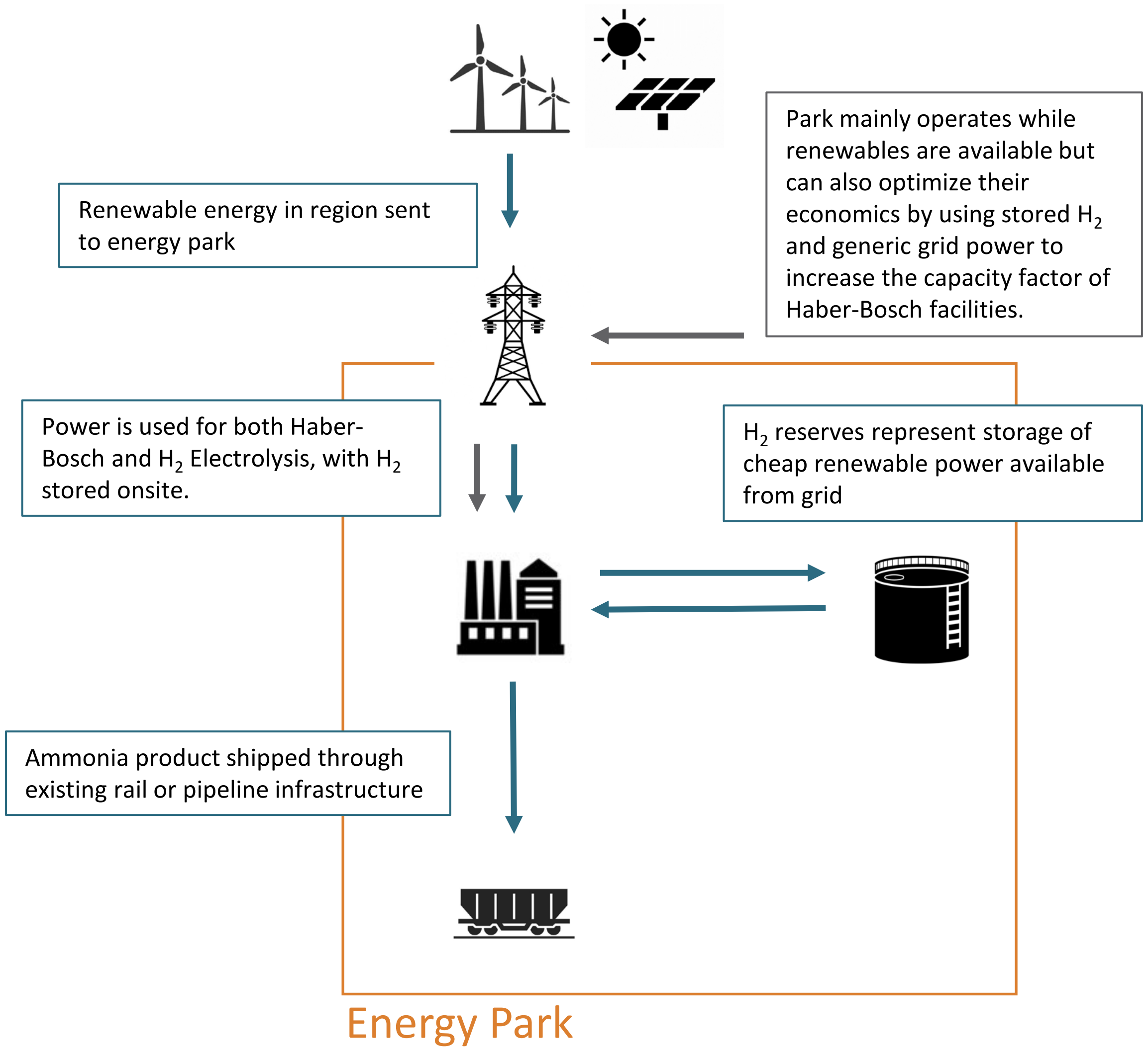
Co-located at existing thermal generation site (coal, natural gas, nuclear)

Uses existing high-capacity HVAC interconnection

Uses existing transport infrastructure such as rail or pipeline

Provides jobs across energy transition

Brownfield sites re-use depreciated assets such as rail and transmission lines to draw renewable electricity from the grid and to create and deliver clean energy in the form of ammonia. This strategy does not require the thermal generation plant to be closed but when they do retire, these energy parks will continue to provide jobs to the community.



Configuration Basics: Greenfield

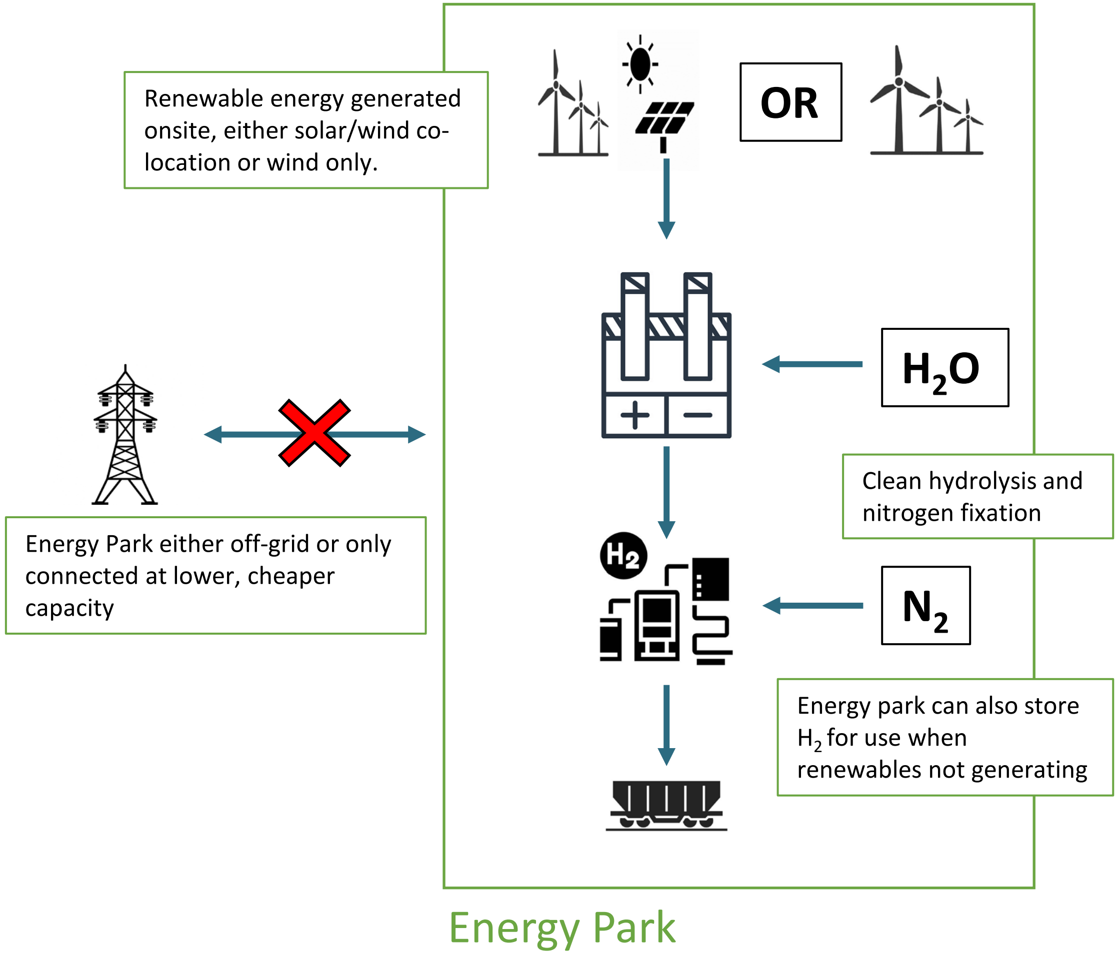
Co-located at new wind or wind/solar parks

Limited or no transmission connection to spurs or grid

Siting in locations otherwise unsuitable due to high transmission costs

Many high resource, remote areas are proximate to energy community locations

Greenfield sites are co-located with highest quality renewable resources in areas that would otherwise not be accessible due to high transmission costs. By remaining largely off grid, these configurations can use otherwise high-value locations while also limiting potential environmental impacts as well.



High Level Results

- **Goal:** This study uses GIS analysis techniques to locate the most suitable sites for both greenfield and brownfield energy parks, based on the levelized cost of fuel (LCOF) produced, non-climate environmental impacts, the potential for infrastructure reuse, economic opportunities for existing energy communities, and the potential for social friction.
- **Result:** The best sites in both greenfield or brownfield configurations are economically and environmentally sound, with low LCOFs. They provide opportunities for local communities, have low transmission barriers, and meet anticipated demand for both domestic ammonia consumption and clean energy and feedstock exports.

High Level Results

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Brownfield

- Clusters of high scoring potential brownfield facilities are found in the Midwest/Rust Belt , in East Texas, and in portions of the West.
- These sites require limited or no transmission upgrades, re-use depreciated infrastructure, and are predominantly located in heavily industrialized regions.

Greenfield

- Greenfield configurations are favored by wind/solar co-location in West Texas, and wind-only sites in the upper Midwest wind belt.
- These regions boast high-quality renewable resources that are difficult to unlock due to transmission costs. Additionally, they are often located in energy communities with existing export infrastructure.

High Level Results

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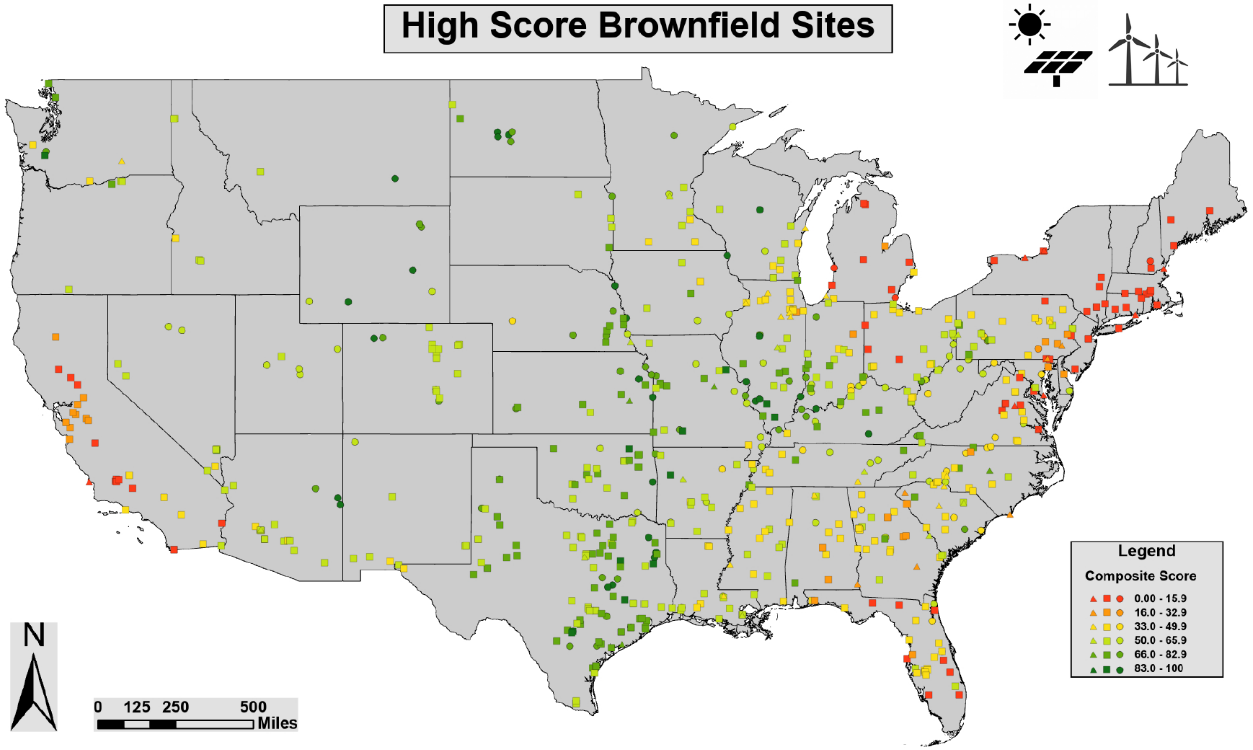

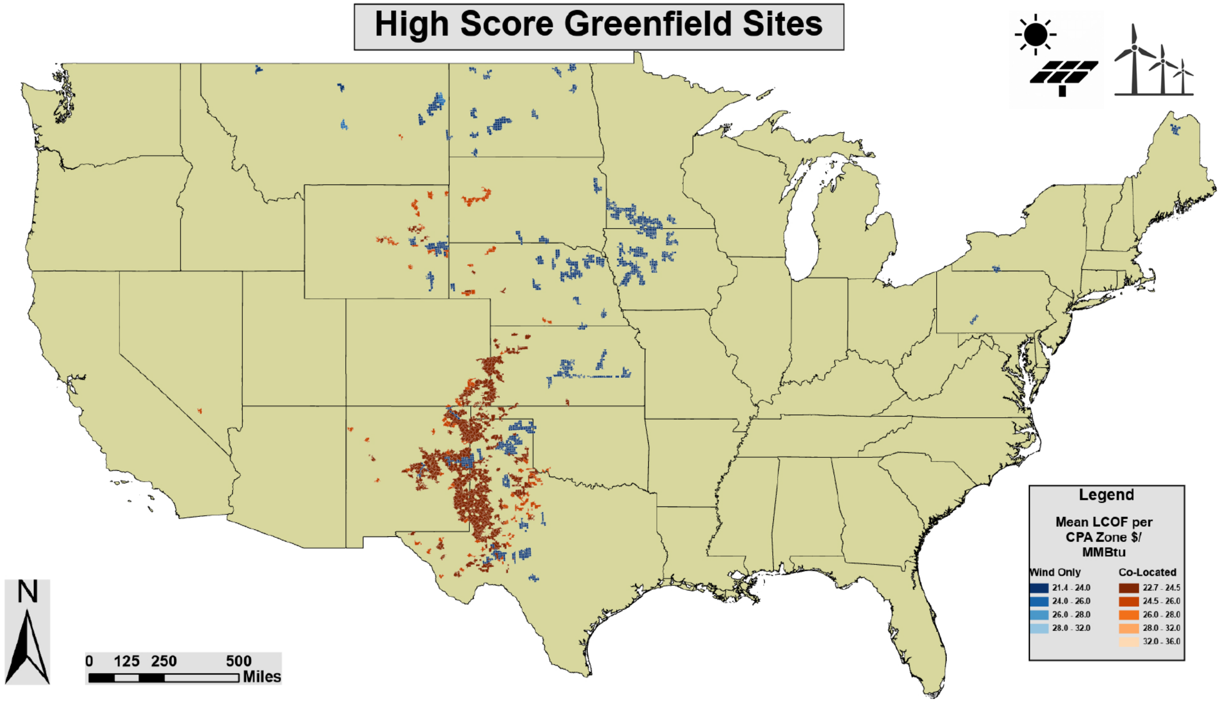

- The most suitable and low-cost greenfield and brownfield clusters are found in the heartland of domestic NH_3 use for agriculture, energy production and transport infrastructure, and energy/industrial communities.
- Regional and temporal conditions dictate which configurations in which places are best, but all take advantage of high-quality renewables. Greenfields create demand in current hard-to-develop areas.

Approach

Identify sites for co-location

Score sites with weighted environmental, social, and other suitability criteria

Restrict sites by environmental, social, and other suitability criteria

Filter sites by highest-scoring to analyze if meets 2050 demand

Progressively stricter criteria are imposed, allowing for assessment of optimal solutions.

Selected sites are compared against demand projections to understand feasibility.

Examining trends in site rejection also highlights selection factors.

Configuration Specific Methodology Overview

Brownfield

Identify Thermal Facilities

Restrict by Size and Available Land

Attach Composite Scores to Facilities

- Create Socio-Techno Suitability Score (STS)
- Project and Assign LCOF to Current Facilities
- Weight and Composite LCOF and STS

Select Sites by Score with ADP 2050 Demand

Greenfield

Union/Combine Solar and Wind CPAs

Create CPA 'Zones' with Genetic Algorithm

Attach LCOF, Friction, and STS to wind-only and Co-Location Configs

- Create LCOF per CPA and Select Configuration
- Build and Score Friction Score
- Socio Techno Suitability Score

Select Highest Scoring CPA Zones by Scenario

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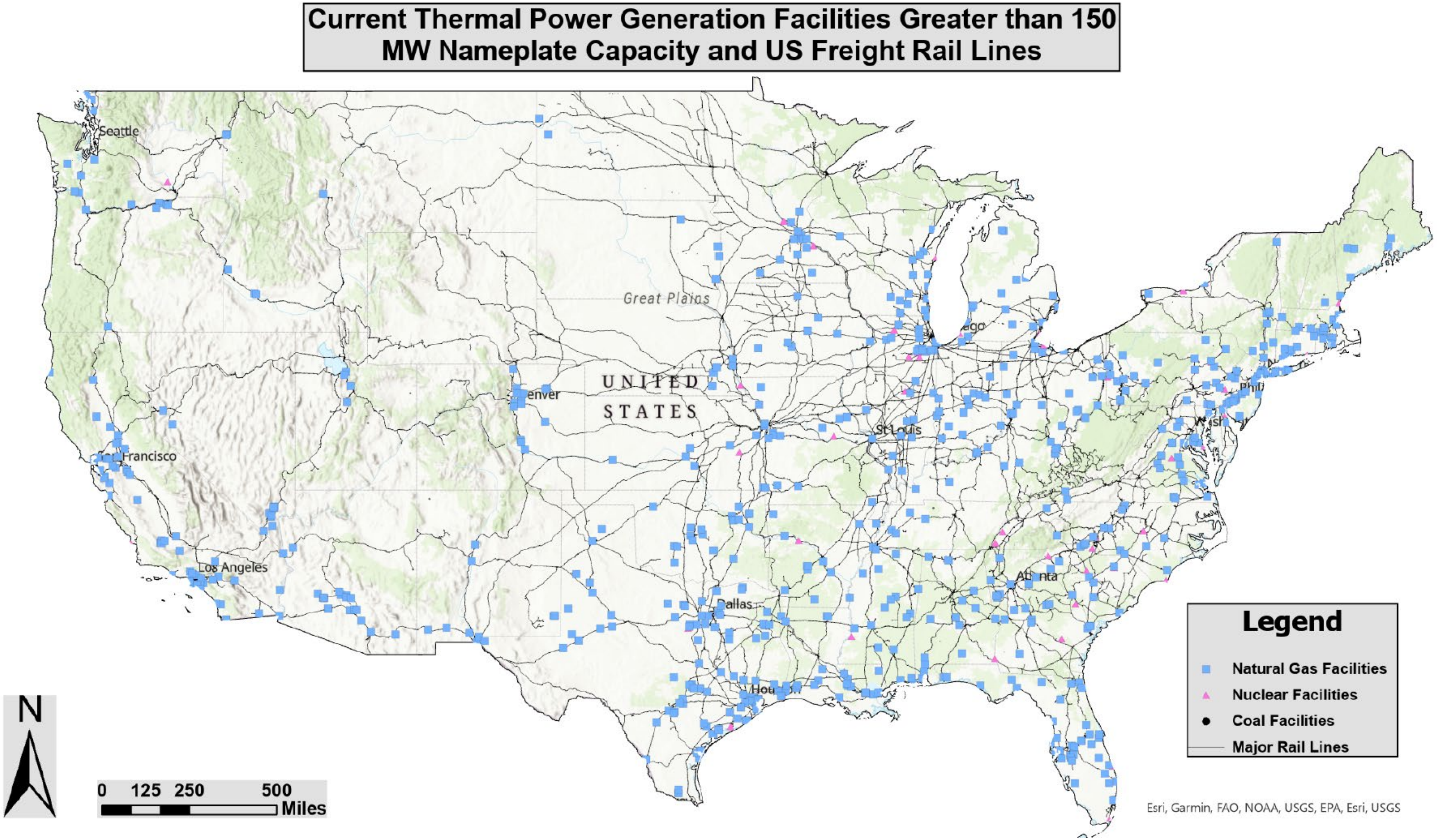
Brownfield Detailed Methodology and Results

Brownfield Planning Assumptions

Assumption	Value	Explanation	Sources
Ammonia Refinery Footprint (including electrolysis)	126,000m^2/100,000 tyr^{-1}	Based on average of 5 median ammonia refineries in US.	*See Brownfield Assumption Sizing Table Slide Below*
Energy Required for Ammonia Production (RE Feedstock)	12 MWh/t	Based on high range estimate from cited sources.	• Giddey, S. *et al*. (2017) • Jain M. *et al.* (2022) • NREL, Technology Brief: Analysis of Current-Day Commercial Electrolyzers (2004) • Tashie-Lewis, B. C., & Nnabuife, S. G. (2021)
Electricity Feedstock for Electrolyzer	55 kWh/kgH_2	Based on estimates from cited sources. Assumes 60% electrolyzer efficiency.	
Electrolyzer Size	<0.1km^2	Based on estimates from cited sources.	
NH_3 2050 Demand	128.4 TWh/yr or 24,731,182 t/yr	Assume 18.6 MJ/kgNH_3	ADP Output Data: • Haley, B. et al. (2022)
Maximum Renewable Feedstock Refinery Capacity Factor	67%	CF as high as 80% may be possible with storage and feedstock management, 67% as median scenario in other studies LCOA analysis.	• Jain M. *et al.* (2022)

Identify Thermal Facilities

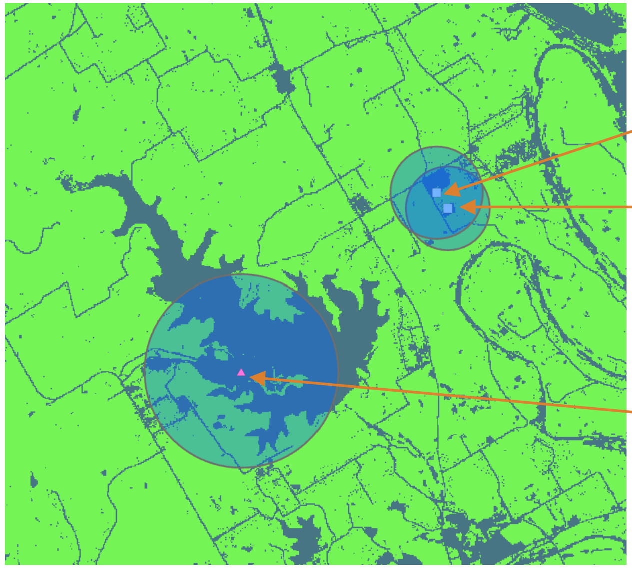


- Data from EIA and rail databases.
- Lowest 55% were removed. Majority of these are <50 MW. Resulting in only facilities >150MW nameplate capacity.
- Under 150 MW unlikely to provide transmission cost savings with co-location.

Restrict by Available Land: Buffer Creation

Facility Type	Average Base Footprint
Coal	2,820 m^2/MW
Natural Gas	1,390 m^2/MW
Nuclear	3,720 m^2/MW

Source: Stephens, Landon (2017). The Footprint of Energy: Land Use of U.S. Electricity Production. *Strata*. https://docs.wind-watch.org/US-footprints-Strata-2017.pdf and Department of Energy, (2017) Ultimate Facts Guide to Nuclear Energy. *DOE*. https://www.energy.gov/sites/default/files/2019/01/f58/Ultimate%20Fast%20Facts%20Guide-PRINT.pdf



A 1 km radius around each selected thermal facility was used to determined whether adequate space existed onsite next to the facility for ammonia production. A 1 km buffer was selected since larger radii have diminishing returns as facilities that did not have adequate space at 1 km rarely met criteria at higher even higher values and would not be considered onsite. Most large-scale space constraints were caused by large urban areas or coastlines/bodies of water.

Correction factor applied to account for larger facility footprints:

$$r_{facility}=1000+(1000*0.25*(Nc*Bf))$$

r= radius [m]

Nc= nameplate capacity

Bf= Average Base Footprint

Brownfield Sizing Assumption Table

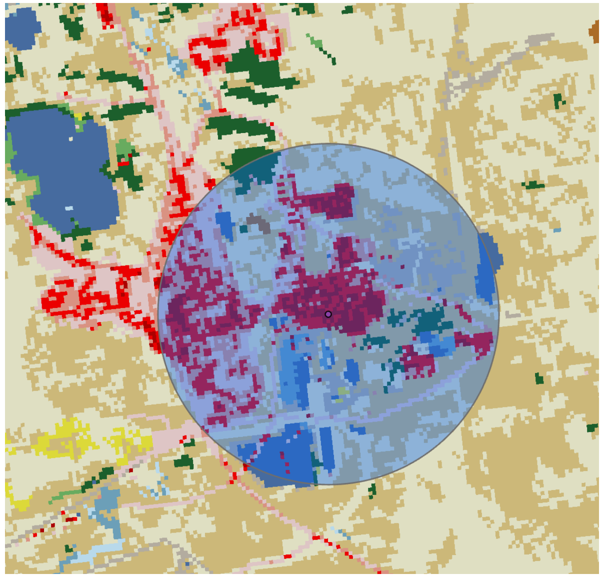
Plant	Output NH_3	Footprint	Sources
Courtright	500,000 t/yr	0.649 km^2	*https://www.cfindustries.com/who-we-are/locations/courtright-nitrogen-facility*
Geismar	535,000 t/yr	0.556 km^2	https://www.statista.com/statistics/1266392/ammonia-plant-capacities-united-states
Port Neal	1,230,000 t/yr	1.35 km^2	https://www.cfindustries.com/who-we-are/locations/port-neal
Verdigris	1,210,000 t/yr	0.421 km^2	https://www.cfindustries.com/who-we-are/locations/verdigris
Woodward	480,000	0.579 km^2	https://www.cfindustries.com/who-we-are/locations/woodward
Average Size → Final Size	**559,000**	**0.65 km^2 → 0.71km^2**	• Nutrien (2022)

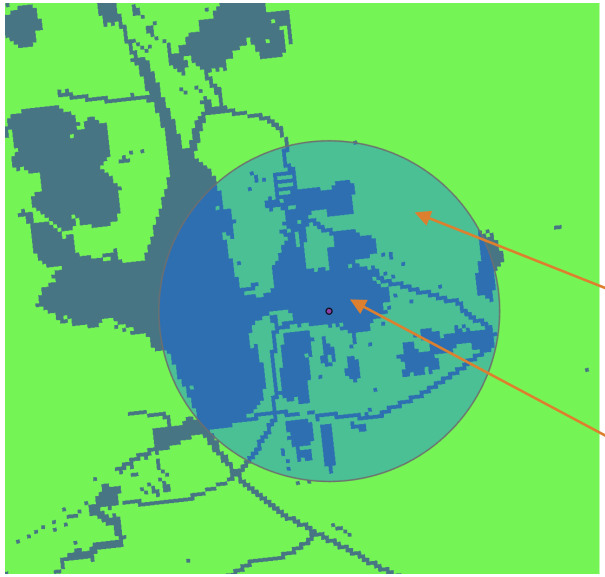
- Satellite imagery and Google Earth used to determine facility footprint size based off current locations.
- *Average Size* determined from all operating facilities and given the footprint value from shown selection average.
- Final output footprint per 100,000 t/yr^{-1} from adding 10% as ancillary error factor and electrolysis addition.

Restrict by Available Land: Suitability

NLCD Type	Suitability
Barren, Deciduous, Evergreen, Mixed, Shrub/Scrub, Herbaceous, Hay/Pasture, Cultivated	Suitable
Open Water, Perennial Snow/Ice, Developed (Open Space), Developed (Low Intensity), Developed (Medium Intensity), Developed (High Intensity), Woody Wetlands, Emergent Herbaceous Wetlands,	Unsuitable

NLCD land classes determine whether pixel is suitable or not. Pixel size 30x30m.





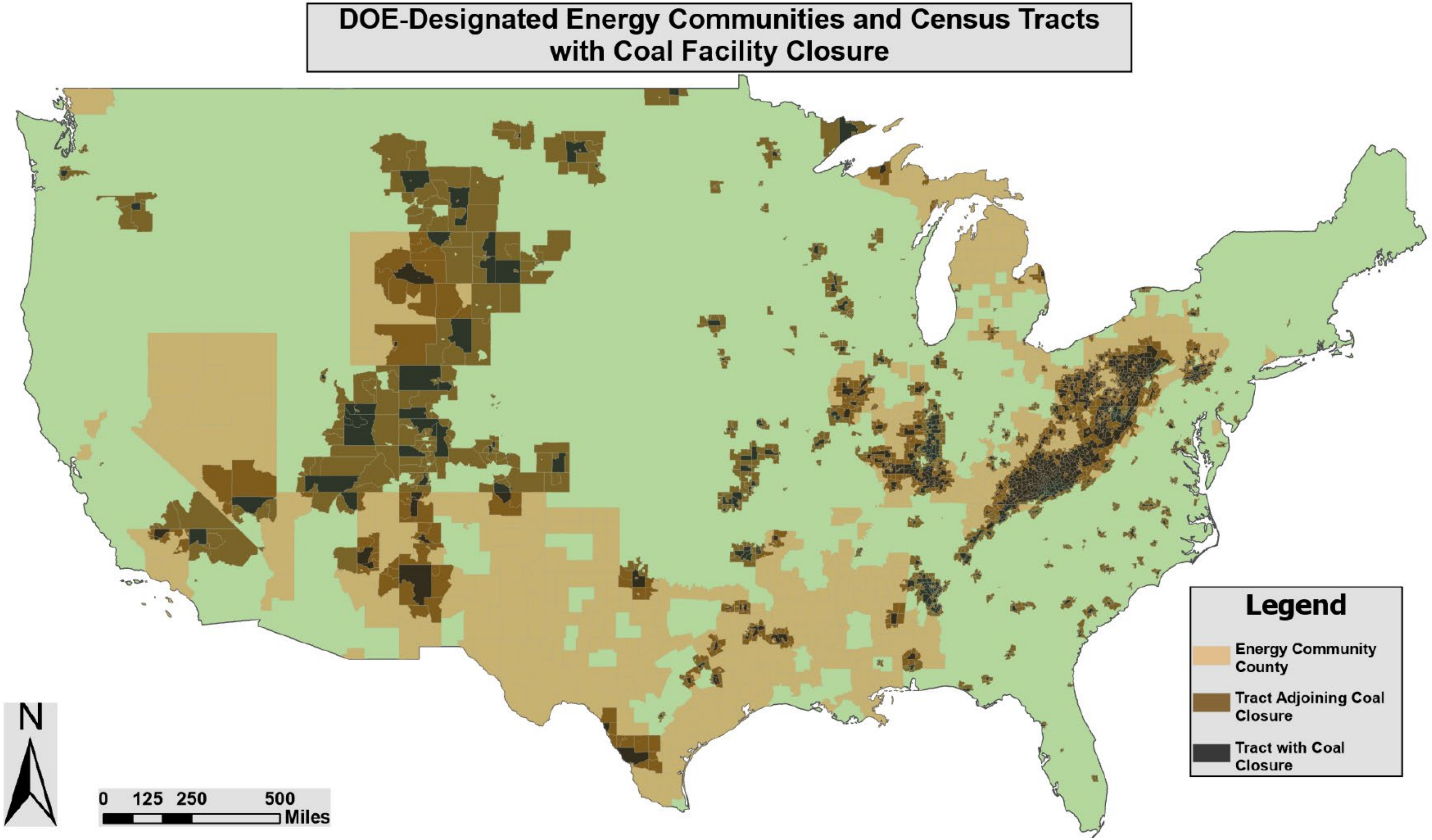
Site selected if buffer contains $\geq$ 0.71km^2 of area for refinery expansion.

Create Socio-Techno Suitability Score (STS)

The Socio-Techno Suitability (STS) Score was created by combining social/economic opportunity data with rail infrastructure data.

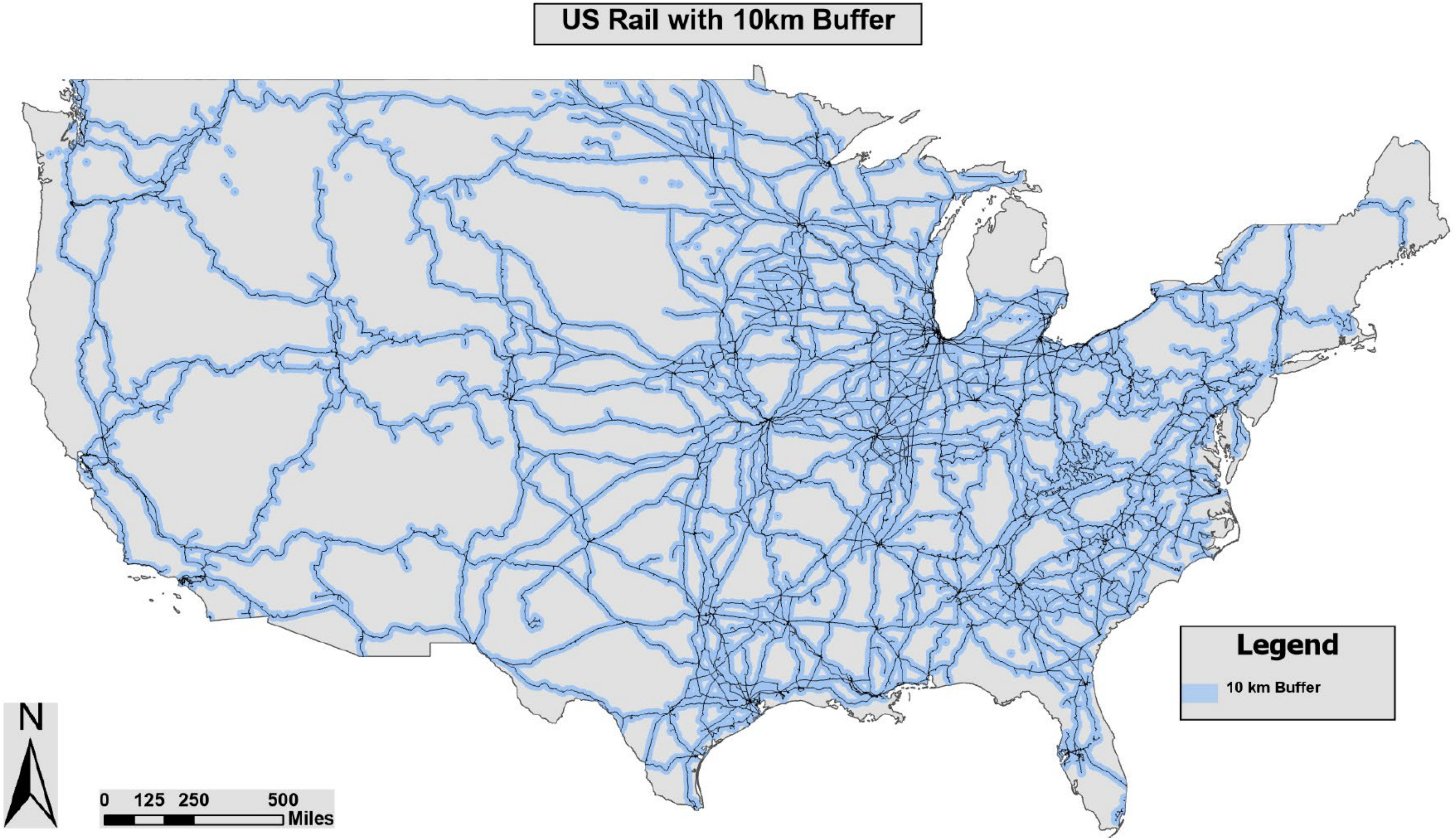
Energy Communities and Coal Closure extracted from Department of Energy Data.

Note: Energy Communities are at county level while coal facility closures are at census tract level.



Create Socio-Techno Suitability Score (STS)

Rail lines as an output vector from thermal facilities. While further techno-economic assessments would examine actual decisions around export from refineries (rail/pipeline/road/barge), rail proximity provides strong proxy for devalued infrastructure re-use.



STS Combination

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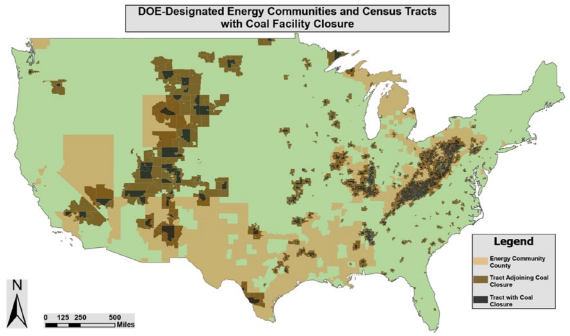
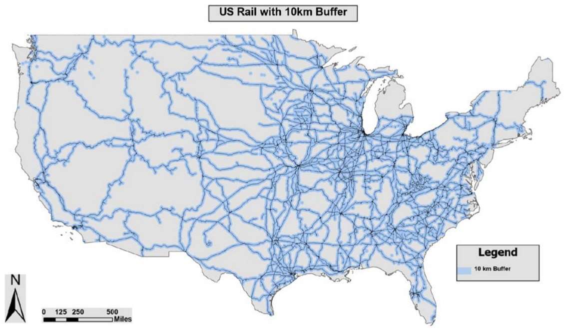
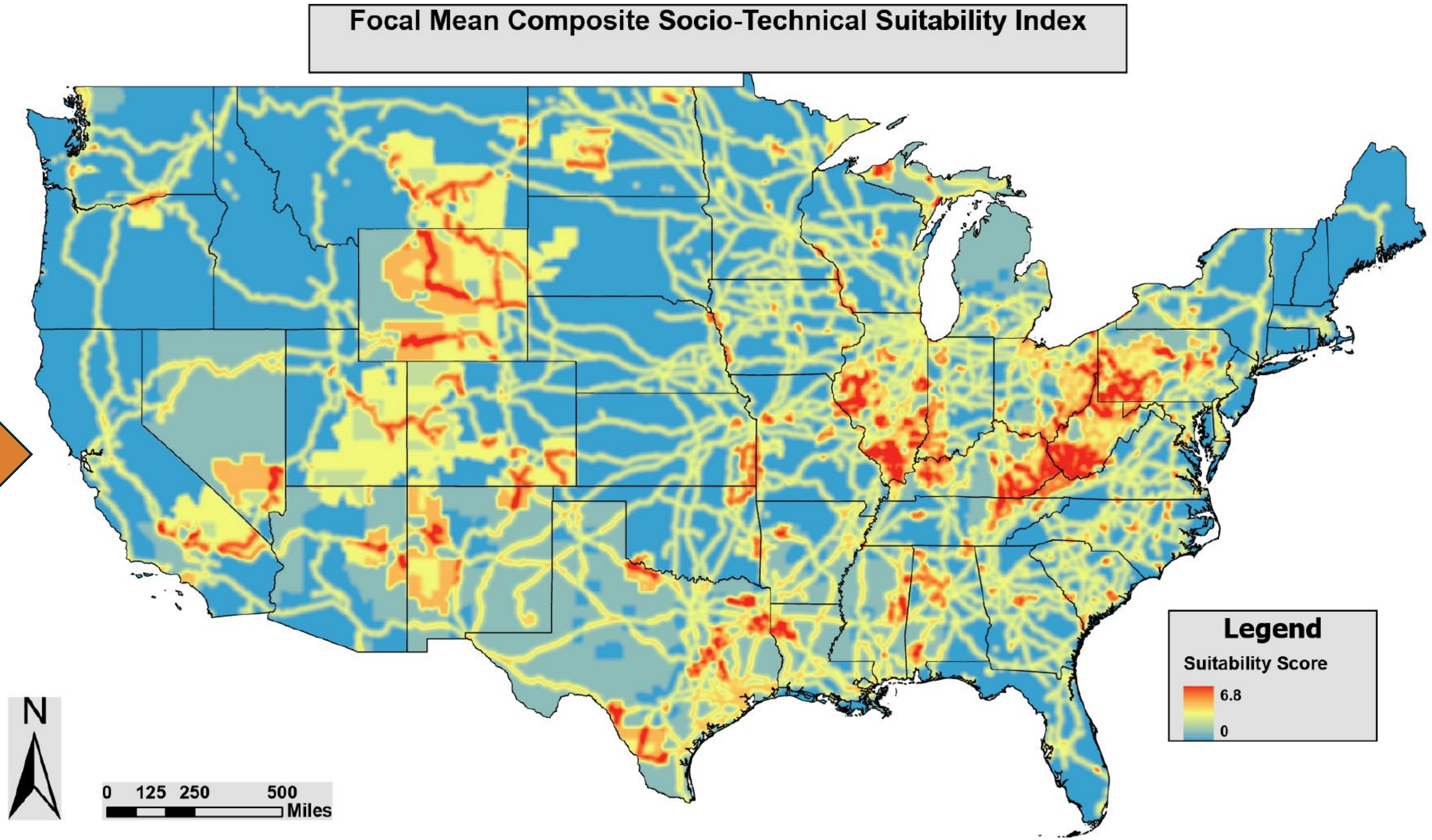
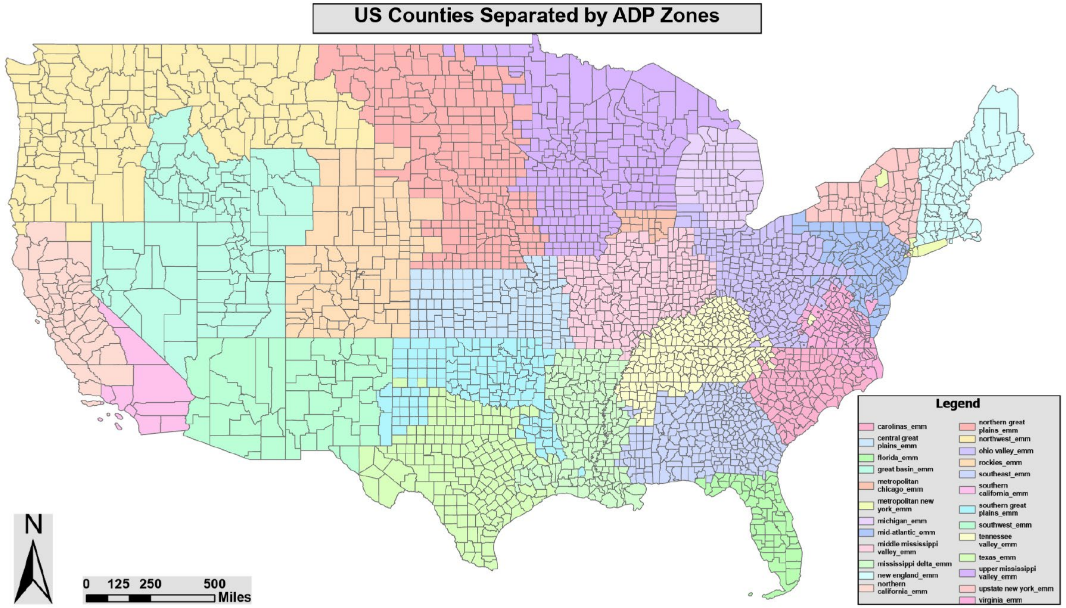






Project LCOF per Zone and Assign to Facilities



1. ADP EMM Zones assigned LCOEs from shadow price of electricity using weighted average of annual demand from 2035, 2040, 2045, and 2050. Data are solely energy, no additional costs. Central Scenario RIO/EP model base.
2. 2035 LCOE used as feedstock for electricity and electrolysis values alongside NH_3 CAPEX and FOM to determine basic LCOF.
3. LCOF attached to plants by ADP Zone

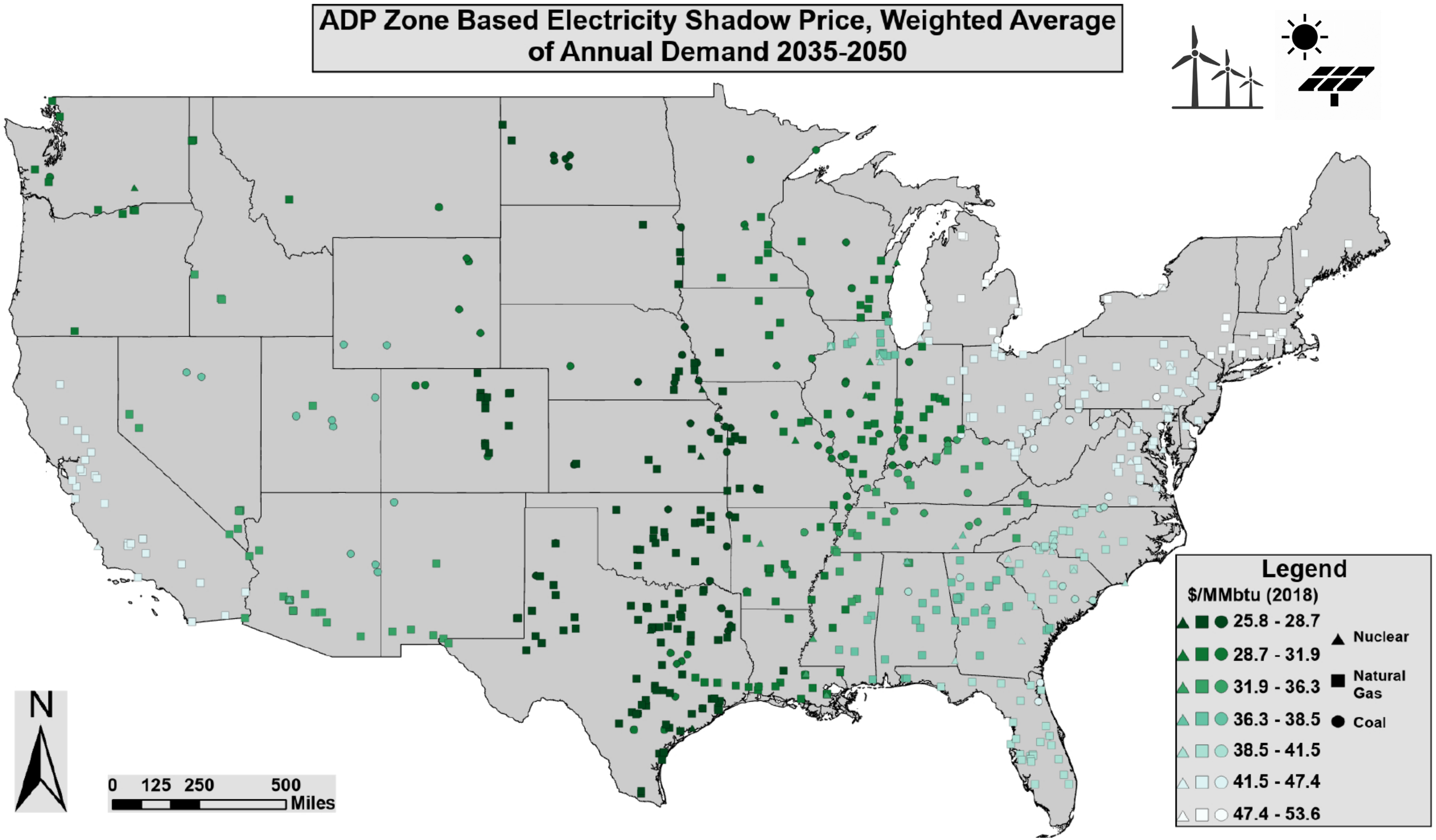
LCOF Calculation Assumption	Value
Refinery CF	67%
Capital Recovery Factor	9.4% (Based on 8% Cost of Capital)
CAPEX	677 \$/kW-output
FOM	20.3 \$/kW-output-yr^{-1}
Feedstock$_{e-}$	0.36 MWh/20MMBtu
Feedstock$_{H2}$	234.7kg/20MMBtu

Adapted from: "Low Carbon Fuel Components" Gabe Kwok, Evolved Energy Research 2021.

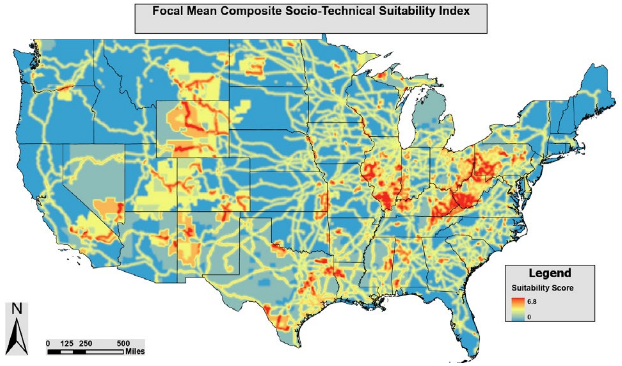
3.17 \$/MMBtu + 1.01 \$/MMBtu + FE + FH=LCOF \$/MMBtu

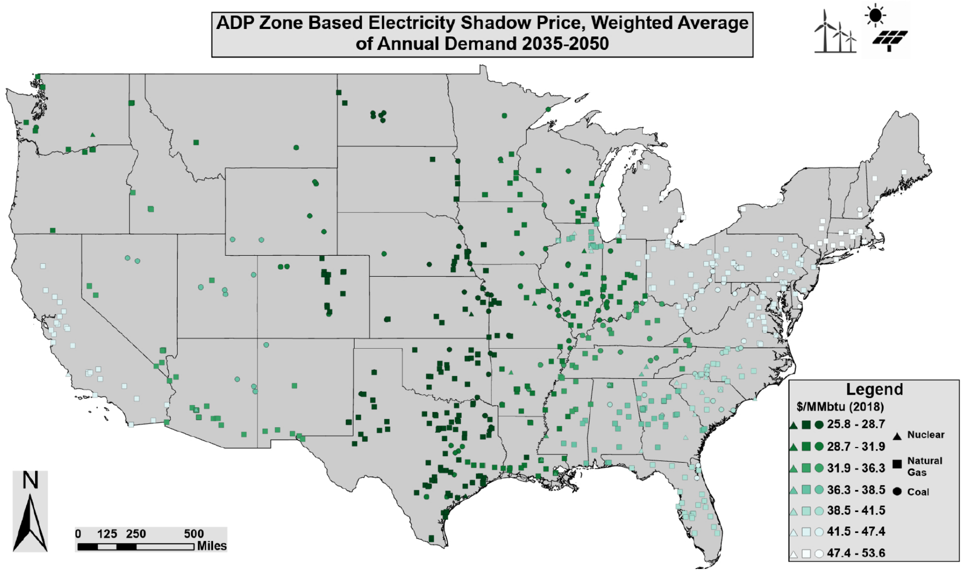
$$FE=[LCOE_{EMM}]*[Feedstock_{e-}]$$
$$FH=[LCOE_{EMM}]*55*[Feedstock_{H2}]$$

Renewable Feedstock LCOF



Weight Scores and Composite





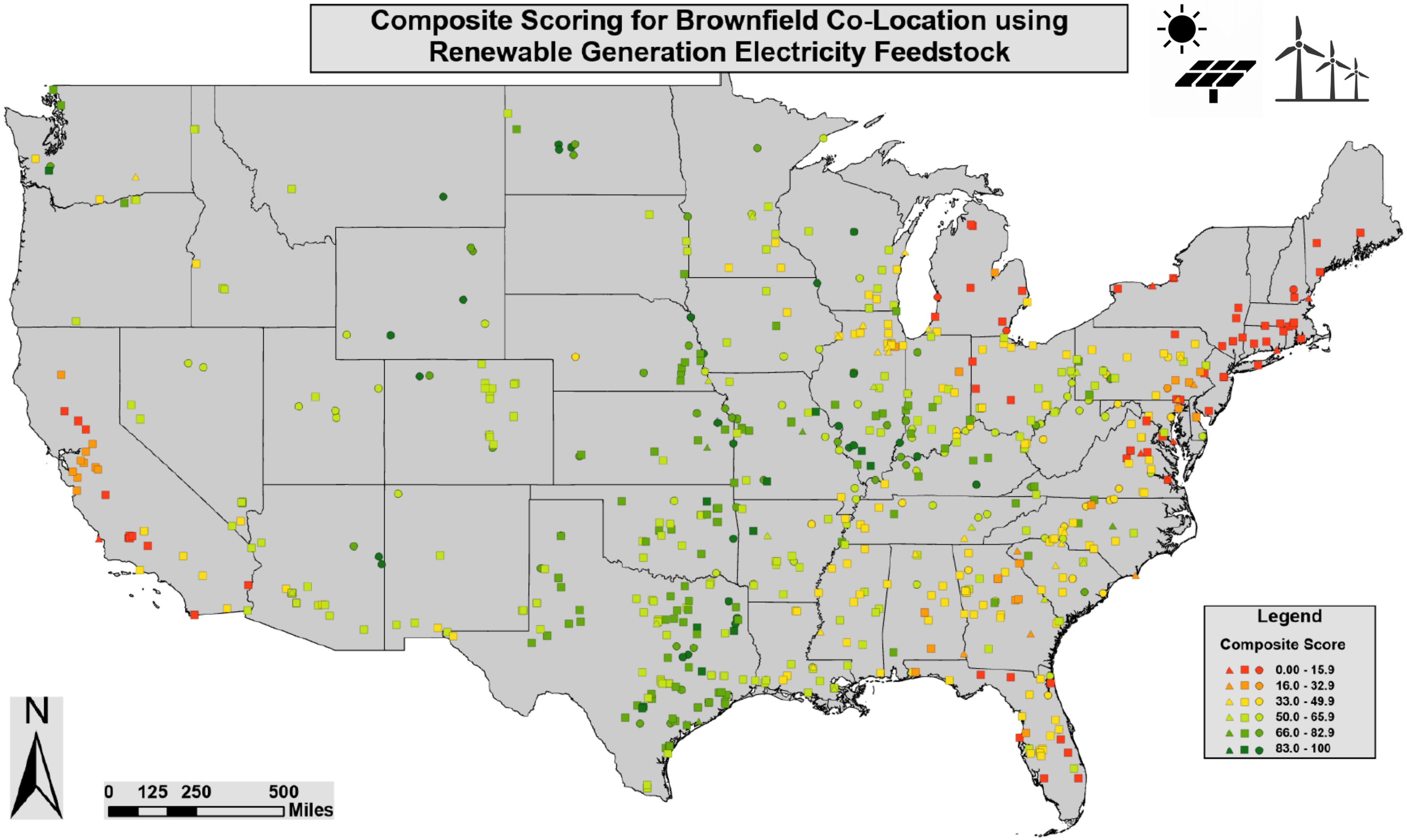
LCOF	Score
25.8-28.7 $/MMBtu	66.6
28.7-31.9 $/MMBtu	55.5
31.9-36.3 $/MMBtu	44.4
36.3-38.5 $/MMBtu	33.3
38.5-41.5 $/MMBtu	22.2
41.5-47.4	11.1
>47.4	0.00

Attribute	Score
Rail within 10km	5.55
Rail within 5km	5.55
Energy Community	5.55
Coal Closure adjacent Tract	11.1
Coal Closure in Tract	16.6
Max	**33.3**

The STS score and the LCOF values are now combined and weighted into a composite score that reflects the relative importance of each attribute for determining the most suitable sites and trend examination. The total maximum score is 100. The weighting was designed to allow high STS to improve medium LCOF areas above solely high LCOF areas but never outweigh the maximum LCOF areas. LCOF categories assigned using Jenks Distribution for natural breaks.

Maximum STS is 33.3 due to cumulative rail scores but exclusive between ‘coal adjacent’ and ‘coal containing’. Rail within 5km will naturally also be within 10km but an adjacent tract cannot also be a containing tract.

Composite Sites and Scores

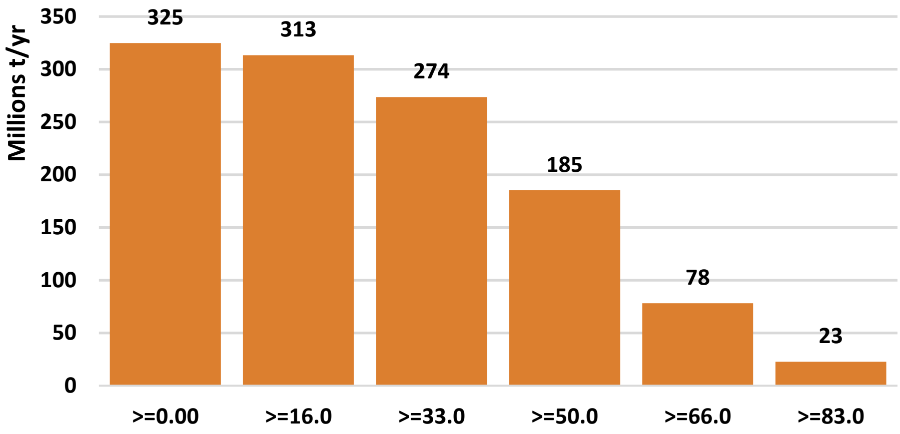


Rustbelt/Midwest experience higher scores due to social benefits combining with average to above average LCOF.

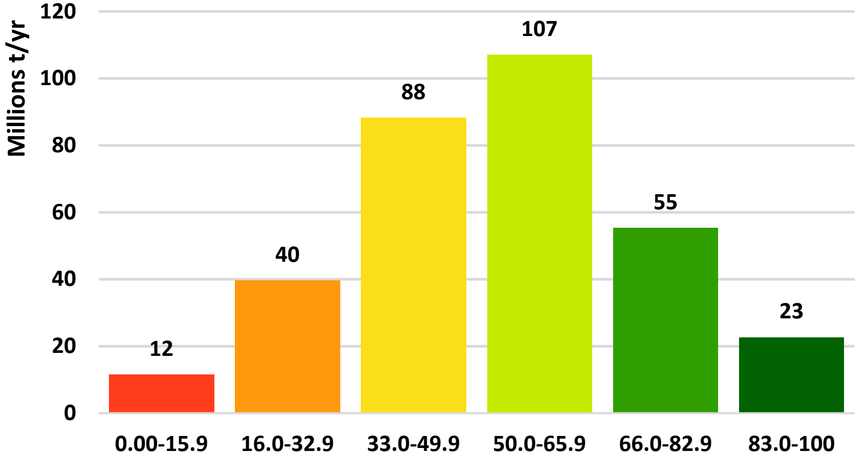
Texas and West/Southwest also gain scores in select locations that benefit from high quality solar but less widespread STS score boosts.

Results: Brownfield Capacity

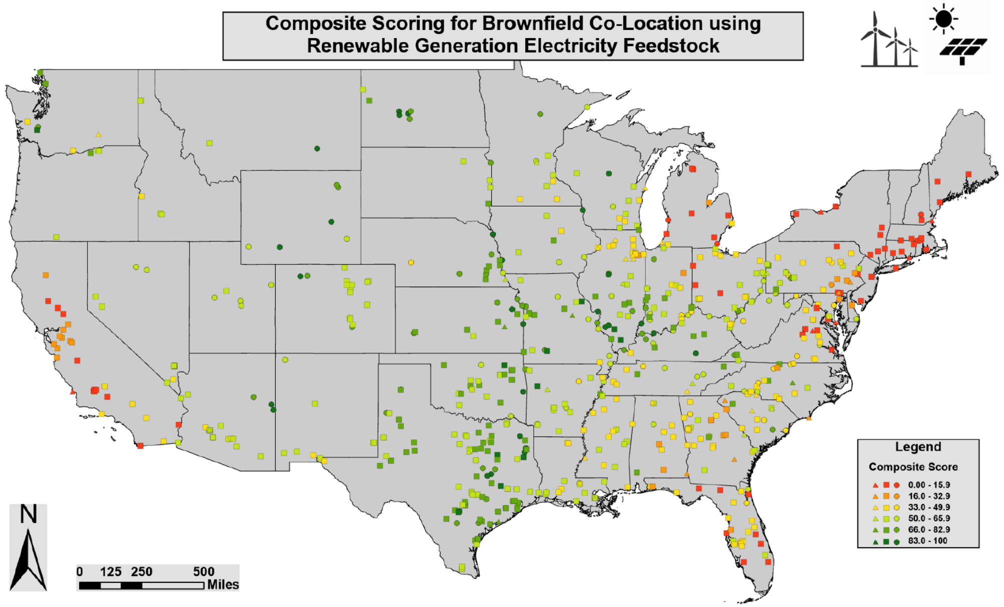
Brownfield Aggregate Potential Yield by Restriction Level



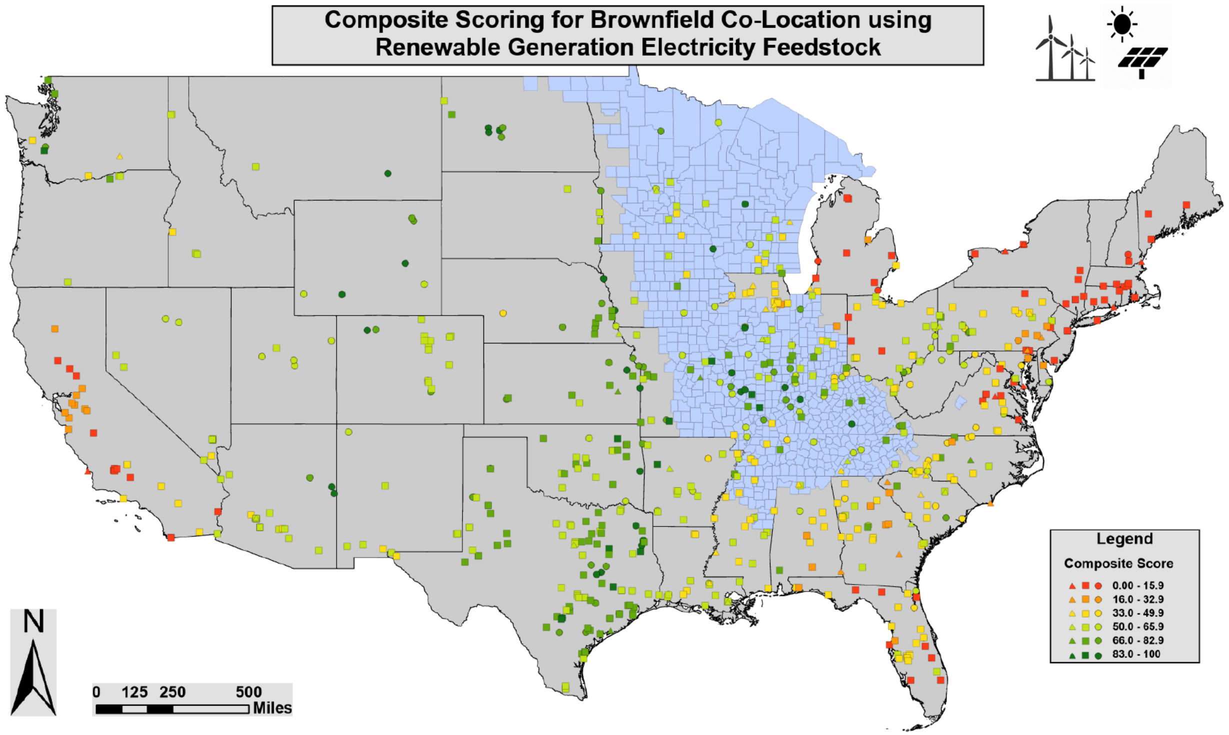
Brownfield Potential Yield by Individual Bin

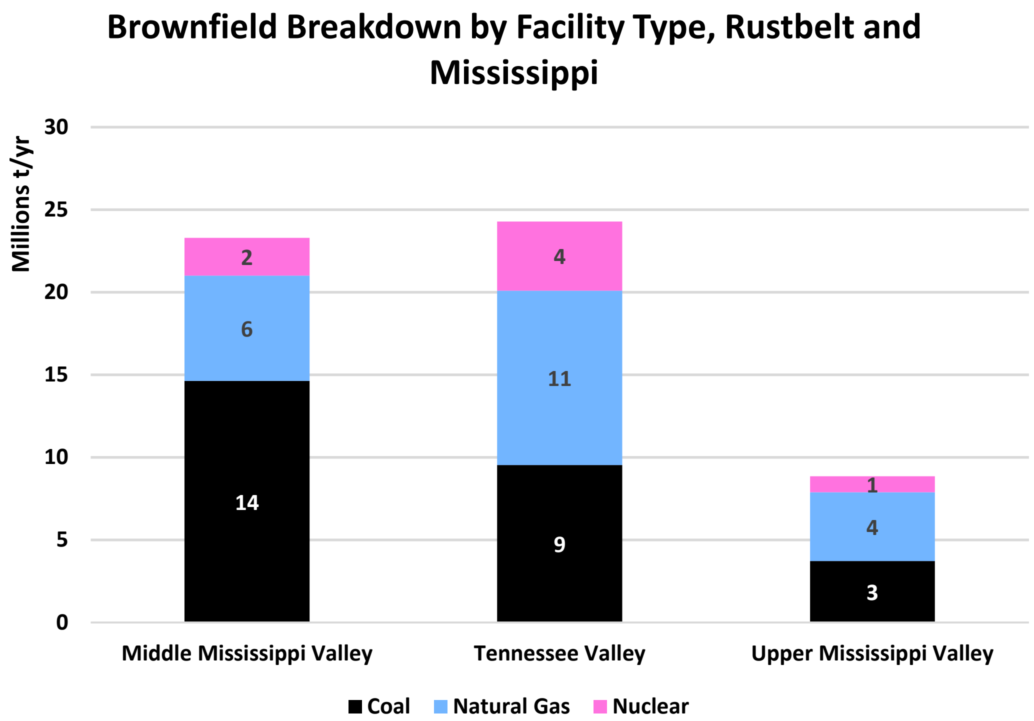


- High-scoring plants provide ample ammonia capacity to exceed 2050 projections for domestic demands of 24 million t/yr.
- Excess ammonia capacity along export routes to the Gulf offer potentially lucrative export of clean energy.
- **Coal sites score high in Midwest and West/Rockies; natural gas scores high in Texas and Great Plains.**



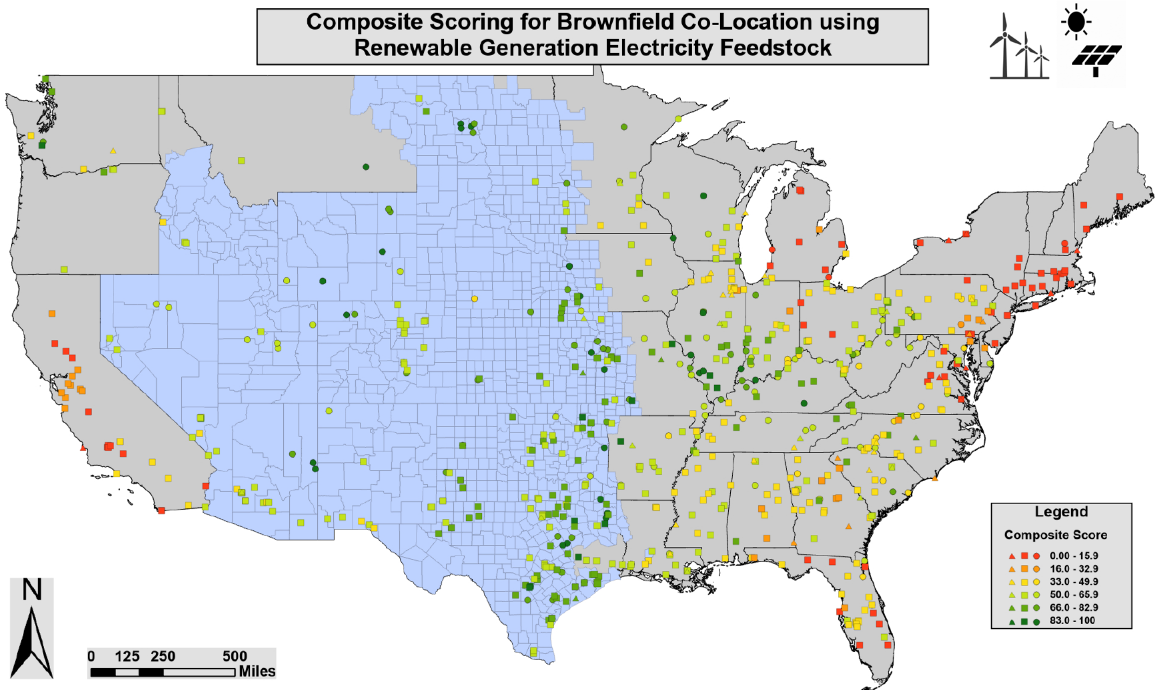
Results: Brownfield Analysis Rust Belt

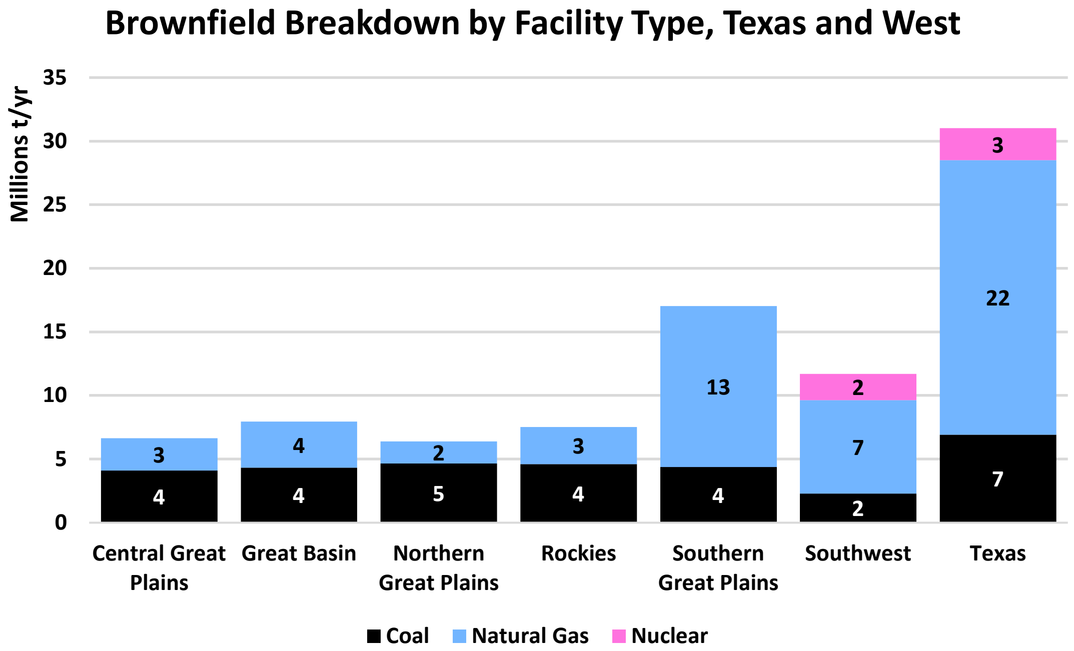




- Rust belt, (Middle Mississippi, Tennessee Valley, and Upper Mississippi Valley Zones) have high average score (59) with coal plant co-location offering strong potential options. *Note: Ohio Valley omitted because despite having high number of facilities LCOF jumps from mid 30 $/MMBtu to low 40 $/MMBtu.*
- Coal also outperforms natural gas in these zones with an average score of 63.

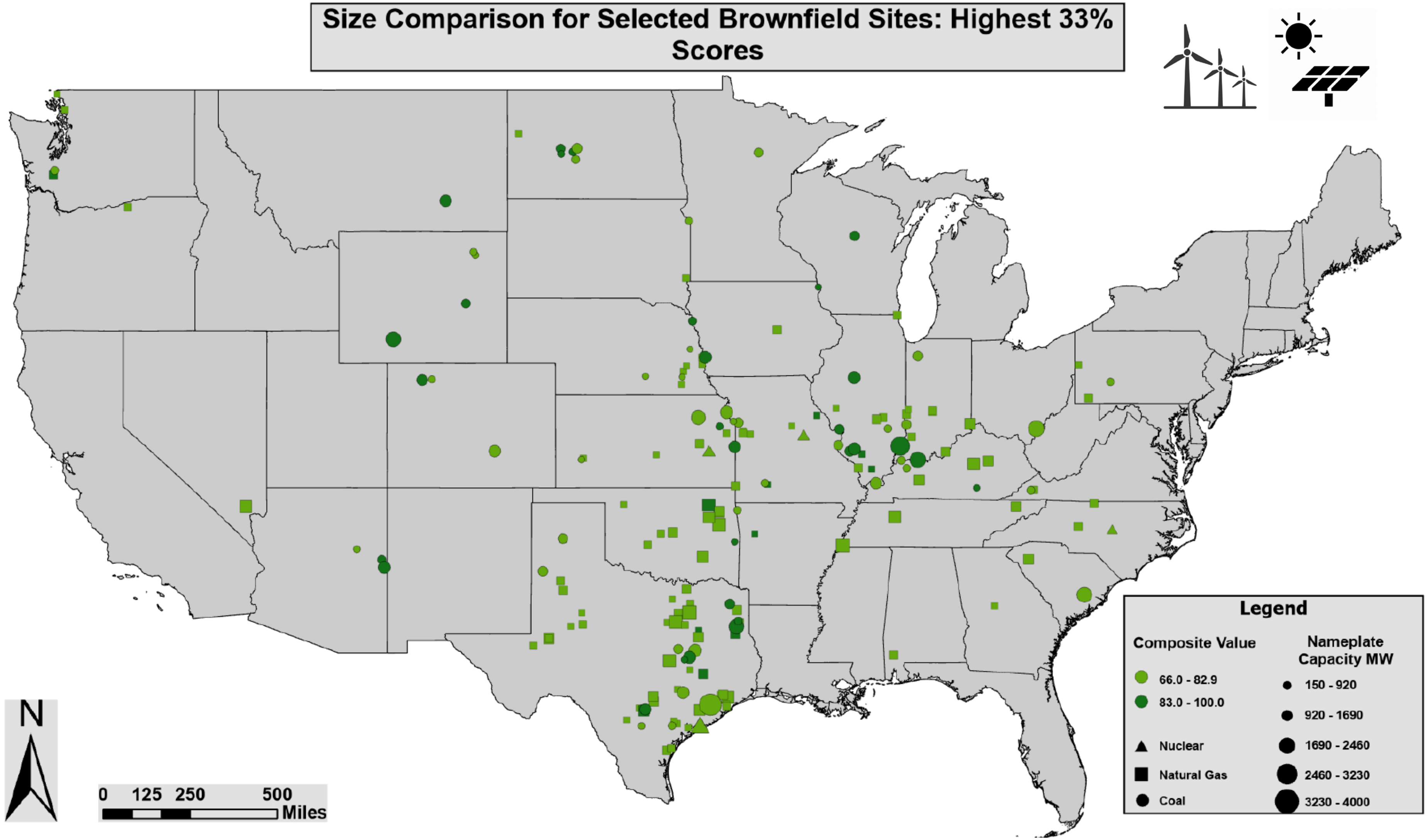
Results: Brownfield Analysis Texas and West





- Natural gas-based brownfields dominate in Texas and the West. Texas itself has a composite average score of 68 while the remainder of the West has a score of 61.
- While STS scores are lower in Texas and the Great Plains, these zones enjoy low LCOF and some regionally-determined energy communities. The proximity to potential export in the Gulf also creates high potential.

Results: Size Analysis Selection



- Applying filter for the highest 33% of scorers further highlights the potential of larger coal plants to contribute significantly as brownfield sites.
- This selection yields roughly **78,000,000 t/yr** compared to the estimated **24,000,000 t/yr** domestic 2050 demand.
- Mid-sized natural gas facilities are also important across most zones

Brownfield Analysis Results Summary

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Examining geographic clustering and facilities by type yields notable trends:

1. Large coal facilities feature prominently in the highest scoring percentile of plants pointing to potential re-use opportunities for large employers that may be shutting down sooner.
2. Medium-sized natural gas facilities in Texas are on average the highest scoring group demonstrating a region with strong growth potential across smaller facilities.
3. Even with strict score requirements, there are more than enough facilities to not only meet domestic demand but also provide opportunities for export.
4. High scoring clusters are found along key export routes towards the Gulf of Mexico.

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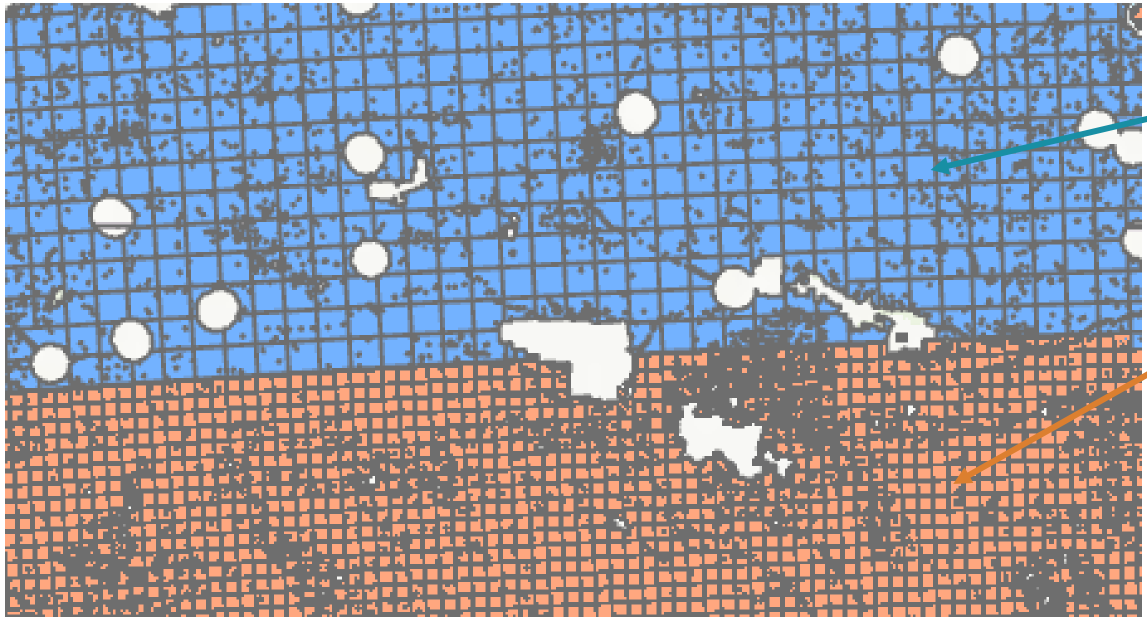
Greenfield Detailed Methodology and Results

Greenfield Assumptions

Assumption	Value	Explanation	Sources
Renewable Candidate Project Areas (CPAs)	See CPA Section	CPAs used in EER's 2023 ADP	Princeton ZERO Lab
Average US NH_3 Refinery Output	559,000 t/yr	Simple mean of NH_3 capacity from source.	Nutrien (2022)
Average Refinery Energy Requirements	6708 GWh/yr	Assume 12 MWh/t.	• Giddey, S. *et al*. (2017) • Jain M. *et al.* (2022) • NREL, Technology Brief: Analysis of Current-Day Commercial Electrolyzers (2004) • Tashie-Lewis, B. C., & Nnabuife, S. G. (2021)
NH_3 2050 Demand	128.4 TWh/yr or 24,731,182 t/yr	Assume 18.6 MJ/kgNH_3	ADP Output Data: • Haley, B. et al. (2022)
Wind and Solar Basic CAPEX and FOM	See LCOF Section	See LCOF Section	*NREL (2023)*

Combine Wind and Solar CPAs



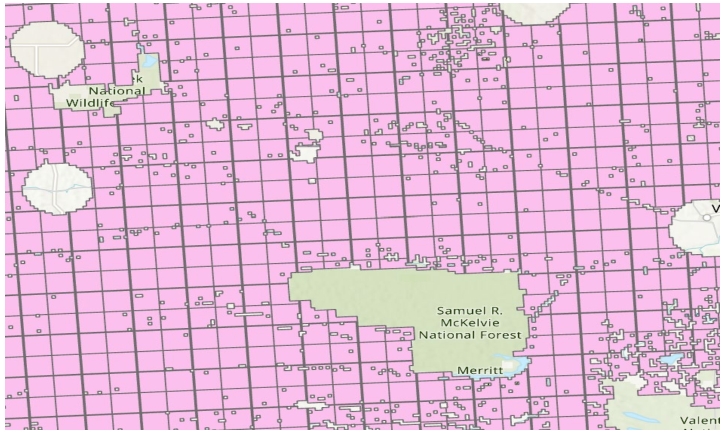
121 km^2

30.25 km^2

1. New CPA geometry is used to determine individual areas.
2. Potential capacity per CPA calculated using **2.7 MW/km²** wind and **6.3 MW/km²** solar tracking with **30:70** deployment ratio.[1]
3. CPA-specific capacity factors extracted from original datasets.
4. CPAs assigned both a summed solar and wind potential (co-location) and a wind-only potential.

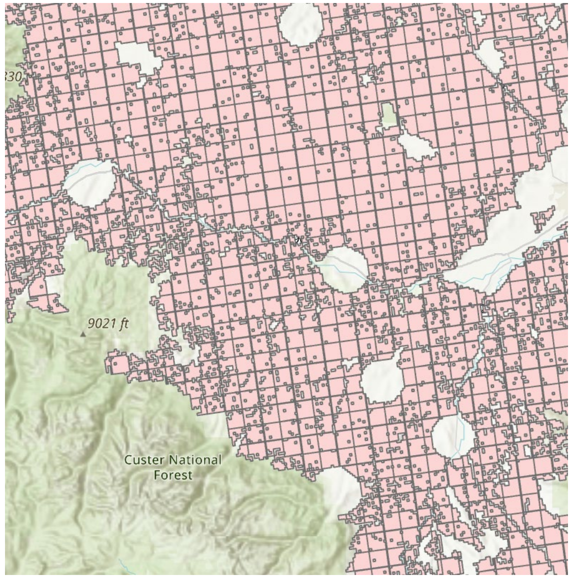
Union all CPAs for polygons that contain both solar and wind inputs for co-location.

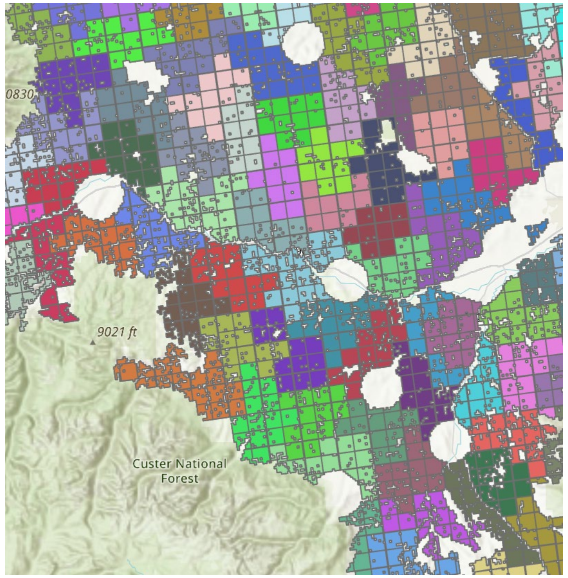
New grid contains data from each previous dataset.



[1] TNC (The Nature Conservancy) (2023). Power of Place: Clean Energy Solutions that Protect People and Nature. *Technical Briefing Deck*. https://www.nature.org/content/dam/tnc/nature/en/documents/TNC_Power_of_Place_National_Technical_Briefing.pdf

Generate CPA Zones





New CPA 'Zones' are created by summing yearly GWh into potential tons [NH_3] output of 'unioned' CPA polygons. New zones are either contiguous by side only (not vertex) or through the nearest disconnected polygon. Attribute target for the zones is potential energy output of **559,000 t/yr [NH_3]**.

Algorithm also set for maximum compactness of zones: more circular zones are prioritized in selection.

Genetic algorithm builds contiguous zones until it reaches the attribute target with initial 'seed' population (set to **500 zones**). It then selects the top 50% by 'fitness score' determined by how far the selection varies from the perfect solution. This process continues for **100 generations** with mutations added (at a **20% rate**) to increase solution diversity.

Assign LCOF Per CPA and Average

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1. Single year LCOE generated by CPA using NREL ATB data for 2035. **This step done for both wind-only configuration and co-location configuration.**
2. LCOE converted to LCOF using same process as brownfields.
3. LCOF attached to each ‘unioned’ CPA with **lower LCOF determining with wind-only or co-location**.
4. ‘Unioned’ CPA combined via genetic algorithm into wind-only or co-locate CPA Zone.
5. LCOF averaged across larger CPA Zone of adjacent wind-only or co-location to create average index.

1

LCOE Calculation Assumption	Value
Wind CAPEX	1,093 $/kW
Wind FOM	26 $/kWyr^{-1}
Solar CAPEX	890 $/kW
Solar FOM	16 $/kWyr^{-1}
Capital Recovery Factor	8.8% (Based on 8% Cost of Capital)

CPA Single Year 2035 LCOE=

$$([(CAPEX_{wind}+CAPEX_{solar})*CRF]+[FOM_{wind}+FOM_{solar}])/Output_{co\text{-}location}$$

Assign LCOF Per CPA and Average

2

LCOF Calculation Assumption	Value
Refinery CF	67%
Capital Recovery Factor	9.4% (Based on 8% Cost of Capital)
CAPEX	677 \$/kW-output
FOM	20.3 \$/kW-output-yr^{-1}
Feedstock$_{e-}$	0.36 MWh/20MMBtu
Feedstock$_{H2}$	234.74kg/20MMBtu

Adapted from: "Low Carbon Fuel Components" Gabe Kwok, Evolved Energy Research 2021.

LCOF \$/MMBtu=3.17 \$/MMBtu + 1.01 \$/MMBtu + FE + FH

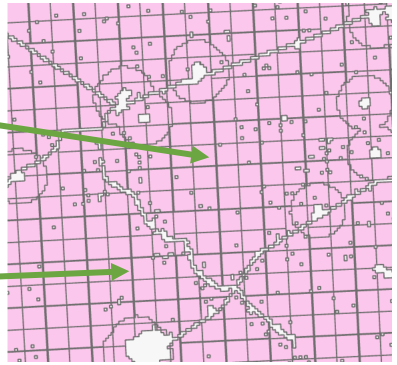
$FE=[LCOE_{co\text{-}locate}]*[Feedstock_{e-}]$

$FH=[LCOE_{co\text{-}locate}]*55*[Feedstock_{H2}]$

3

Co-locate=25.1 MMBtu
Wind= 22.9 MMbtu

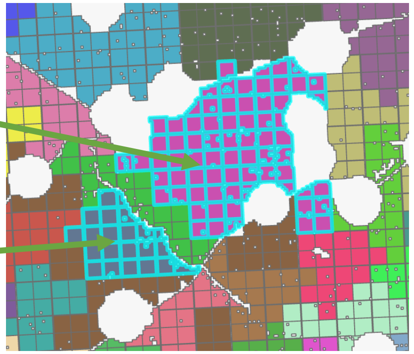
Co-locate=23.9 MMBtu
Wind= 24.2MMbtu



4

CPA Zone built with CPAs where wind-only LCOF is lower.

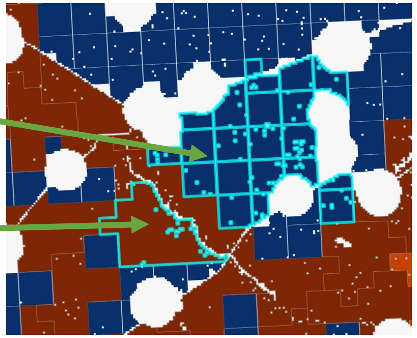
CPA Zone built with CPAs where co-location LCOF is lower.



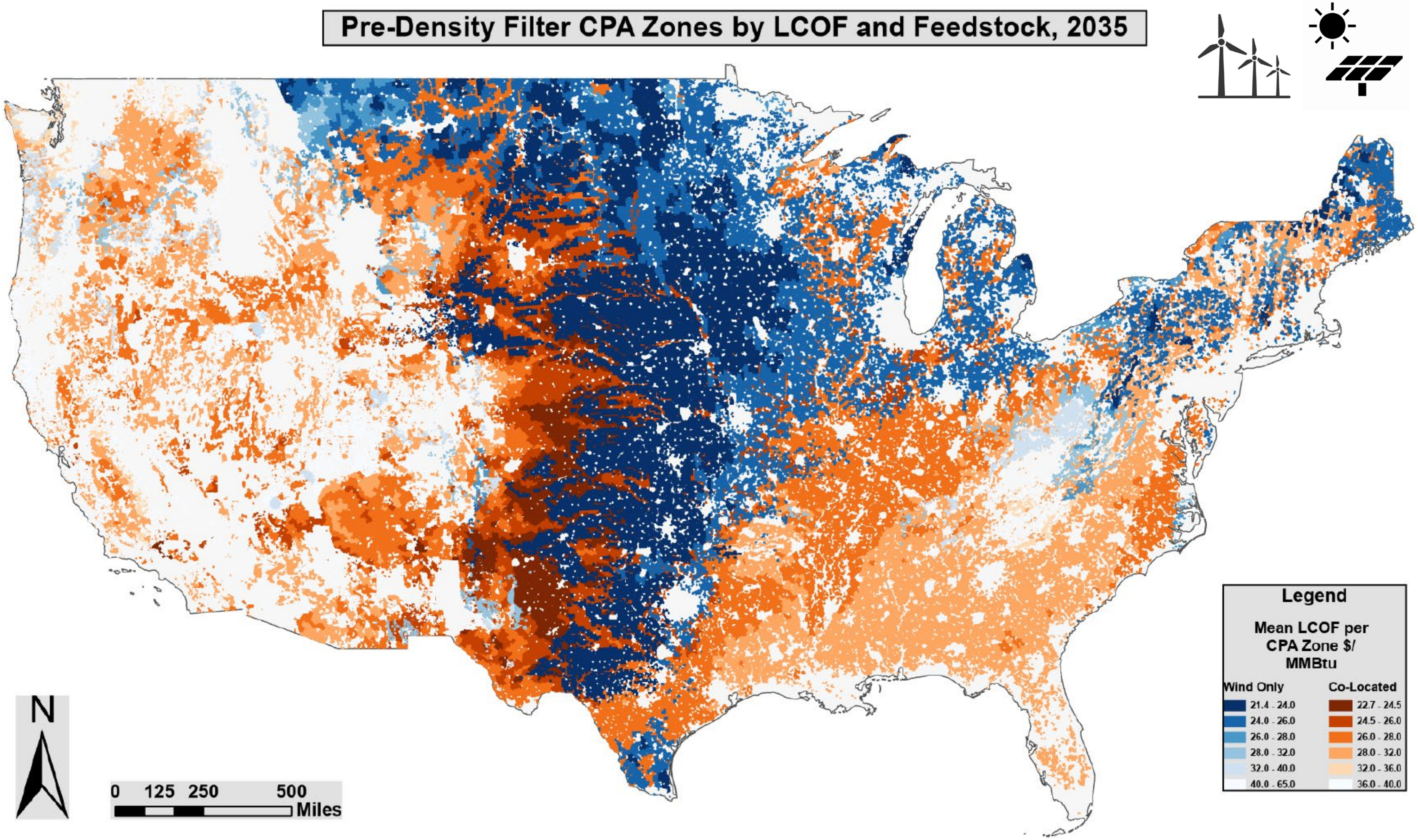
5

Zonal Average: 23.0 MMBtu

Zonal Average: 23.6 MMBtu



Technical Filter for Density

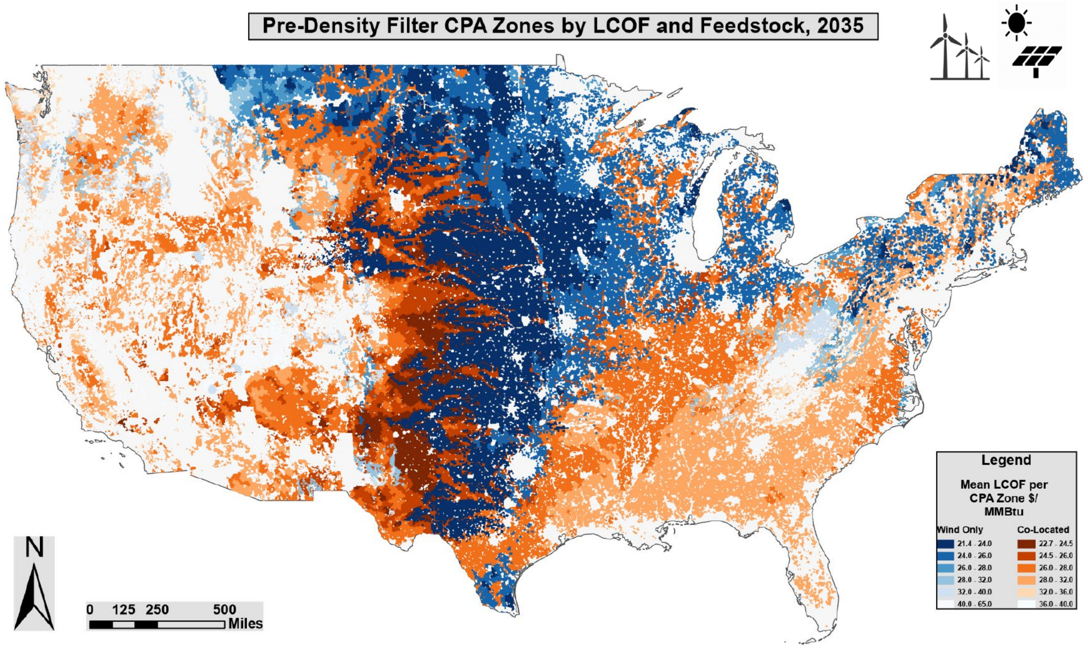


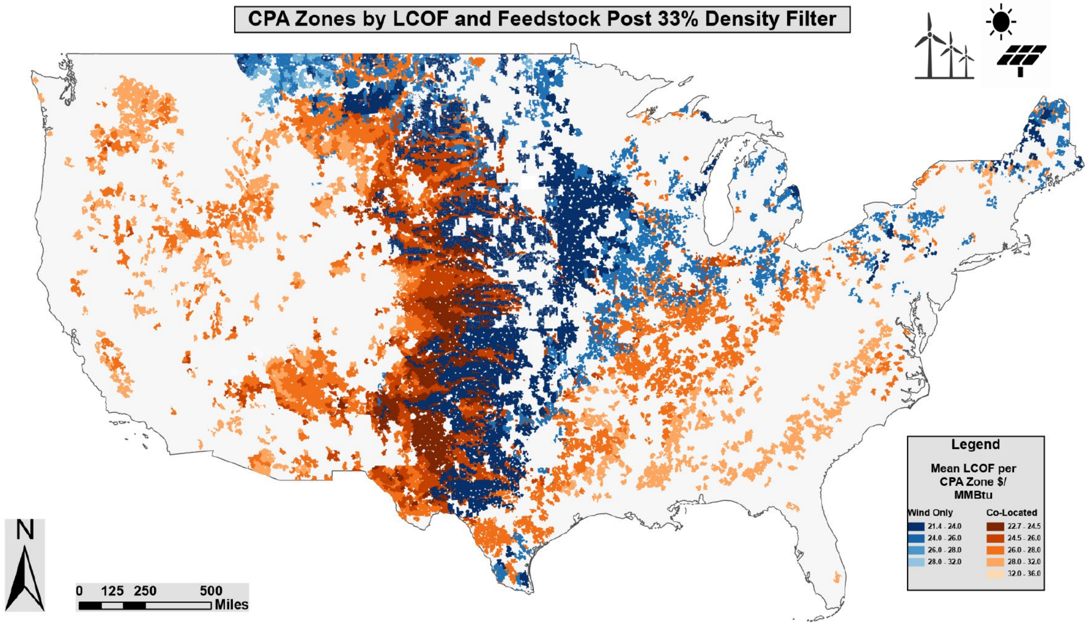
Single year LCOE calculation determined whether CPA was a ‘wind-only’ CPA or ‘co-location’ CPA.

Genetic algorithm completed for both wind-only and co-location.

Majority of new CPA Zones are realistically ineligible due to poor resource quality making them sprawling and not dense.

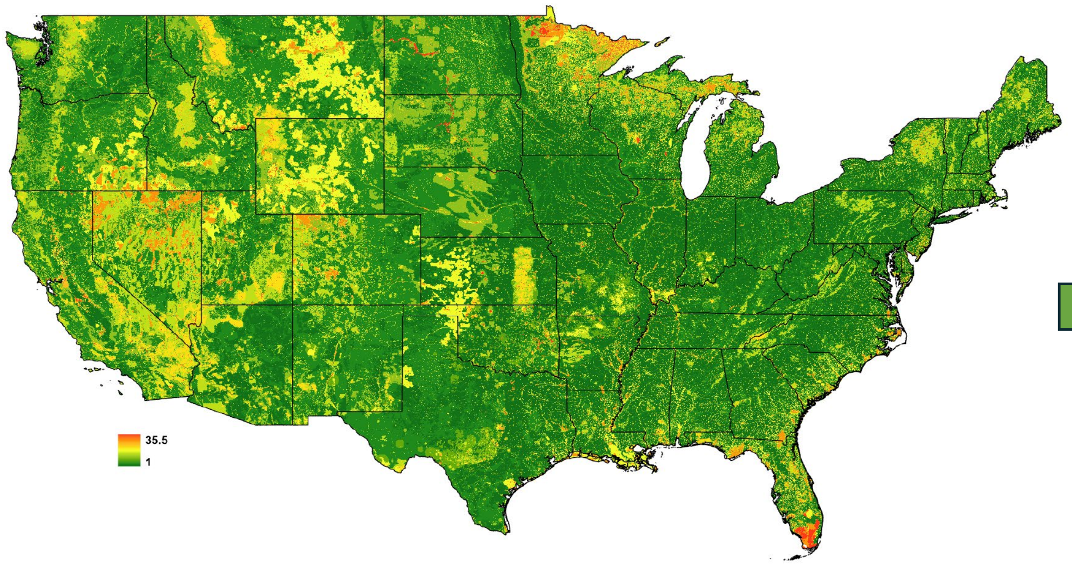
Technical Filter for Density

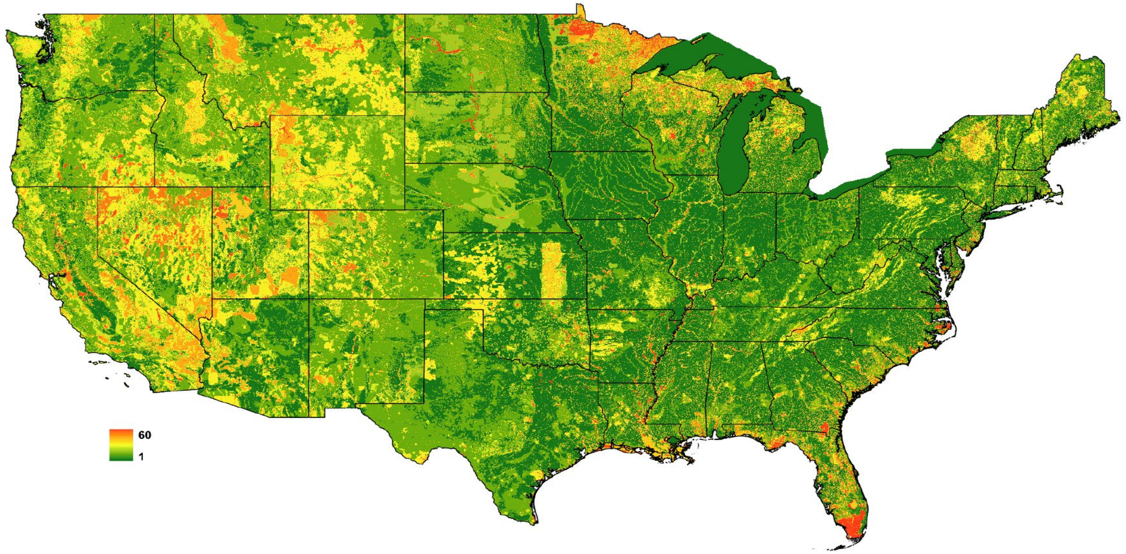




- Shape Length data used as proxy for density and sprawl of selected CPA Zones. Due to the creation of disconnected zones through the genetic algorithm, shape length reflected density and anti-sprawl the most accurately.
- Most sprawling 33% of CPA Zones eliminated.

Friction Score: Environmental Component





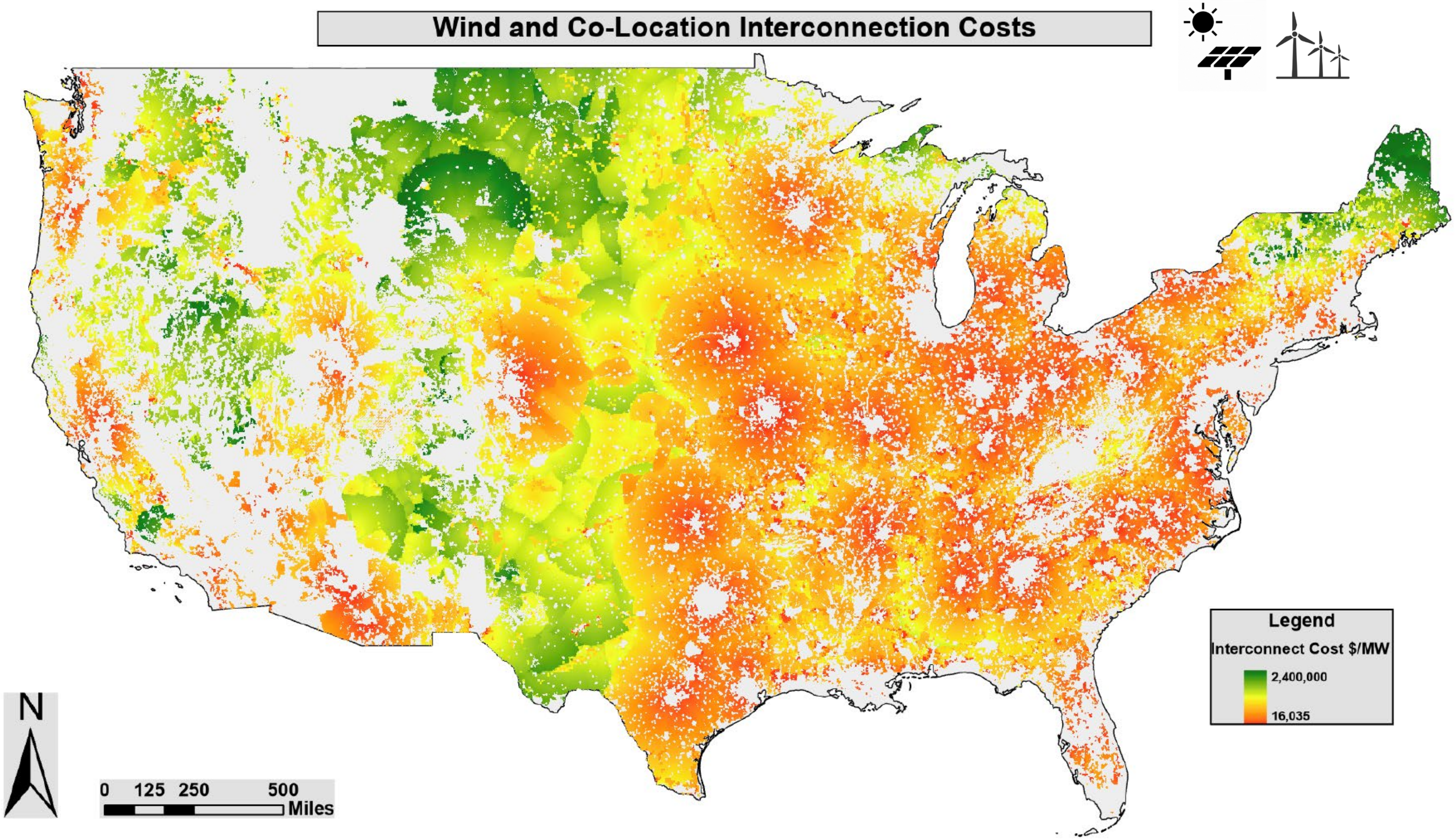
For Power of Place scoring parameters please see:

TNC (The Nature Conservancy) (2023). Power of Place: Clean Energy Solutions that Protect People and Nature. *Technical Briefing Deck*. https://www.nature.org/content/dam/tnc/nature/en/documents/TNC_Power_of_Place_National_Technical_Briefing.pdf

- Base environmental score built for both wind and co-location zones. Both scores normalized to 50 and co-location score based on average of solar and wind raw inputs.
- The environmental impact score makes up the first part of the friction score

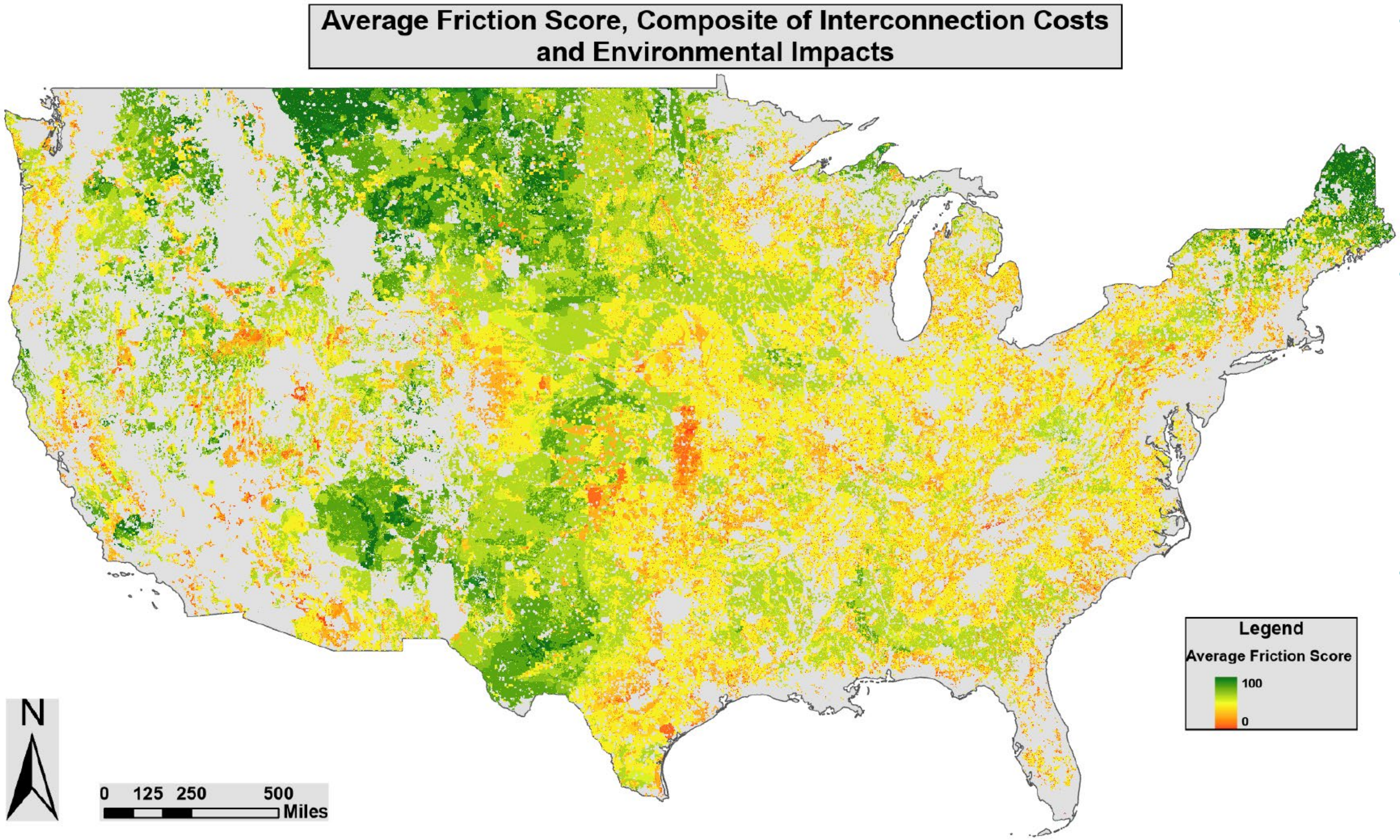
Friction Score: Interconnect Cost

- Interconnection cost used as a proxy for the siting of greenfield facilities (which are ideally only partially grid-connected) at high quality renewable locations that would otherwise be difficult to cost-effectively connect/access.
- Longer spur lines increase site risk and lower investment.[2]
- This score was combined with the environmental impact index to create the friction score.



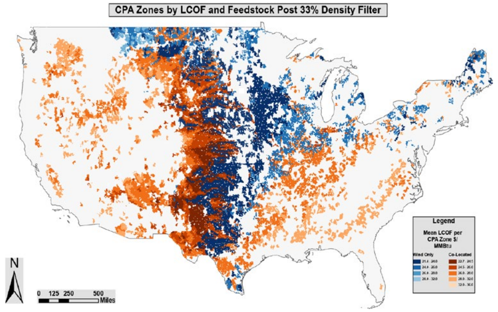
[2] Patankar, N., Sarkela-Basset, X., Schivley, G., Leslie, E., & Jenkins, J. (2023). Land use trade-offs in decarbonization of electricity generation in the American West. *Energy and Climate Change*, *4*, 100107.

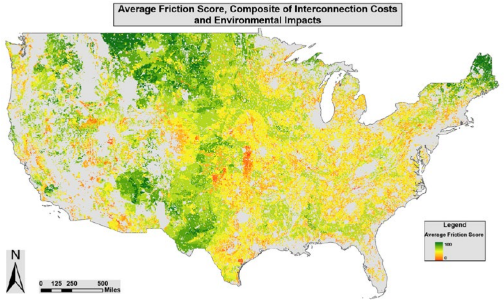
Friction Score

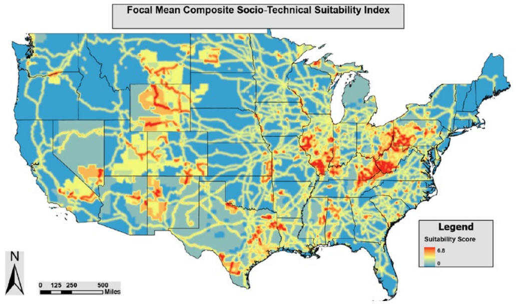


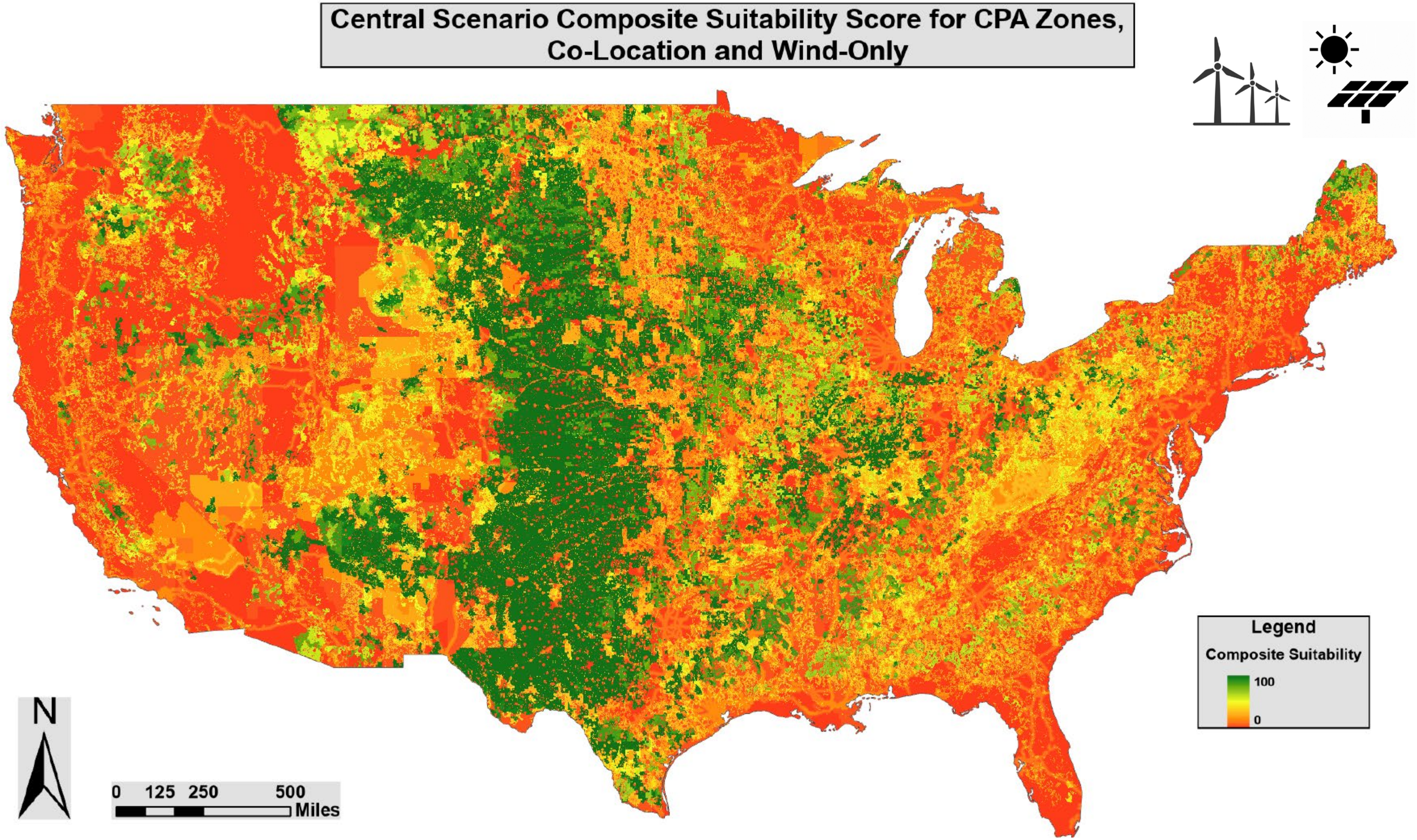
- Higher scores reflect CPA zones that are both in minimally-impacting environmental areas and have higher transmission costs.
- These zones are optimal locations for off-grid energy parks that do not need expensive transmission lines and simultaneously minimize environmental impact.
- This is a delicate balance as often areas furthest from demand have strong correlation to areas of high environmental protection.

Results: Central Scenario









Central Scenario: Weighting

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LCOF

LCOF	Score
22.7-24.6	60
24.6-25.8	50
25.8-27.0	40
27.0-28.3	30
28.3-29.9	20
>29.9	10
Max	**60**

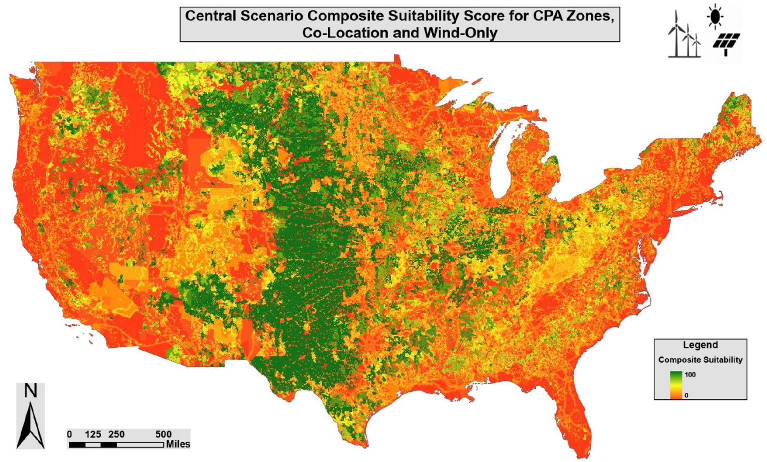
STS

Attribute	Score
Rail within 10km	3.3
Rail within 5km	3.3
Energy Community	3.3
Coal Closure adjacent Tract	6.7
Coal Closure in Tract	10
Max	**20**

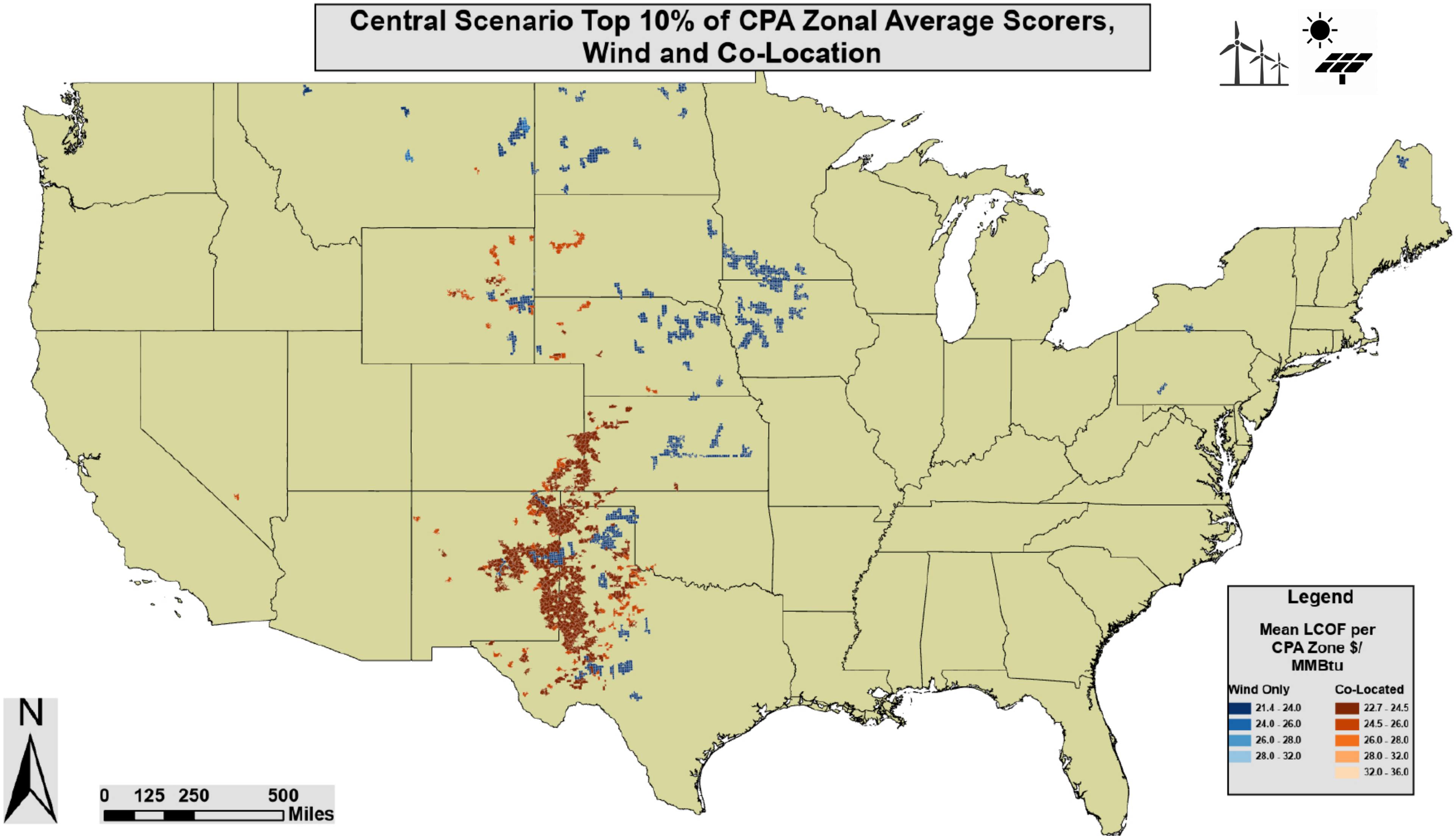
Friction

Attribute	Score
Highest Interconnect Cost	10
Lowest Interconnect Cost	0
Lowest Environmental Impact	10
Highest Environmental Impact	0
Max	**20**

- Central Scenario weighting prioritizes LCOF 3x STS and Friction.
- Friction breakdown of bins:
  - Interconnection and Environmental Impact prioritized equally.
  - Interconnection MW costs discretized into 25 equal size bins, increments of 2.
  - Environmental Impact raw scores normalized to 0-50 from raw Power of Place scores.

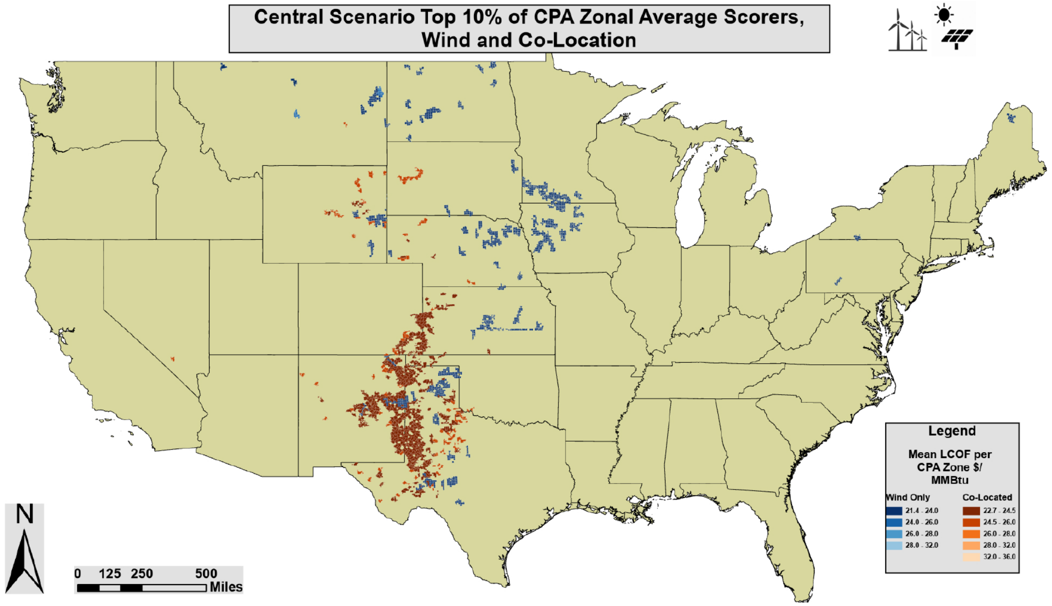


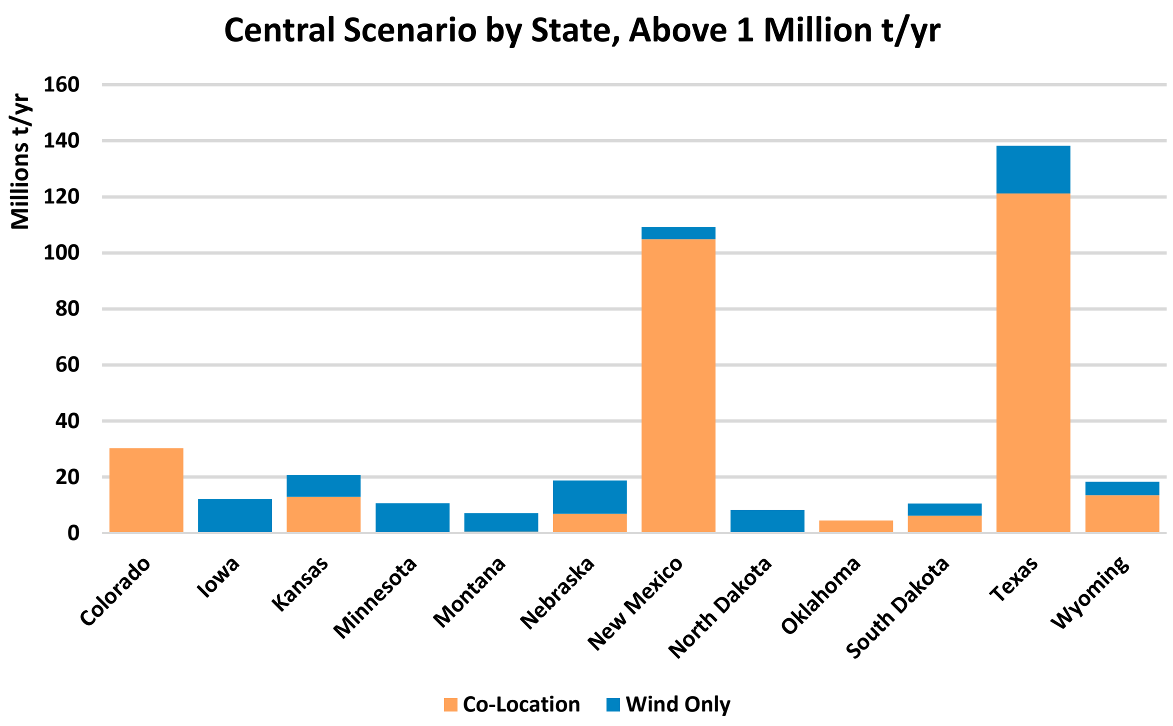
Central Scenario: Results



- Strong clustering in West Texas and northern portions of the Wind Belt.
- LCOF remains low in this scenario however some locations, particularly towards Iowa and Nebraska may have poorer friction scores due to proximity to demand.
- Depicted CPA zones yield approximately **392,000,000 t/yr** compared to projected **24,000,000 t/yr** 2050 demand

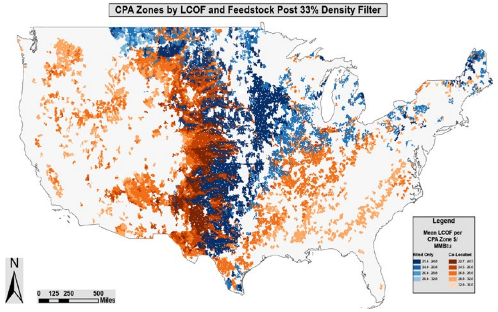
Central Scenario: Results Analysis

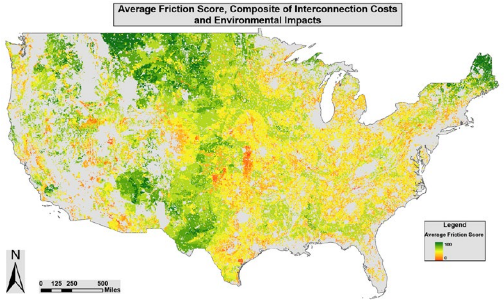


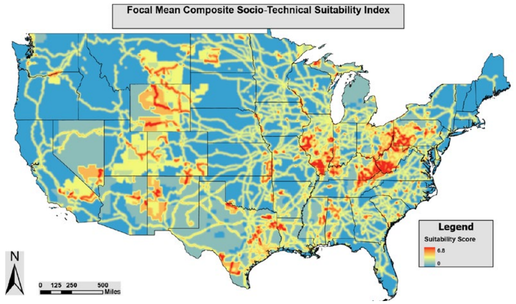


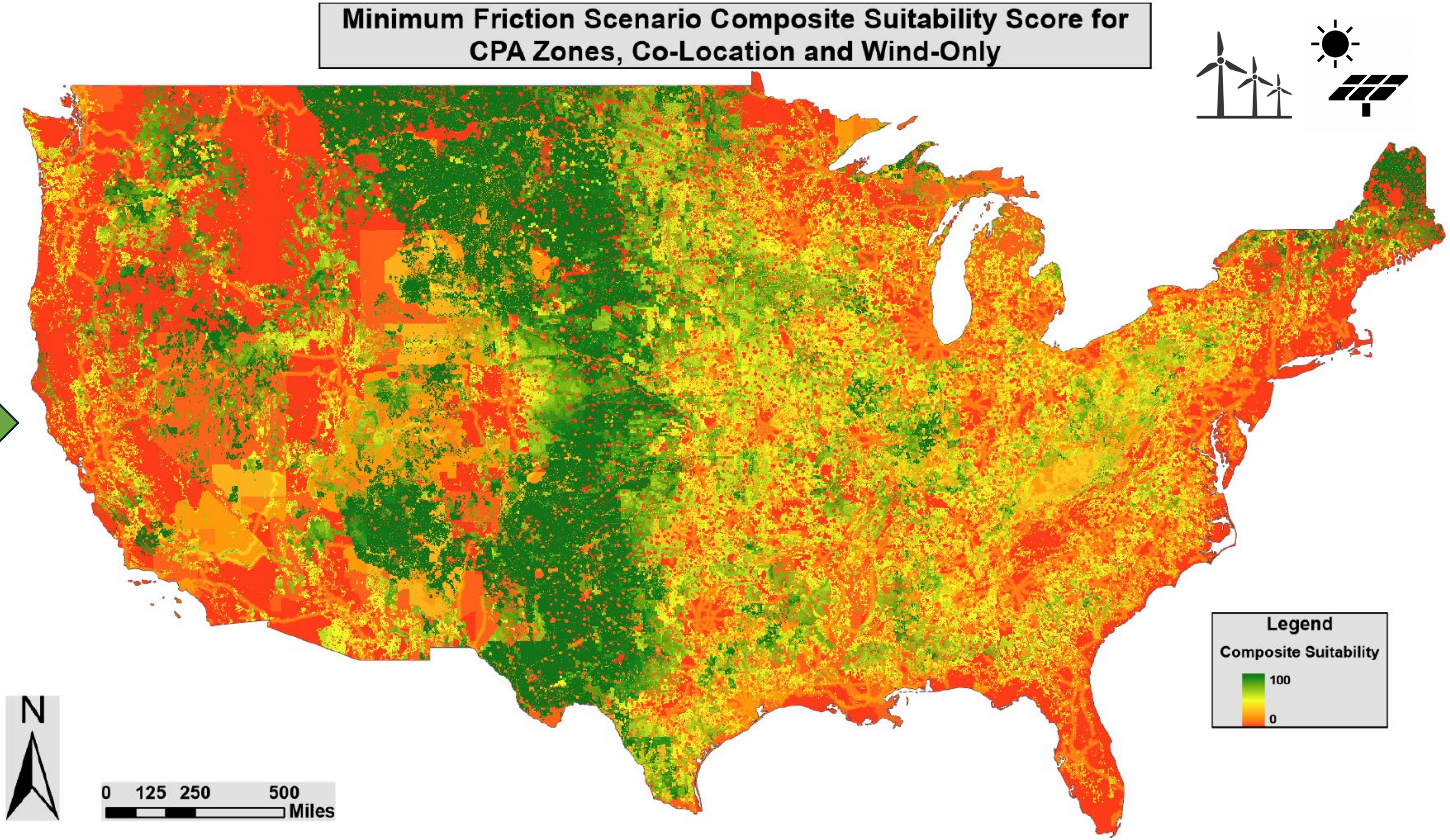
- Co-location CPA Zones benefit from having smaller footprint per output than wind-only configurations. Because it is also more land intensive this may lead to stronger drop-off with stricter siting friction criteria. However, if LCOF is a greater priority co-location not only facilitates higher electrolyzer capacity factor but more strongly clustered areas that can built out into larger scale projects.

Results: Minimal Friction Scenario









Minimum Friction Scenario: Weighting

LCOF

LCOF	Score
22.7-24.6	20
24.6-25.8	16.7
25.8-27.0	13.3
27.0-28.3	10
28.3-29.9	6.7
>29.9	3.3
Max	**20**

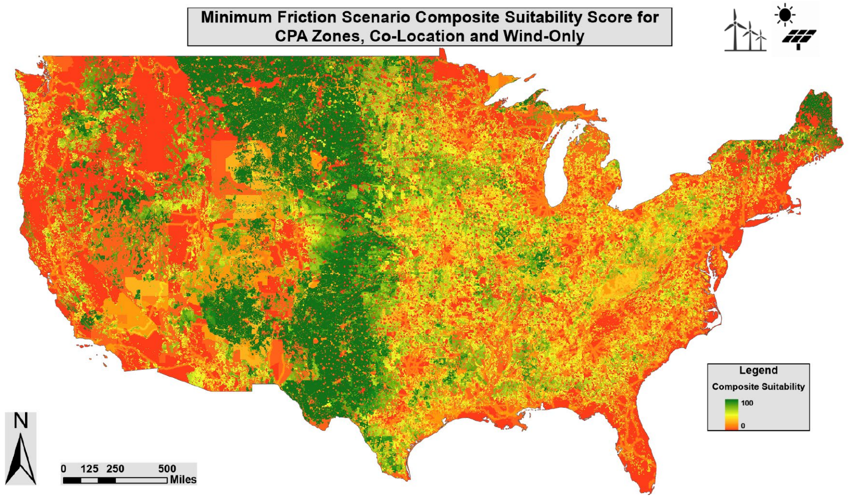
STS

Attribute	Score
Rail within 10km	3.3
Rail within 5km	3.3
Energy Community	3.3
Coal Closure adjacent Tract	6.7
Coal Closure in Tract	10
Max	**20**

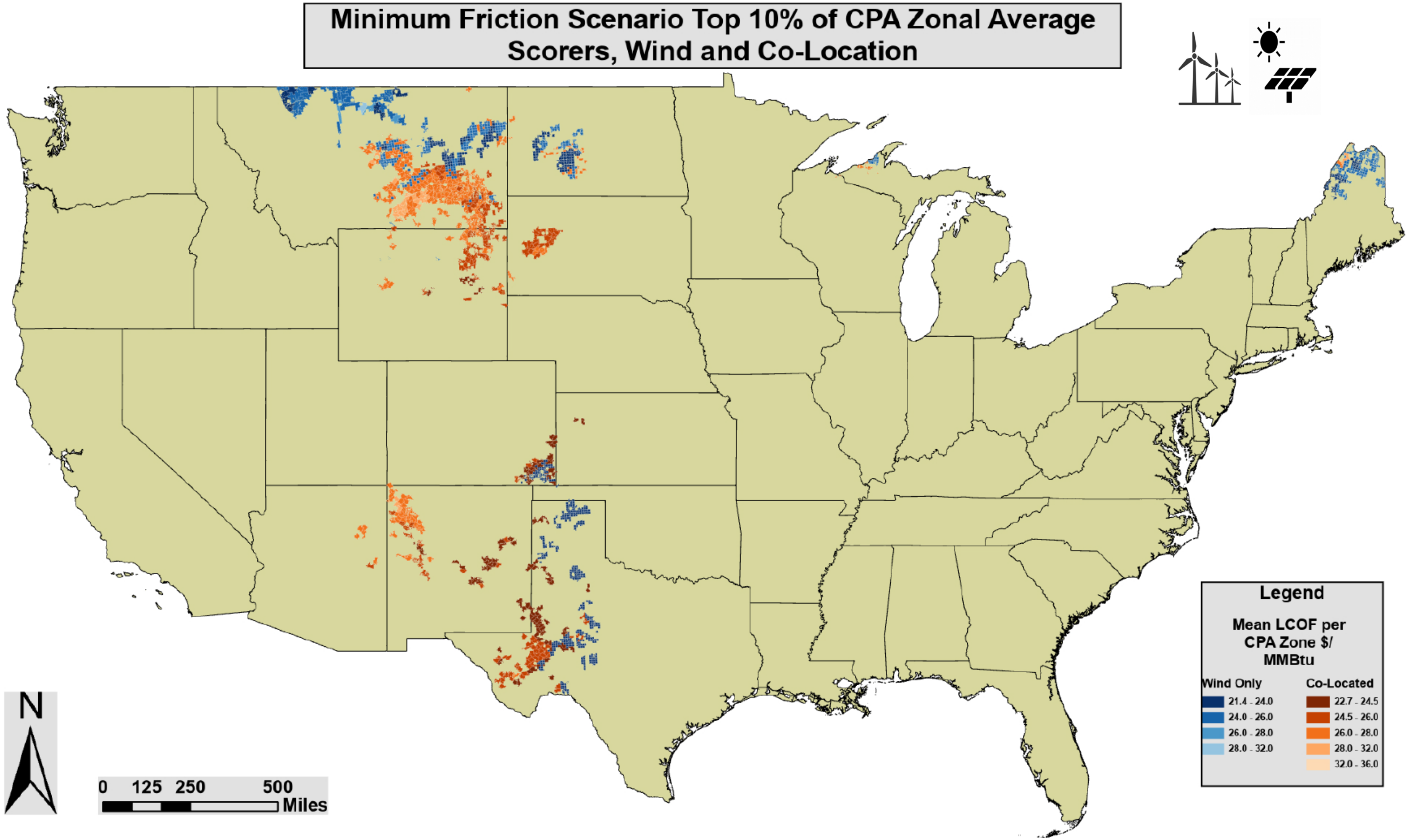
Friction

Attribute	Score
Highest Interconnect Cost	50
Lowest Interconnect Cost	0
Lowest Environmental Impact	10
Highest Environmental Impact	0
Max	**60**

- Minimum Friction Scenario weighting prioritizes interconnection distance and environmental impact 3x STS and LCOF.
- Friction breakdown of bins:
  - Interconnection emphasized 5x to outweigh importance overall.
  - Interconnection MW costs discretized into 25 equal size bins, increments of 2.
  - Environmental Impact raw scores normalized to 0-50 from raw Power of Place scores.

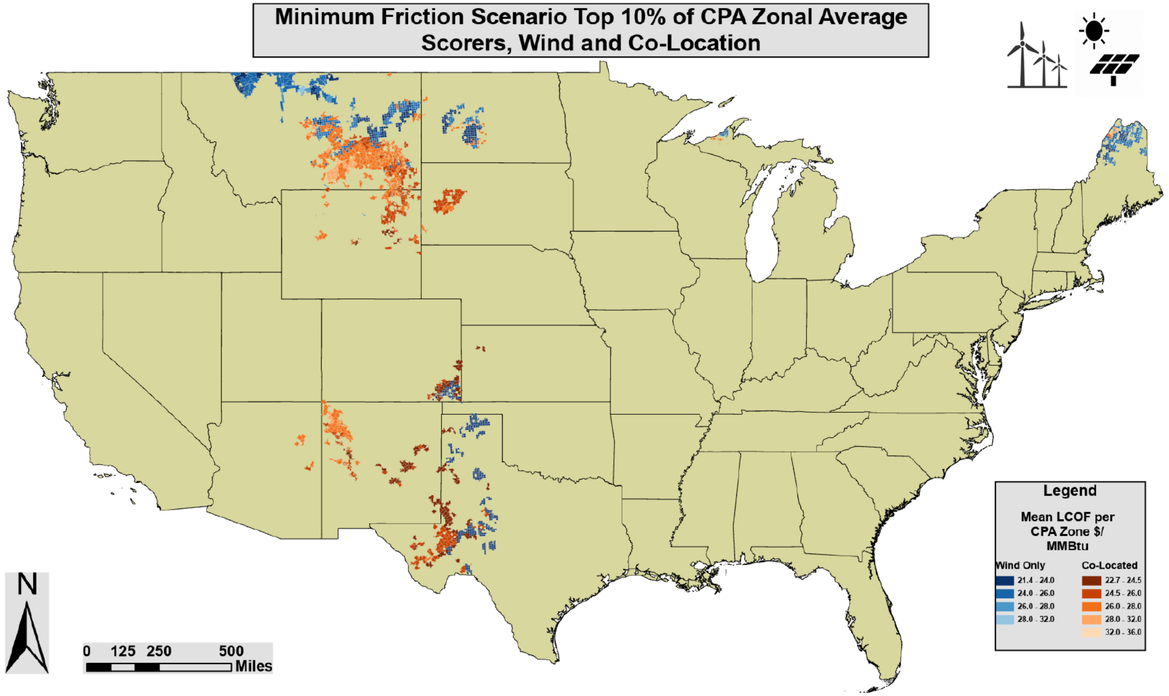


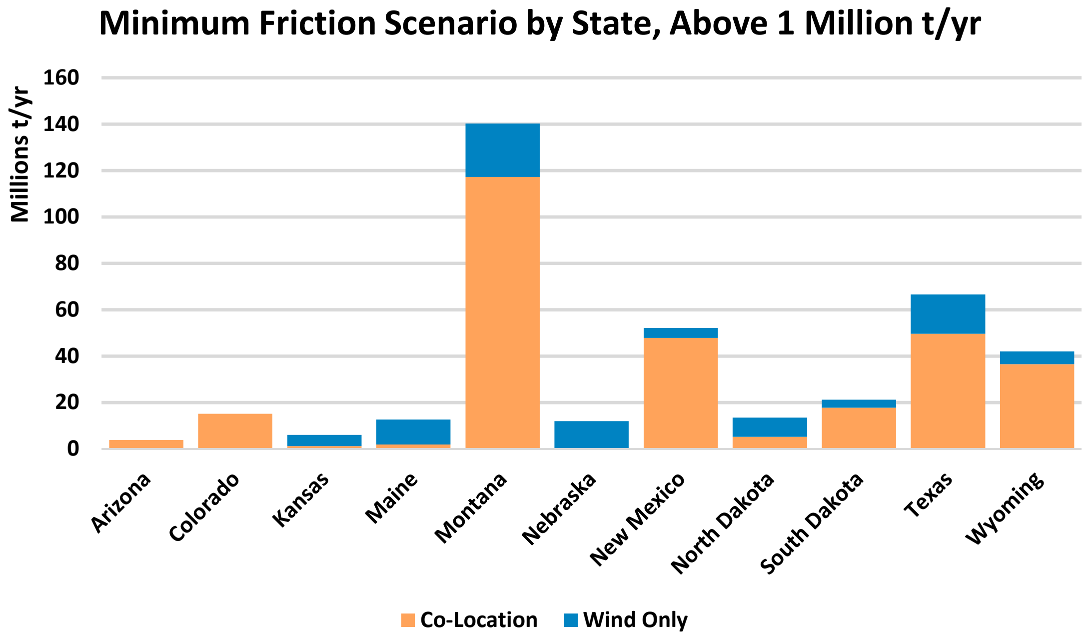
Minimum Friction: Results



- With LCOF de-emphasized and interconnection friction prioritized, clustering shifts to Northern Great Plains.
- Some CPA zones remain in West Texas and Southwest demonstrating the strong viability of this region. Of note is the loss of all Eastern Windbelt zones which benefit from low LCOF but may be riskier in terms of friction.
- Additional priority on environmental scoring above baseline would likely restrict the shown sites further.
- Depicted CPA zones yield approximately **387,000,000 t/yr** compared to projected **24,000,000 t/yr** 2050 demand

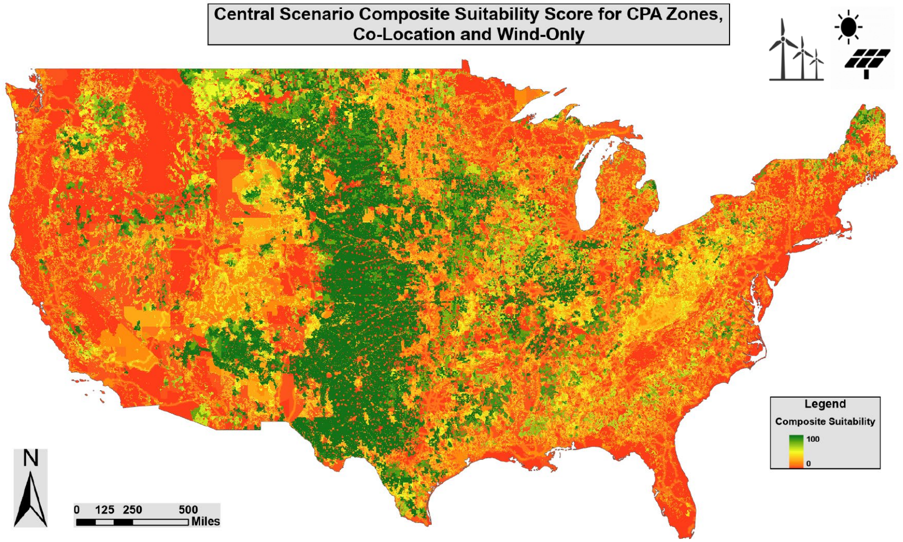
Minimum Friction Scenario: Analysis

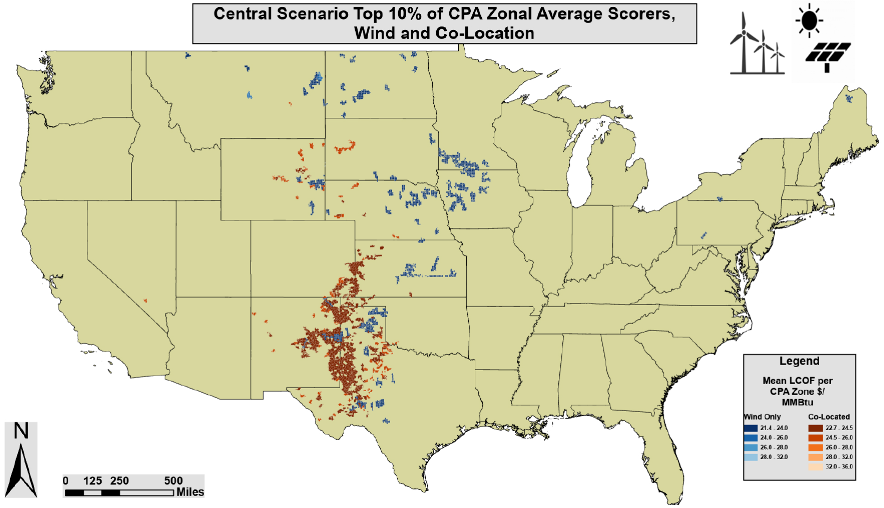


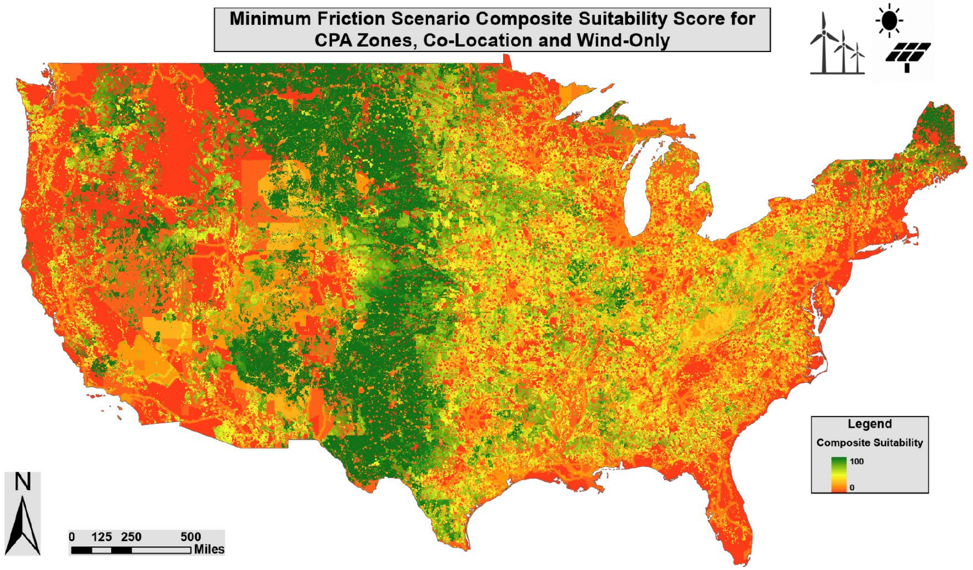


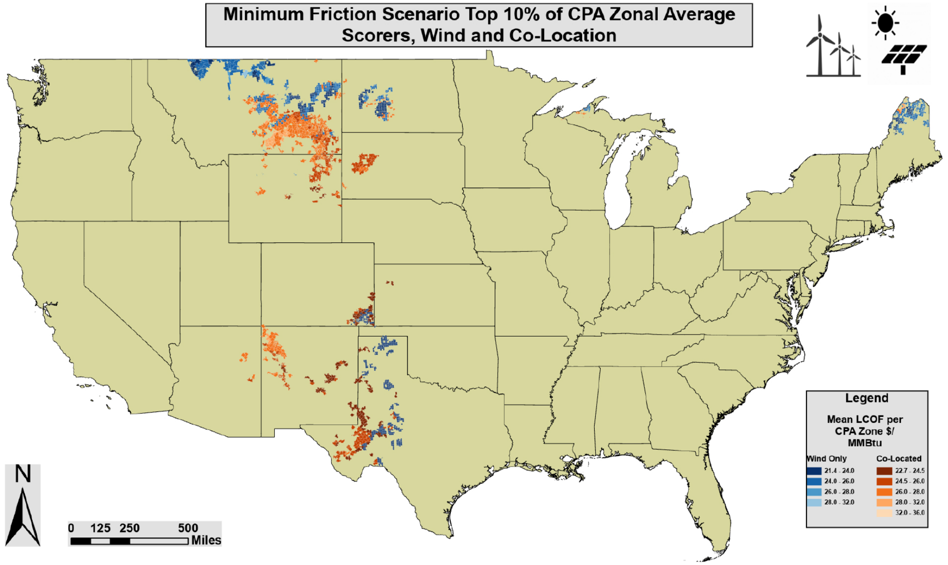
- With LCOF impacts decreased and minimum friction prioritized, LCOFs do increase particularly with the co-location CPA Zones. While co-location still makes up most of the potential output, many of the selected wind-only sites have much lower LCOFs.

Comparative Results









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Conclusions

Main Conclusions

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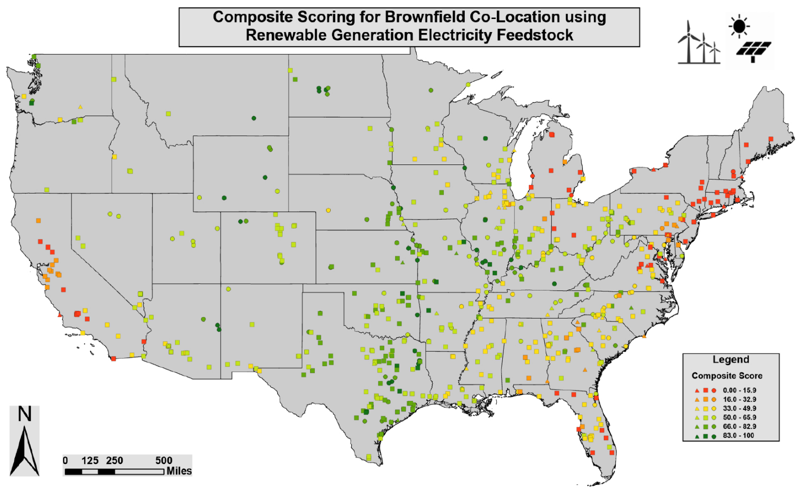
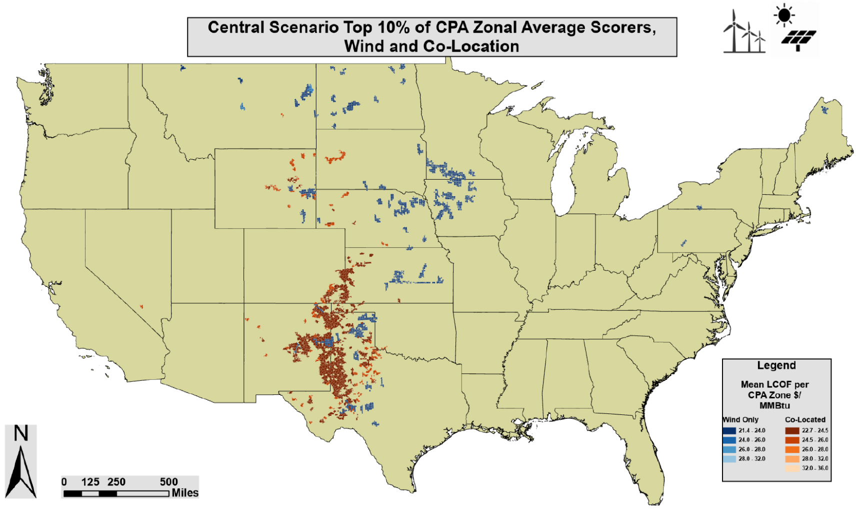


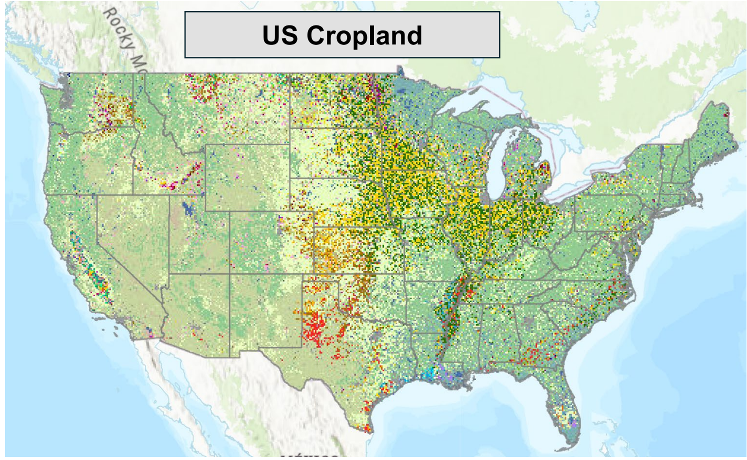


1. Energy parks make economically beneficial use of renewable energy with no or limited new transmission build-out.
    A. Brownfield sites use existing thermal power plant interconnections extending the life of that transmission infrastructure.
    B. Greenfield sites are either off-grid or only require low-capacity interconnections, limiting costs.
2. Energy parks facilitate just energy transitions by siting ammonia production in former oil, gas, coal, and industrial areas.
3. Energy parks are well-situated to not only meet domestic demand through existing infrastructure, but also to develop new clean energy exports.

This analysis demonstrates that energy parks can achieve these results while simultaneously providing fuels with low LCOFs capitalizing on high-quality renewable feedstocks.

Further Implications

- While not explicitly examined in this study, both brownfield and greenfield clusters were either near domestic demand and potential export sites or linked by freight rail and fossil fuel pipeline to such sites.
- Additionally, these energy park configurations are not unique to ammonia. Electrolysis can be combined with clean CO_2 sources for other green fuel production such as Fischer-Tropsch synthetic fuels.



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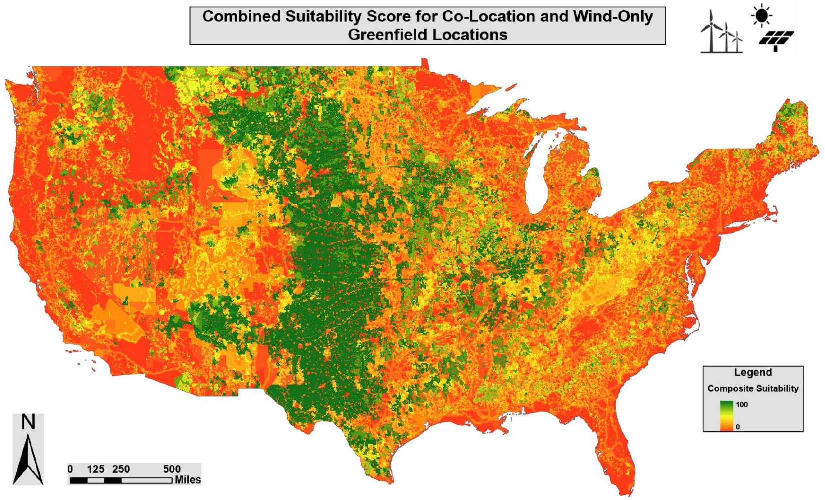

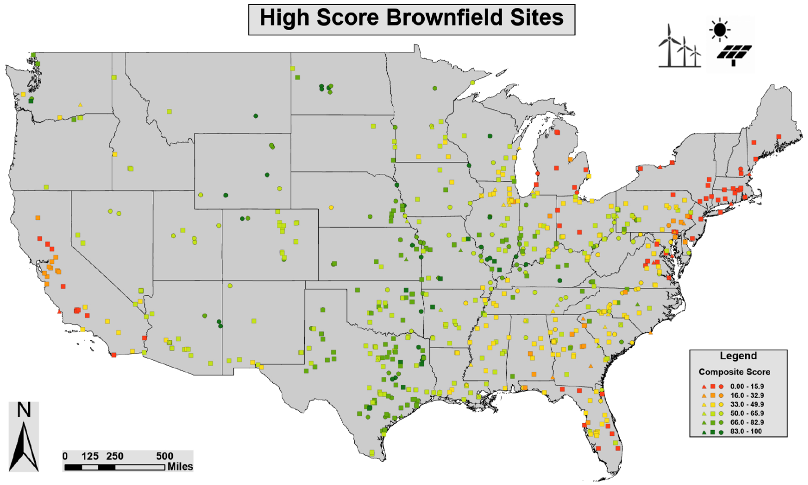

A Possible Future Trajectory for Energy Parks

- Both configurations are ultimately economically feasible. However, brownfield configurations:
    1. Can take advantage of IRA incentives
    2. Are located at or near current industrial areas facilitating more rapid development
- As a result, brownfield development will likely be more common in the near term.
- As brownfield locations that use renewables close to nearby load are exhausted, greenfield sites will become far more optimal and will unlock hard-to-access renewables by locating energy demand/load on-site.

THANK YOU

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