Power of Place – National Technical Briefing

The Nature Conservancy

MAY 2023

Agenda

- The Nature Conservancy's Climate Mitigation Program

- Power of Place
  - Background
  - Power of Place-National
  - Q&A

About The Nature Conservancy

- The Nature Conservancy (TNC) is a global environmental nonprofit working to create a world where people and nature can thrive.
- The mission of The Nature Conservancy is to conserve the lands and waters on which all life depends.
- TNC priorities are:

TACKLE CLIMATE CHANGE

PROTECT LAND & WATER

PROVIDE FOOD & WATER SUSTAINABLY

BUILD HEALTHY CITIES

The Nature Conservancy

Jennifer Morris | Chief Executive Officer

www.nature.org

North America Climate Mitigation Program

U.S. Climate Action

Natural Climate Solutions

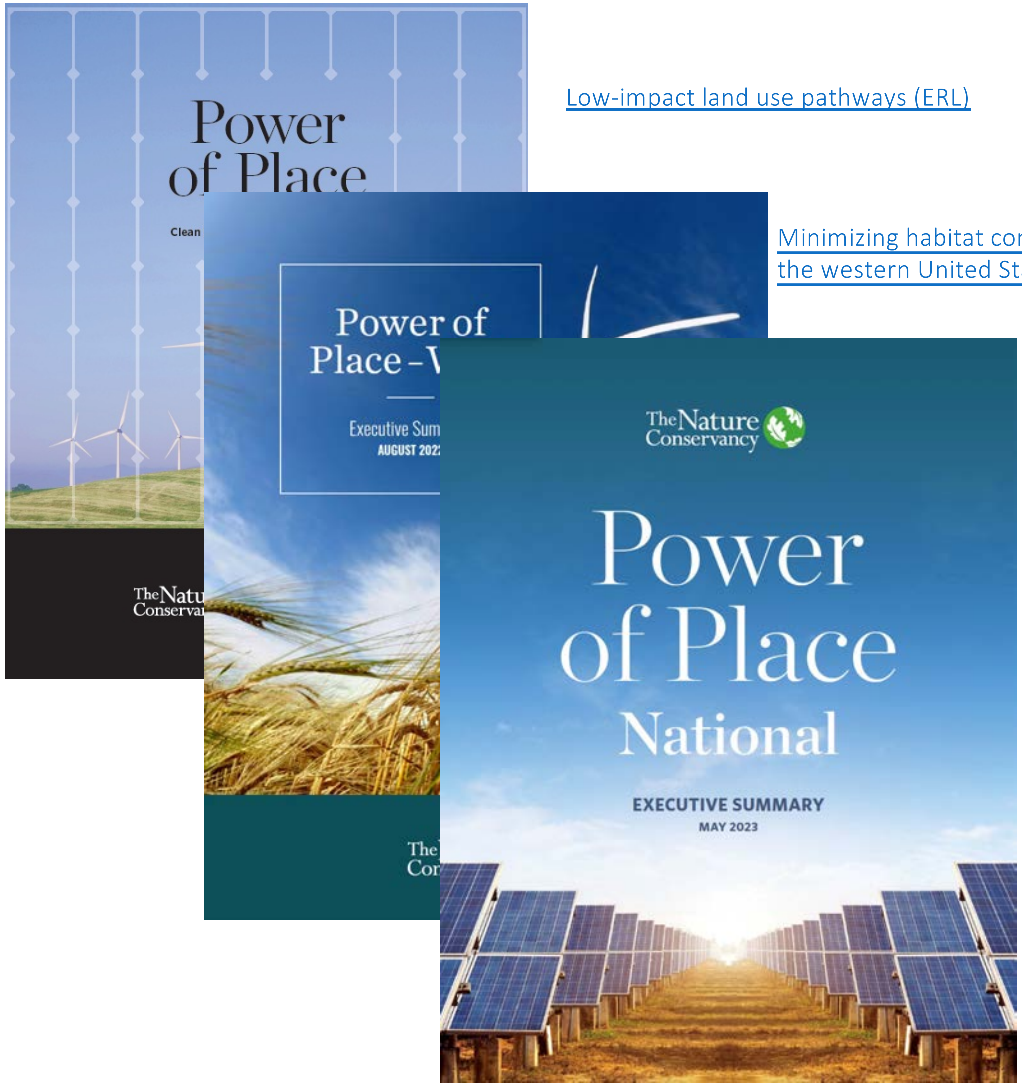
Renewable Energy Deployment

The Nature Conservancy

Power of Place: A National Vision for Clean & Green Decarbonization

Methodology for identifying pathways to get to net-zero, economy-wide decarbonization by 2050 under different social and conservation constraints

Evolution of Power of Place



Low-impact land use pathways (ERL)

Minimizing habitat conflicts in meeting net-zero energy targets in the western United States (PNAS)

In prep (download social and environmental data on Zenodo here)

- 2015: California only
- 2019: California and supply from western interconnect
- 2022: 11 Western U.S. States
- **2023: National (lower 48)**

Power of Place Project Team

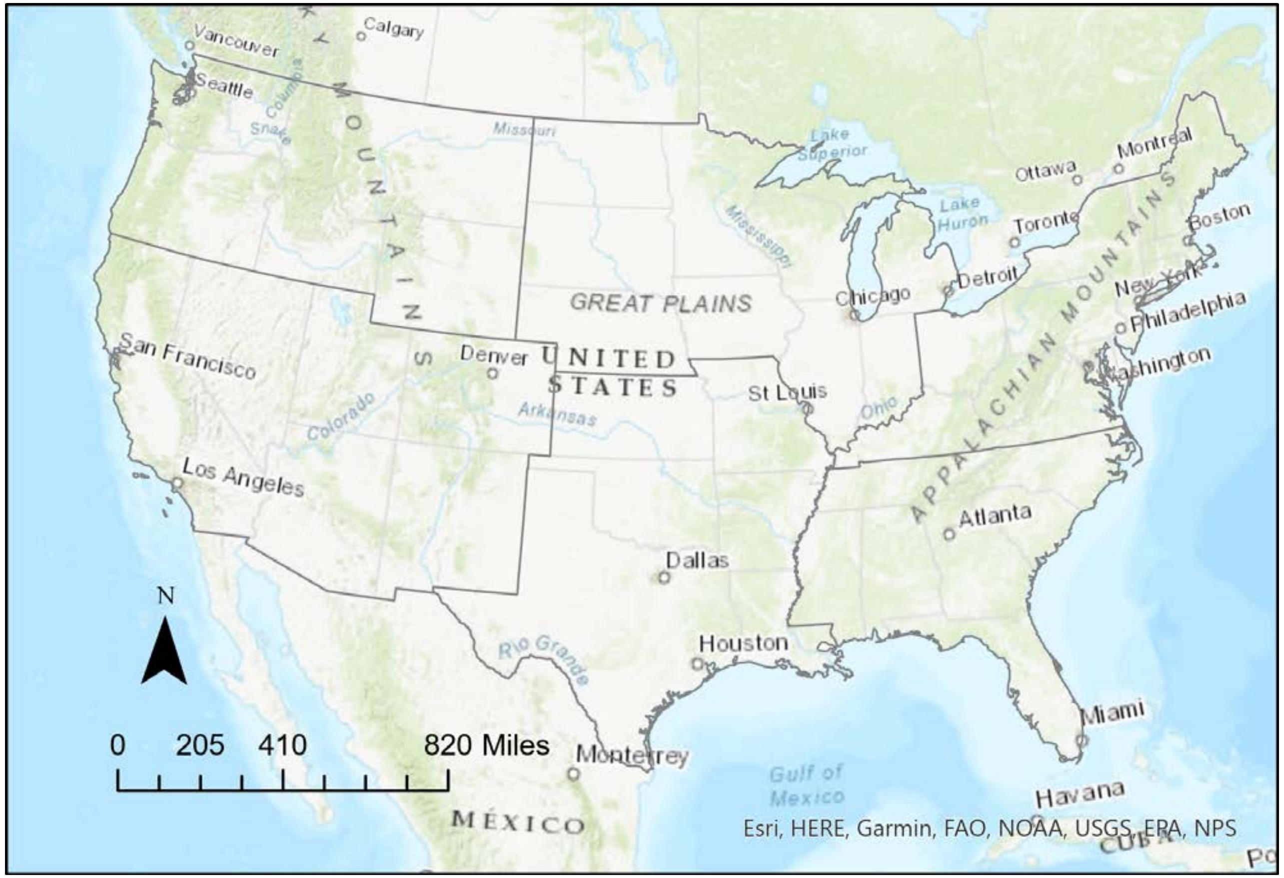
Power of Place National team

Science Team
Ryan Jones, Emily Leslie, Grace Wu, Chris Hise, Joe Fargione, Liz Kalies, Jim Williams, Nels Johnson, Christel Hiltibran

Partner Organizations
UC Santa Barbara, Evolved Energy Research, Montara Mountain Energy

Data Partner
American Farmland Trust

TNC project leadership team:
Project Sponsor: Jason Albritton
Project Director: Jessica Wilkinson
Project Manager: Christel Hiltibran
Science and Technical Lead: Nels Johnson
Communications Lead: Julia Leopold
Media Relations: Alessandra Clark



Manuscript detailing methods and results is in preparation for submission to academic peer-reviewed journal

Overview of Approach

Energy planning steps for reducing environmental and social impacts

Energy modeling identifies different pathways—the mix of technologies and amount of each technology — that will be needed to meet specific goals, such as net-zero emissions, economy-wide by 2050. The Power of Place–National *model also takes into account environmental and social considerations.*

Objectives and research questions

- How much **clean energy** will be needed to achieve economy-wide net-zero emissions by 2050?
- How much **land area** will be needed for the clean energy transition?
- How do shifts in clean energy technologies affect **costs and impacts on natural areas and working lands**?

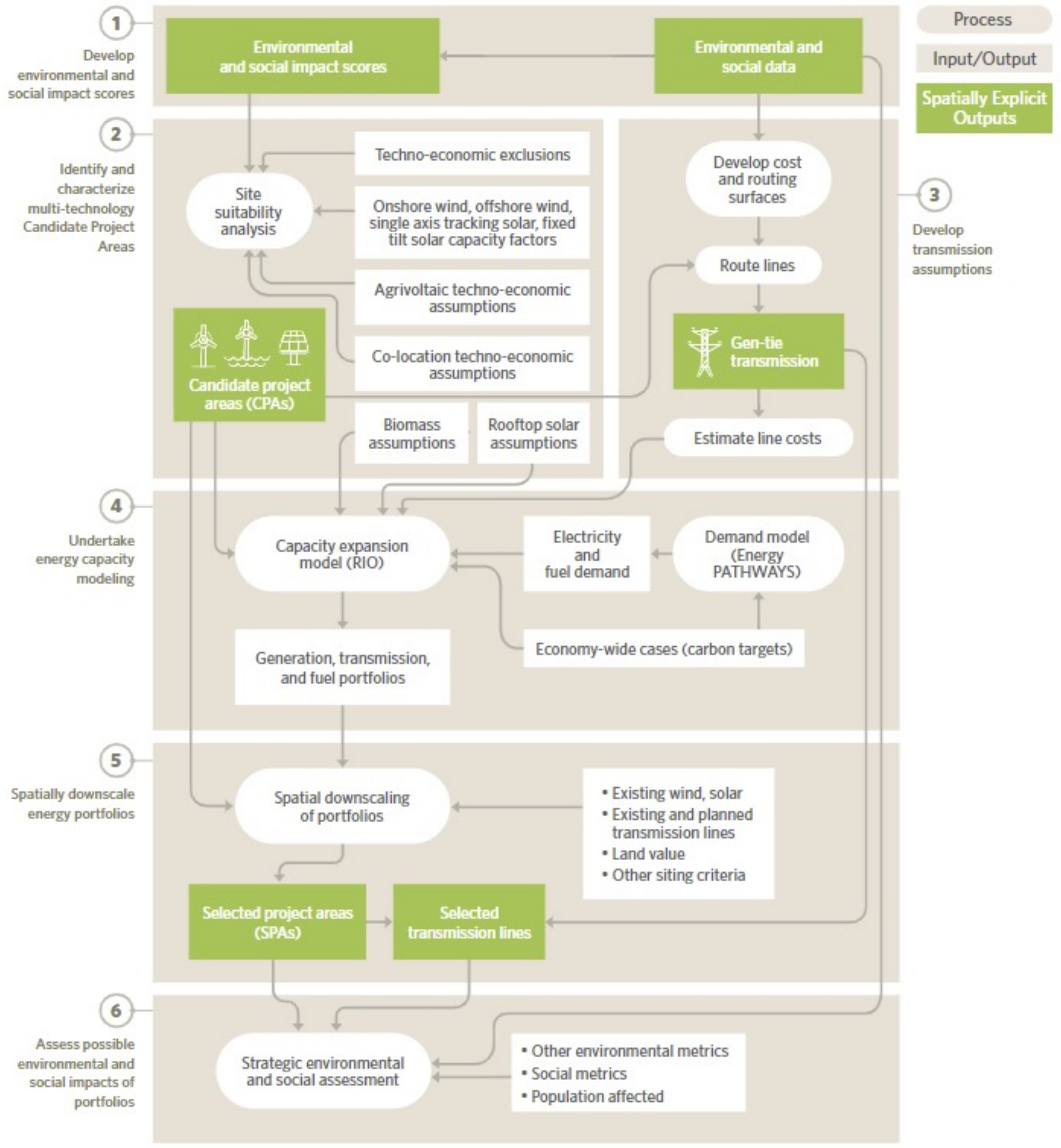
- What role could **land-saving renewable energy siting approaches** play in the scale of the buildout?
- How much renewable energy will be built in the "**energy communities**" that will receive tax incentives from the Inflation Reduction Act, and how many people live in these communities?

Power of Place National Methods

Power of Place National introduces a new methodology that attempts to provide a richer perspective on avoiding environmental and social impacts

	PoP West & PoP California	PoP National
Methodology Summary	Zones are developed with high environmental impact. Decarbonization is tested w/wo these zones available to wind and solar development.	Environmental and social scores differentiate more and less desirable locations for energy infrastructure. Decarbonization scenarios are constrained to minimize total impact.
Core Research Question	Are net-zero goals possible while protecting our most important landscapes?	What technologies and strategies reduce relative social and environmental impacts while achieving net-zero goals?
Policy Considerations	• Ease of communication • Establishes public land exclusions • No direct incorporation of social factors • Policy around private land is difficult • Focus on wind & tracking PV	• Incorporates all primary energy • Explores different tech configurations • Includes social & environmental factors • All lands given consideration • Interpretation is more challenging

PoP National methods framework



1 Environmental impact scoring system

Categories	Score[1]	Solar Discount	Wind Discount	Examples
Wetlands	30	1	0.5[2]	Priority wetlands inventory, globally important wetlands with buffers, central valley wetland and riparian areas, vernal pools
Managed areas	15	1	0.5	Areas of critical environmental concern, BLM lands with wilderness characteristics, habitat conservation plan lands, State reserves, national inventoried roadless areas
Threatened and Endangered species habitat and occurrences	10	1	0.5	Critical Habitat for Threatened or Endangered Species, Desert tortoise connectivity and critical habitat, USFWS upland species recovery units
Intact habitat	10	1	0.5	Big game crucial habitat, areas of critical environmental concern (ACEC), high integrity grasslands, essential connectivity areas, Important Bird Areas, big game priority habitat and corridors, TNC Ecologically Core Areas, “Resilient and Connected Network”, priority conservation areas, sagebrush focal area
Focal bird habitat	10	1	1	Sage Grouse core areas and Priority Habitat Management Areas (high and moderate), whooping crane stopover sites
Bat habitat	3	1	1	Bat caves, tree roosting bats

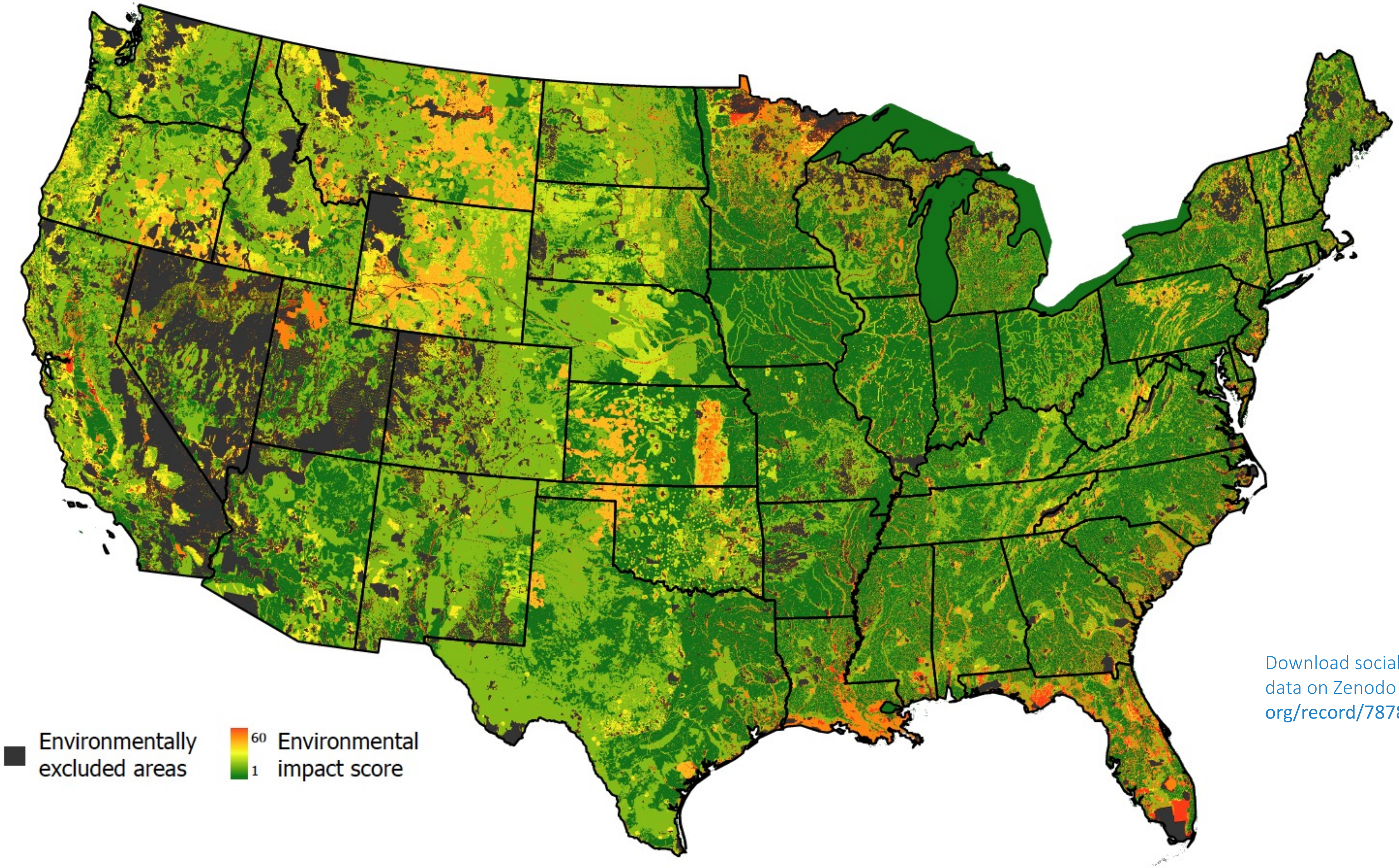
[1] **Impact score = land area equivalent impact (e.g., wetlands have 30x the environmental value as a unit of land with a score of 1); scores can be additive where categories overlap**

[2] **Wind discount factor based on extensive literature review indicating wildlife avoidance around wind turbines (see references in appendix)**

1 Social impact scoring system

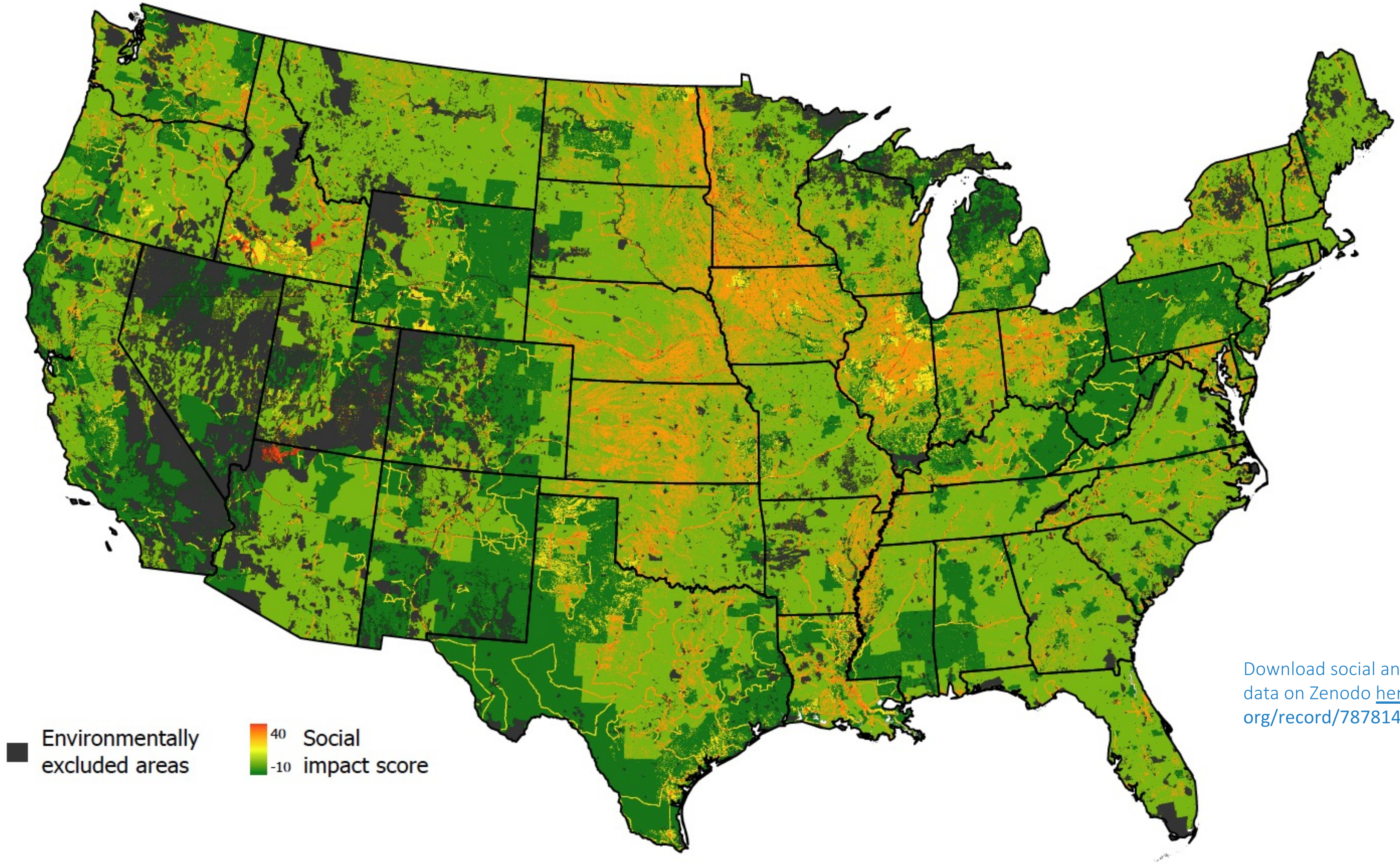
Categories	Score	Solar Discount	Wind Discount	Examples
Productive and valuable farmland (prime farmland)	15	1	0	Productive, Versatile, Resilient (index >= 0.53) from the American Farmland Trust
Scenic areas	15	1	0.5	BLM Visual Resource management II lands BLM Visual Resource management III lands Scenic byways/highways/roads with 2 mile buffer
Recreational Areas	10	1	0.5	Off Highway Vehicle areas Extensive Recreation Management Area Special Recreation Management Area
Populated areas	3-5	0	1	> 5 persons/km2: 5 <=5 & >4 persons/km2: 4 <=4 & >3 persons/km2: 3
Marginal farmland	-5	1	1	SSURGO (land capability classes 8, 7 and 6, plus 5 if highly erodible or waterlogged, plus 4 if waterlogged); Central Valley farmland likely to be retired (Bryant et al. 2020)
Energy communities	-5	1	0.1	Definition from the Inflation Reduction Act (does not include brownfields)

1 Environmental impact score – solar PV



Download social and environmental data on Zenodo here: https://zenodo.org/record/7878144

1 Social impact score – solar PV



Download social and environmental data on Zenodo here: https://zenodo.org/record/7878144

Renewable assessment

Legally protected excluded, e.g.,

- National Wildlife Refuges
- National Parks
- Marine Sanctuaries
- Military Training Areas

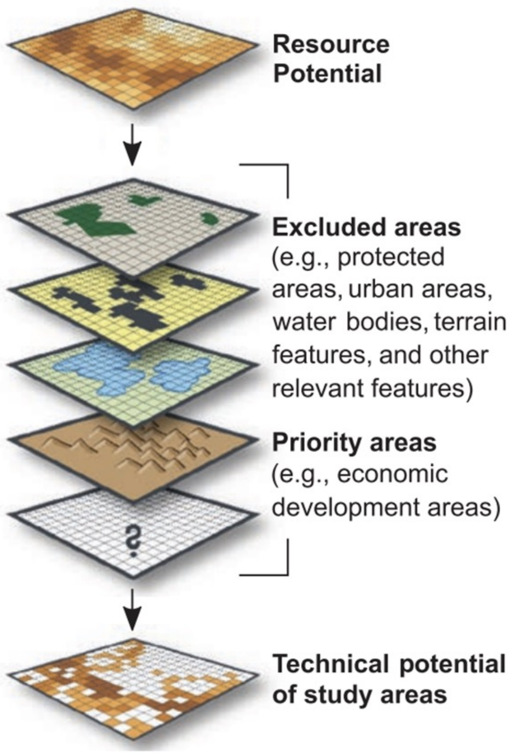
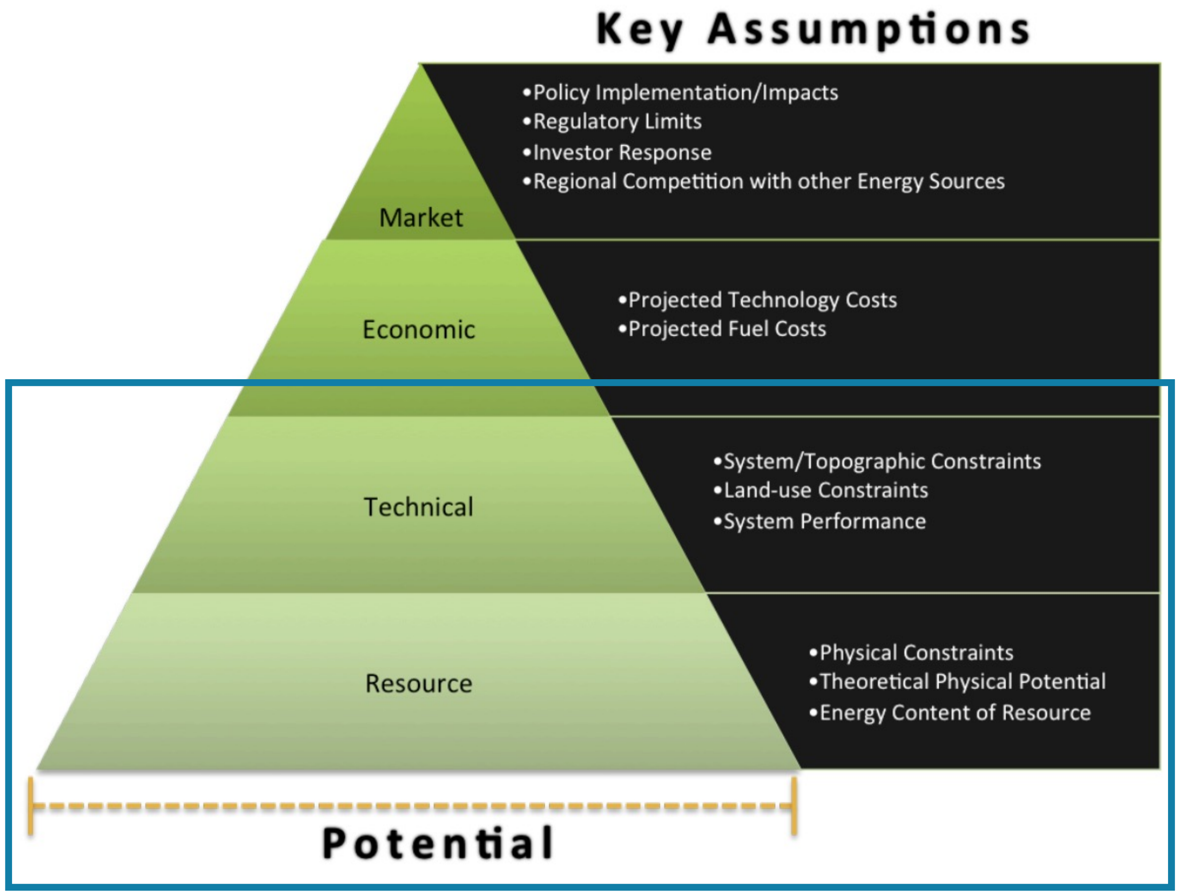


Figure 3. Process of screening resource potential to calculate the technical potential of study areas.

Adapted from Lopez (2016)



https://greeningthegrid.org/Renewable-Energy-Zones-Toolkit

2 Renewable assessment

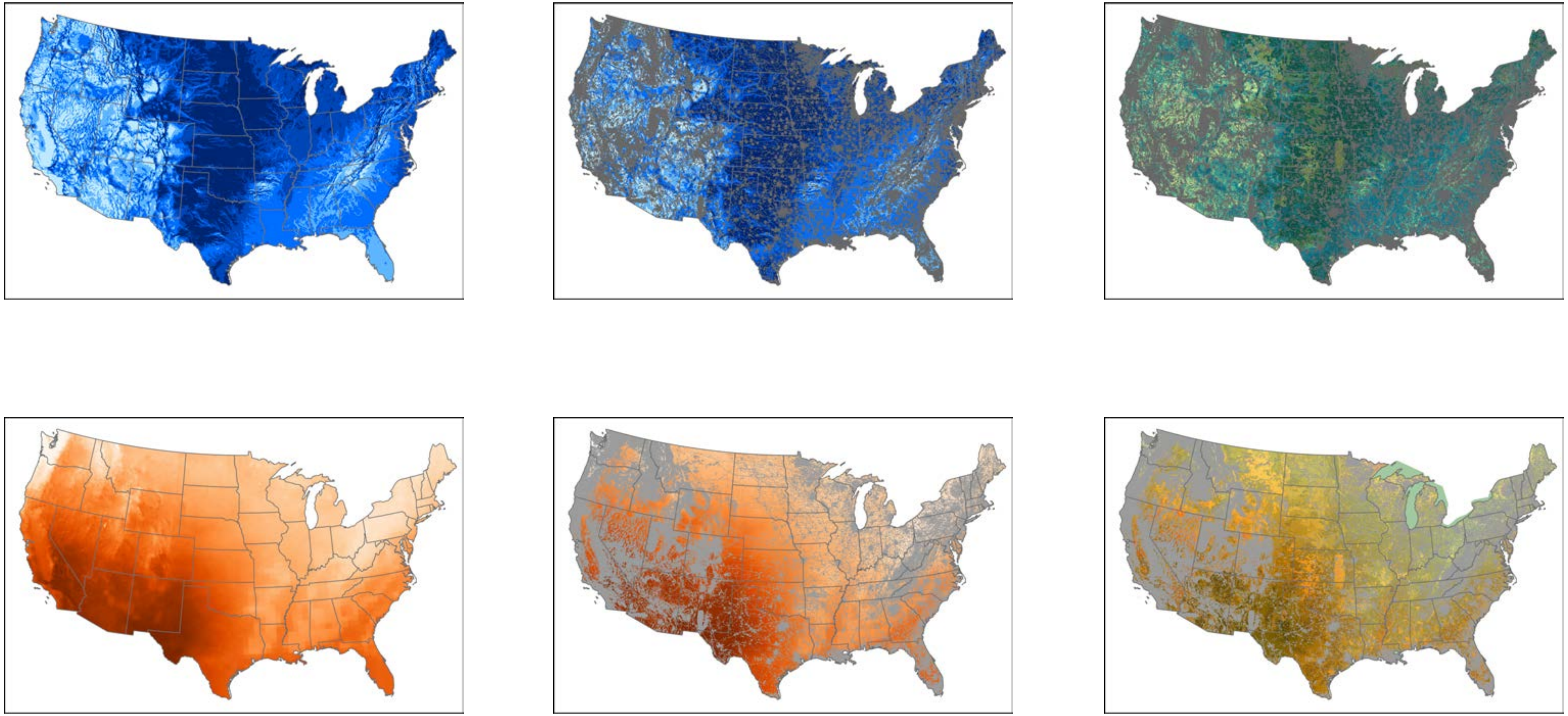
Raw resource potential

Techno-economic resource potential

Resource potential with impact scoring system applied

Wind

Solar Photovoltaic



2 Characterizing sub-technologies: Agrivoltaics (APV) on croplands

Key assumptions	CF differences	Cost differences	Power density differences
• Assume commercial scale agrivoltaics for specific crops that have been studied/are suitable • Enough spacing to allow for machinery between rows, which reduces land use efficiency/power density • Assume panels will not be fully racked but ground mounted at an elevated height of 6-8 ft. • Does not interfere significantly with farming and thus is compatible with all farmland	1% increase in arid climates (potentially negligible in non-arid climates) (Barron-Gafford et al. 2020)	6% capital cost increases (5-7% higher based on slightly elevated ground mounted panels that were installed with minimal soil compaction (Jack's solar farm)	18% reduction in power density (Trommsdorff et al. 2021)

See appendix for references

source

Specific crops compatible with APV:

- Misc Vegs and Fruits
- Cucumbers
- Tomatoes
- Grapes
- Broccoli
- Peppers
- Lettuce
- Cabbage
- Cauliflower

2 Characterizing sub-technologies: Wind-Solar Colocation

Key assumptions	CF differences	Cost differences	Power density differences
• Assuming 2:1 ratio of solar capacity to wind capacity • Future work to consider changes to interconnection sizing based on anticorrelated output between wind and solar.	0.75% PV-only losses due to shading (Ludwig et al. 2021)	8% reduction in solar PV CAPEX and 9.5% reduction in OPEX when added to a wind farm (AECOM 2016)	1:1 ratio Up to 88:12 ratio PV to wind (AECOM 2016 and Ludwig et al. 2021)

See appendix for references

Australia's first hybrid wind-solar farm to be built near Canberra

Co-location of renewables leads to 'significant cost savings'

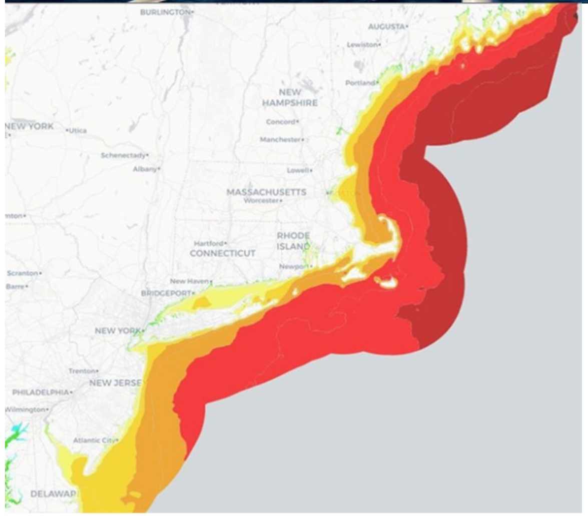
2 Characterizing sub-technologies: Fixed-tilt solar vs. single-axis tracking PV

Key assumptions	CF differences	Cost differences	Power density differences
• System Advisor Model (SAM) runs uses same losses and assumptions for both technologies • Calibrated regional multipliers based on historical Fixed vs. Tracking deployment patterns	Provided for each CPA for each technology based on SAM runs	**CAPEX**: $0.83/Wdc for fixed tilt vs. $0.89/Wdc for tracking in 2021 **OPEX**: $14.61/kWdc/year for fixed tilt vs. $16.06/kWdc/year for tracking (NREL 2021)	On average, fixed tilt is 46% higher than tracking (Bolinger and Bolinger 2022) See appendix for references

2 Characterizing sub-technologies: Offshore wind

Key assumptions	Losses	Power density
• NREL Wind Toolkit for marine regions • Global Wind Atlas for Great Lakes • NREL 7 MW reference turbine • 100m hub height • Weibull parameters were used to estimate annual generation from meteorological data • Minimum distance from shore: 5-8 km	Availability: Turbine Performance: 3.95% Wake effect: 8.75% Environmental: 2.39%	5 MW/km2

See appendix for references



Offshore wind site suitability analysis took into account spatially explicit techno-economic and environmental factors consistent with current federal and regional planning efforts. More information available upon request.

2 Characterizing sub-technologies: Biomass, rooftop PV, fossil, geologic storage

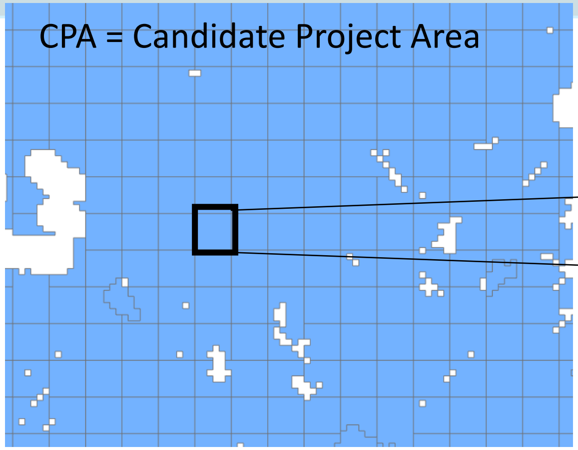
- Land use assumptions assuming x 1 impact factor
  - **Biomass** [see table at right] (Supply curve: Billion Ton Study)
  - **Oil & gas extraction:** 0.066 m^2/GJ
  - **Uranium**: 0.02 m^2/GJ
  - **Geologic storage**: 2 m^2/t stored

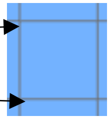
- Economic build of **rooftop PV** with minimum constraint/amount by dispatch feeder (residential, commercial, industrial) by zone based on scenarios from Princeton REPEAT

Biomass feedstock	Yield (dry tons/ha)
Switchgrass	15
Miscanthus	25
Biomass sorghum	27.6
Energy cane	16.4
Eucalyptus	24
Hardwood	11.7
Mixed wood	15.5
Pine	19.2
Poplar	11.7
Willow	11.7
Softwood	19.2

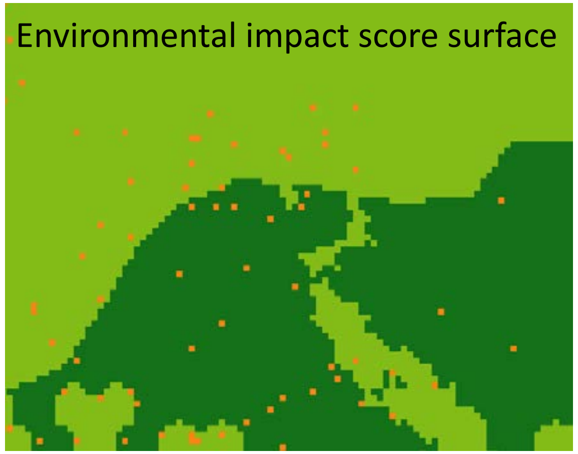
See Wu et al. (2023) PoP West for sources

2 Calculating social and environmental impact scores





Area = 2.25 km2



CPA Characteristics:

- Env score for PV = 10
- Env score for wind = 5
- Env score for APV = 1

- Social score for PV = -5
- Social score for wind = -0.5
- Social score for APV = -5

Technology-specific impacts

Technology	Env impact score	Social impact score	Installed Capacity (MW)
Fixed tilt PV	2.25 km2 × 10 = **22.5**	2.25 km2 × -5 = **-11.25**	58 MW/km2×2.25 km2 = **130.5 MW**
Tracking PV	2.25 km2 × 10= **22.5**	2.25 km2 × -5 = **-11.25**	**40** MW/km2×2.25 km2 = **90 MW**
Wind	2.25 km2 × 5 = **11.25**	2.25 km2 × -0.5 = **-1.125**	**2.7** MW×2.25 km2 = **6.08 MW**
Colocation – Tracking PV & wind	2.25 km2 × (5+10)/2 = **16.88**	2.25 km2 × (-0.5 + -5)/2 = **-6.19**	2.7 MW×2.25 km2 ×**3** (1:2 ratio of wind to solar) = **18.23 MW**
Agrivoltaics (if suitable)	2.25 km2 × 1 = **2.25**	2.25 km2 × -5 = **-11.25**	32.8 MW/km2×2.25 km2 = **73.8 MW**

3 Gen-tie/spur line modeling

1. Develop cost and routing surfaces using multipliers
2. Route spur lines using routing surface
3. Estimate line costs using costing surface

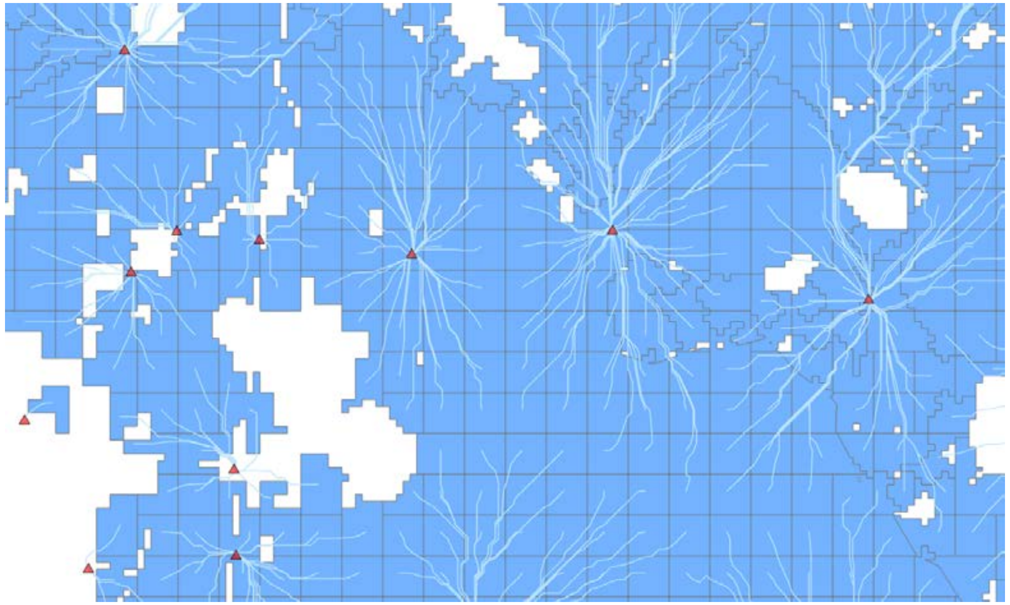


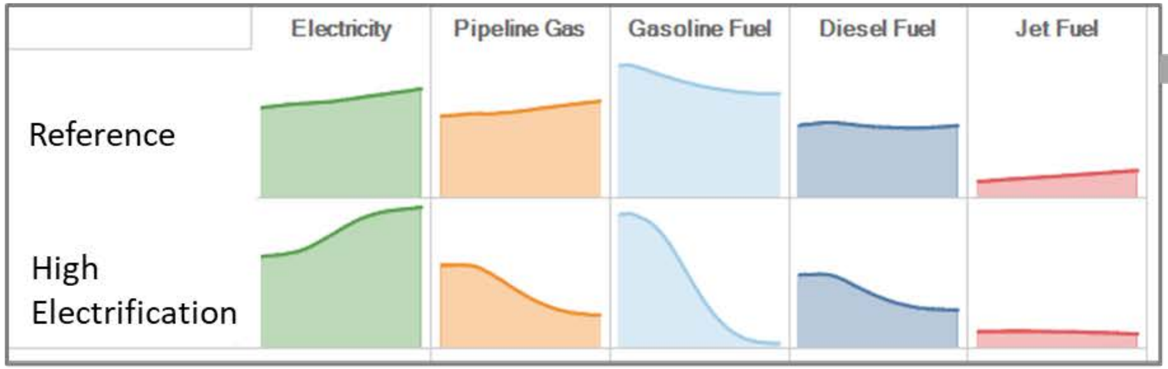
Table S7. Transmission routing multipliers

Multiplier	GIS layer	Use	Criteria	Value[1]
Terrain	MRLCD (30)	routing	Forested	2.25
Terrain	MRLCD (30)	routing	Urban	1.59
Terrain	MRLCD (30)	routing	Wetlands (and water)[5]	1.20
Terrain	MRLCD (30)	routing	Desert/barren	1.05
Terrain	MRLCD (30)	routing	Scrubbed/Farmland/(& other)[5]	1.00
Slope	USGS (31)	routing	mountain (greater than 4 degrees)	1.75
Slope	USGS (31)	routing	rolling hills (between 1 and 4 degrees)	1.40
Slope	USGS (31)	routing	flat (less than 1 degree)	1.00
Environmental Risk	The Nature Conservancy	routing	Category 1	100 (TNC)[3]
Environmental Risk	The Nature Conservancy	routing	Category 2	20 (TNC)
Environmental Risk	The Nature Conservancy	routing	Category 3	15 (TNC)
Environmental Risk	The Nature Conservancy	routing	No Category	1 (TNC)
Airports and Runways	EZMT [ref] [ref]	routing	$<$ 5km from either	100 (32)
Existing ROW	HILFD (28)	routing	New builds + in existing ROW	9 (TNC)[7]
B&V Terrain/Slope	USGS (31) MRLCD (30)	costing	Forested	2.25
B&V Terrain/Slope	USGS (31) MRLCD (30)	costing	Mountain	1.75
B&V Terrain/Slope	USGS (31) MRLCD (30)	costing	Urban	1.59
B&V Terrain/Slope	USGS (31) MRLCD (30)	costing	Rolling hills	1.40
B&V Terrain/Slope	USGS (31) MRLCD (30)	costing	Wetland (& water)[5]	1.20
B&V Terrain/Slope	USGS (31) MRLCD (30)	costing	Desert/barren land	1.05
B&V Terrain/Slope	USGS (31) MRLCD (30)	costing	Scrubbed/Farmland/(& other)[5]	1.00
Environmental Risk	The Nature Conservancy	costing	Category 1	1.2 (TNC)[4]
Environmental Risk	The Nature Conservancy	costing	Category 2	1.1 (TNC)[8](35)
Environmental Risk	The Nature Conservancy	costing	Category 3	1.05 (TNC)[8](35)
Environmental Risk	The Nature Conservancy	costing	No Category	1 (TNC) (35)

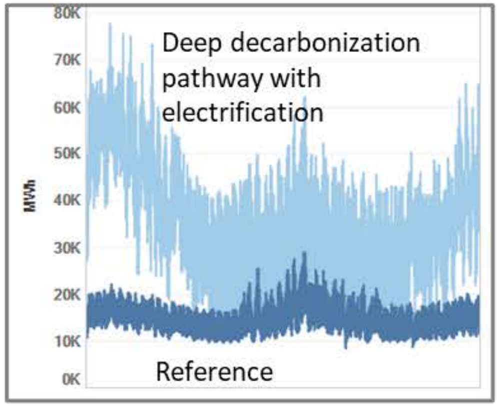
4 Economy-wide Energy Modeling Framework - Tools

EnergyPATHWAYS (EP)

Annual End-Use Energy Demand



Hourly Load Shape



Regional Investment and Operations (RIO)

Inputs

- End-use energy demand
- CO_2 emissions constraints
- RPS or CES constraints
- Technology and fuel cost projections
- New resource constraints
- Biomass and CO_2 Sequestration costs
- Hourly load shape

Outputs

Electricity sector
- Wind/solar build
- Energy storage capacity/duration
- Capacity for reliability
- Curtailment
- Hourly operations

Hydrogen production

Synthetic fuel production

Biomass allocation

Carbon capture, utilization & storage

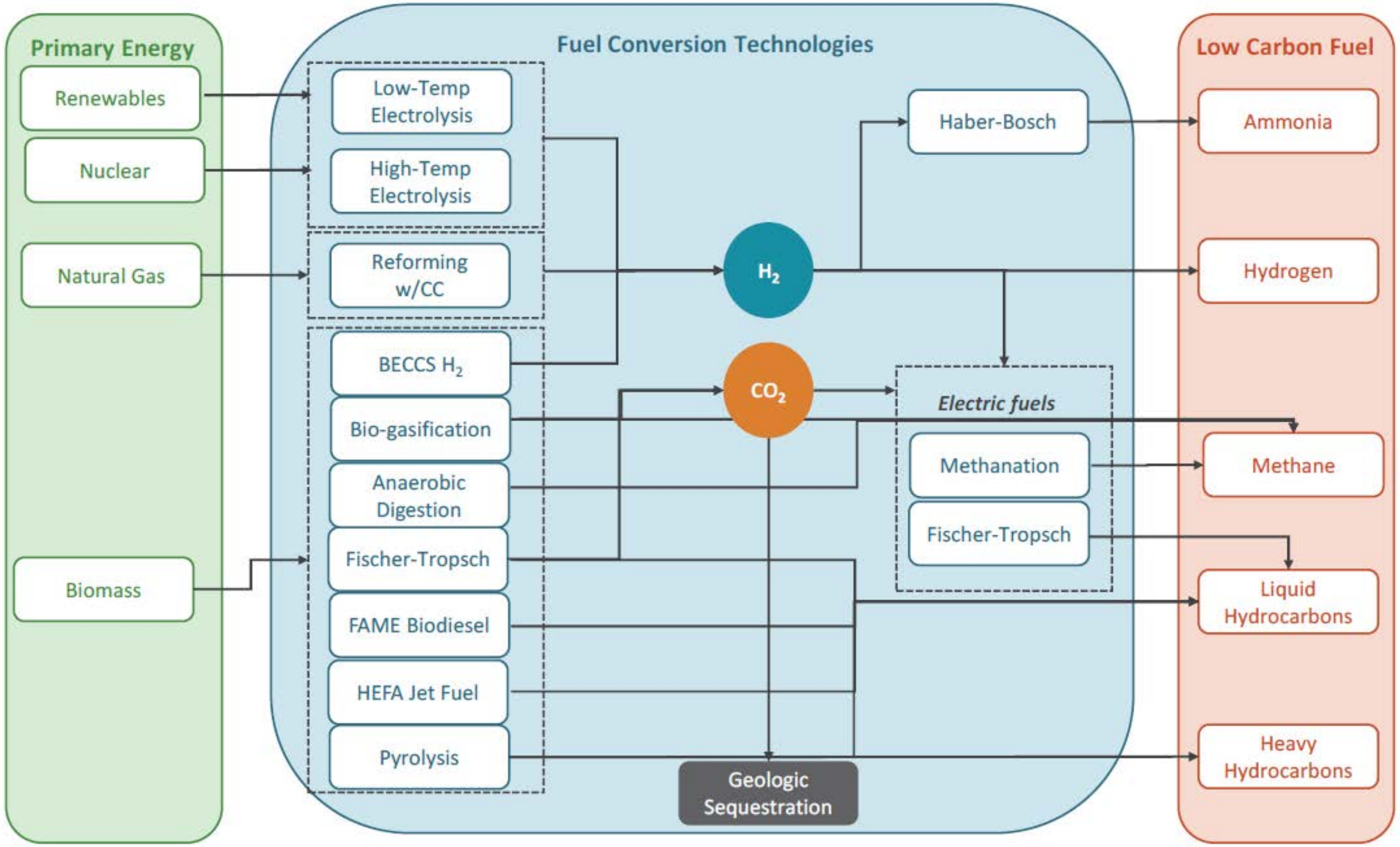
④ Wide set of technologies options represented

215 Demand-Side Technologies

Electricity Technologies:

- Rooftop solar, urban infill, ground-mounted
- Onshore wind, offshore wind
- Nuclear, Gas CCGT w/CC, Biomass w/CC
- Gas CCGT & CT
- Geothermal
- Electricity Storage
- Flexible load

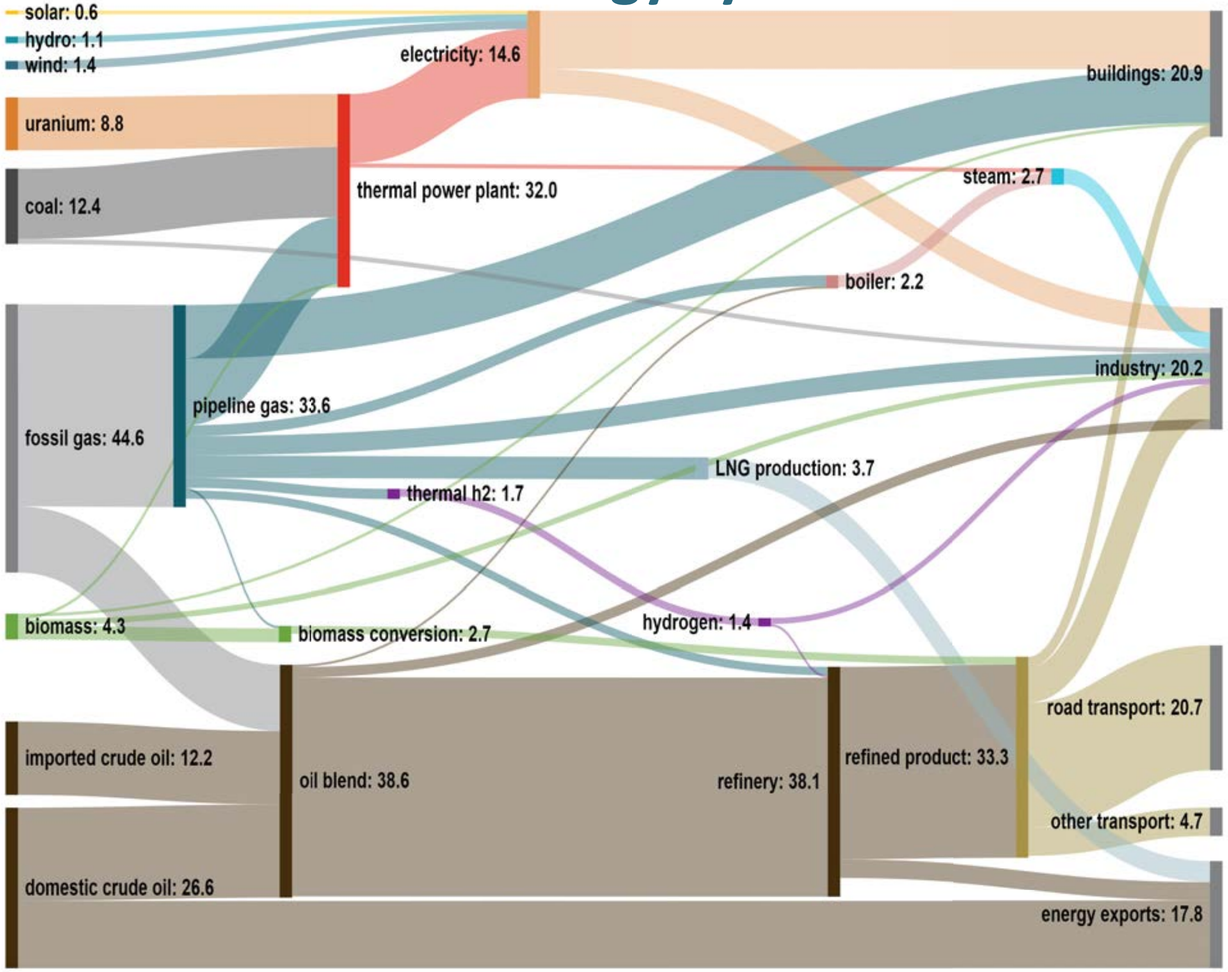
Fuel Technologies



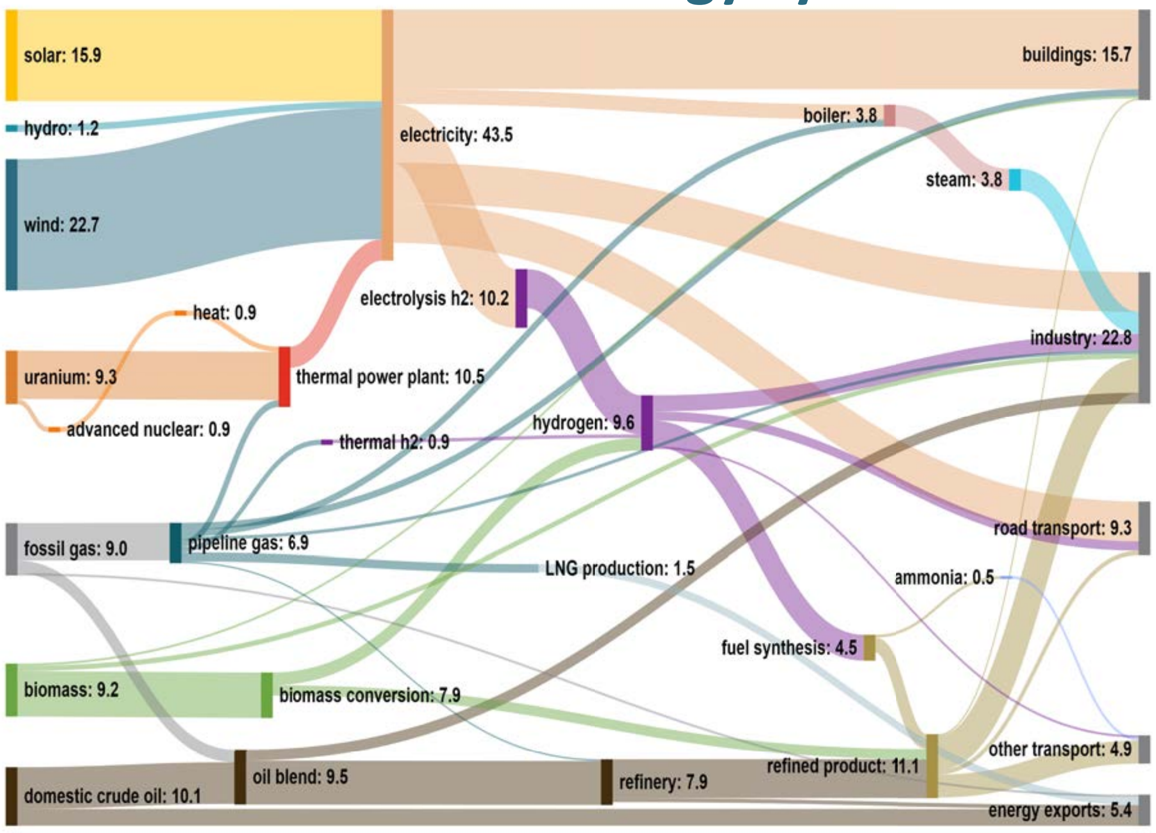
4 Envisioning a decarbonized energy system for the U.S.

Sankey diagrams (EJ)

2021 Energy System



2050 Net-Zero Energy System

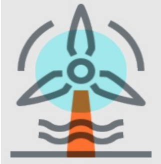


Source: ADP2022 Central Case

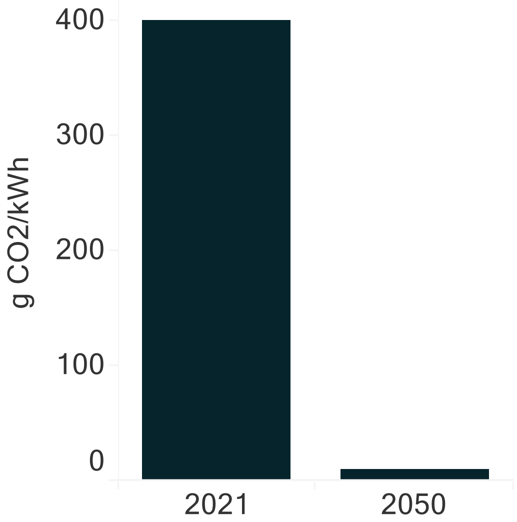
4 Economy-wide Energy Modeling Framework – Four Pillars

U.S. Benchmarks

Electricity Decarbonization

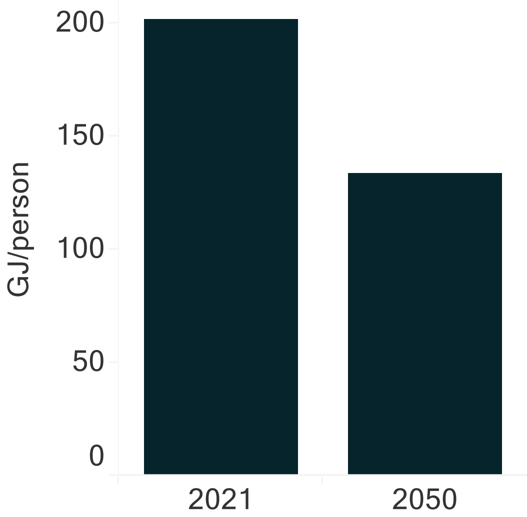


95% reduction in emissions intensity



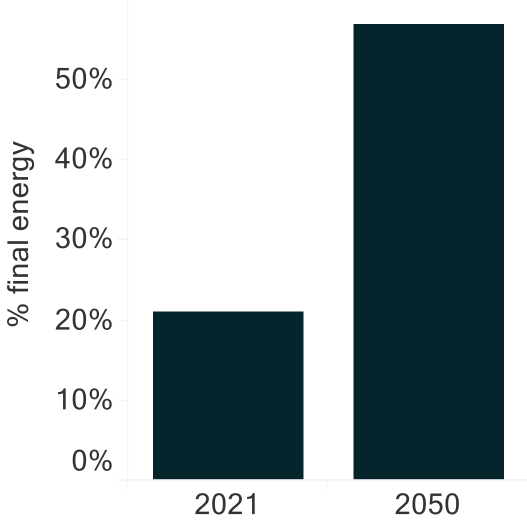
Energy Efficiency

40% reduction in per-capita final energy demand



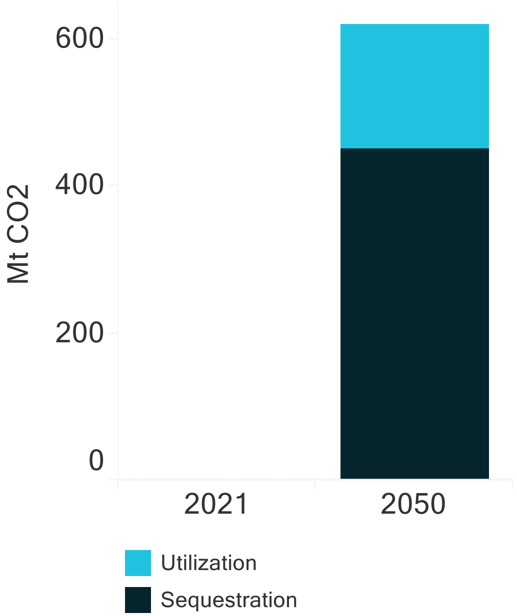
Electrification

300% increase in share of energy from electricity



Carbon Capture

600 MMT+ carbon capture and use/storage



Haley, B., Jones, R.A., Williams, J.H., Kwok, G., Farbes, J., Hargreaves, J., Pickrell, K., Bentz, D., Waddell, A., Leslie, E., Annual Decarbonization Perspective: Carbon Neutral Pathways for the United States 2022. Evolved Energy Research, 2022.

4 Environmental and social impact scenarios

1. Run RIO without any social or environmental constraints — Unconstrained (SAU) scenario (0% impact avoided)

2. Calculate the **total impact** — **Total unconstrained (SAU) impact** = Sum(area × score for all wind and solar CPAs) + Sum(Other energy system land consumption[1] × 1)

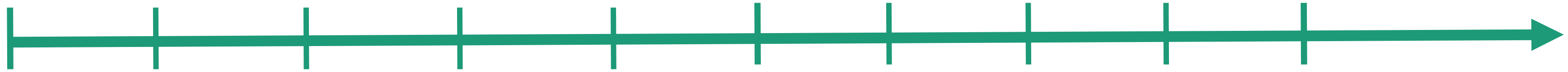
   [1]Other energy system: biomass, interzonal tx, fossil extraction

3. Ratchet down unconstrained total impact in 10% increments — **Total constrained impact (10% impact avoided) = Total unconstrained impact *0.90**

4. Run RIO — Constrained scenarios (0%, 10%, …, 90% impact avoided)

Unconstrained (SAU) scenario
(**0% impact avoided**)

Most constrained scenario
(**90% impact avoided**)



Moderately constrained scenario
(**50% impact avoided**)

⑤ Wind and solar downscaling

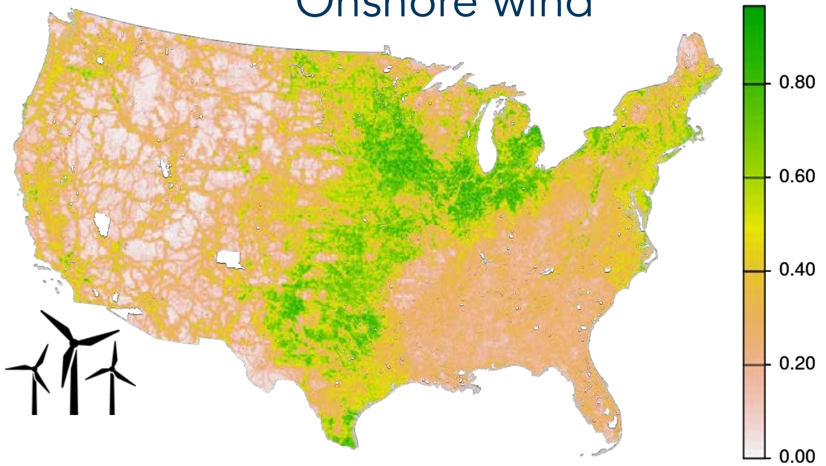
Empirical approach for predicting most suitable new locations for wind and solar development

The following predictive variables were used in a random forest regression:

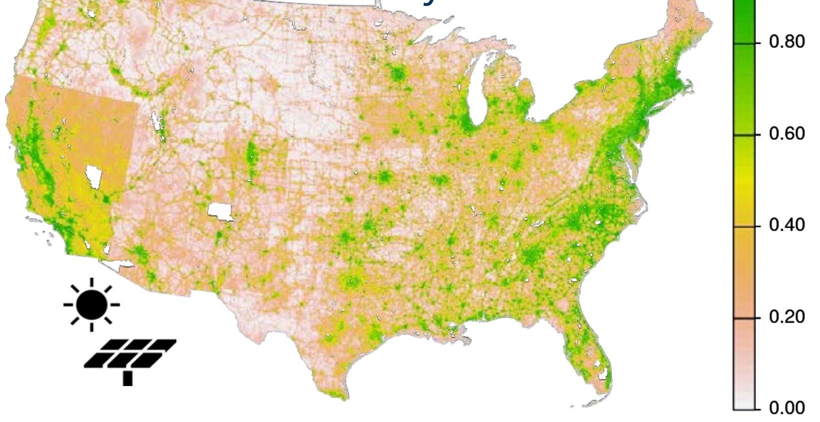
1. Environmental exclusion categories (environmental sensitivity)
2. Land acquisition cost
3. Population density
4. Distance to roads
5. Distance to existing **and proposed** substations
6. Distance to existing **and proposed** transmissions
7. Slope
8. Capacity factor (i.e., resource quality)
9. Renewable Portfolio Standards
10. Regional dummy variables

Random forest prediction surfaces

Onshore wind



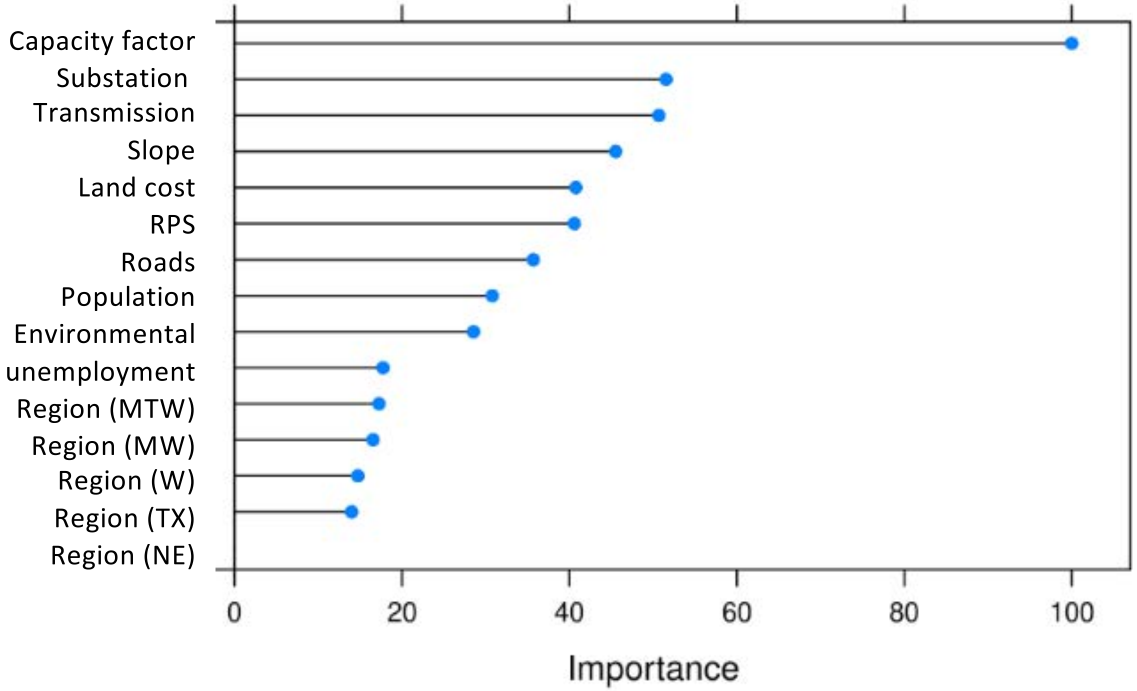
Utility-scale PV



5 Wind and solar downscaling

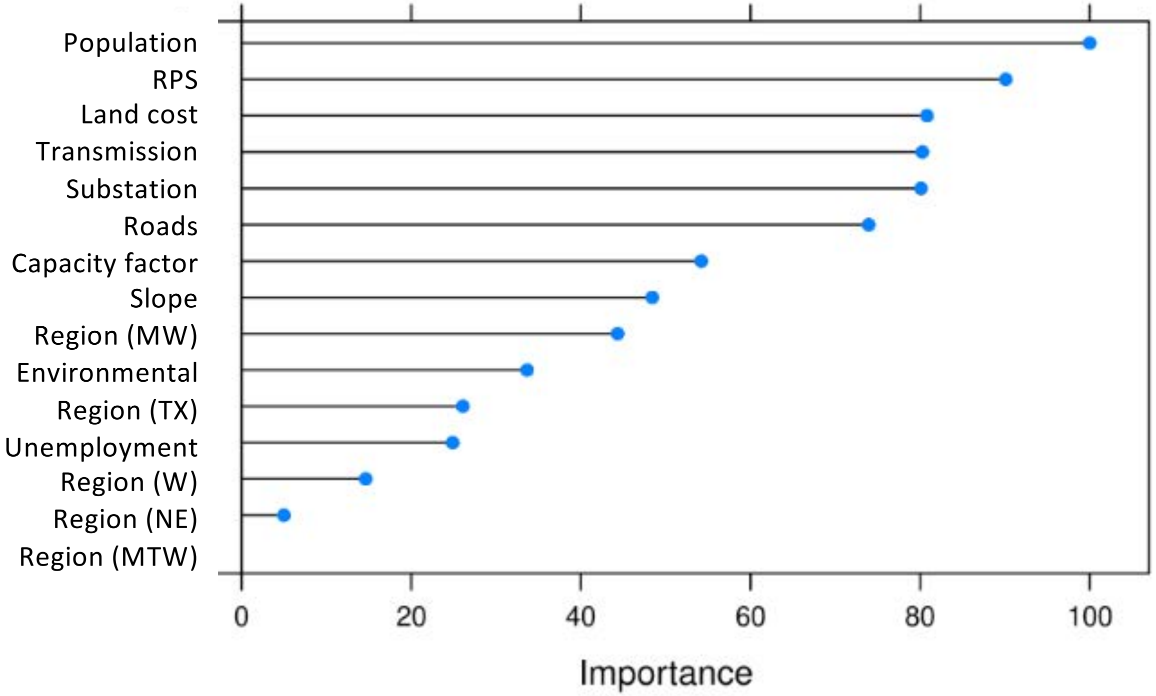
Onshore wind

Variables ranked by contribution to machine learning predictive approach



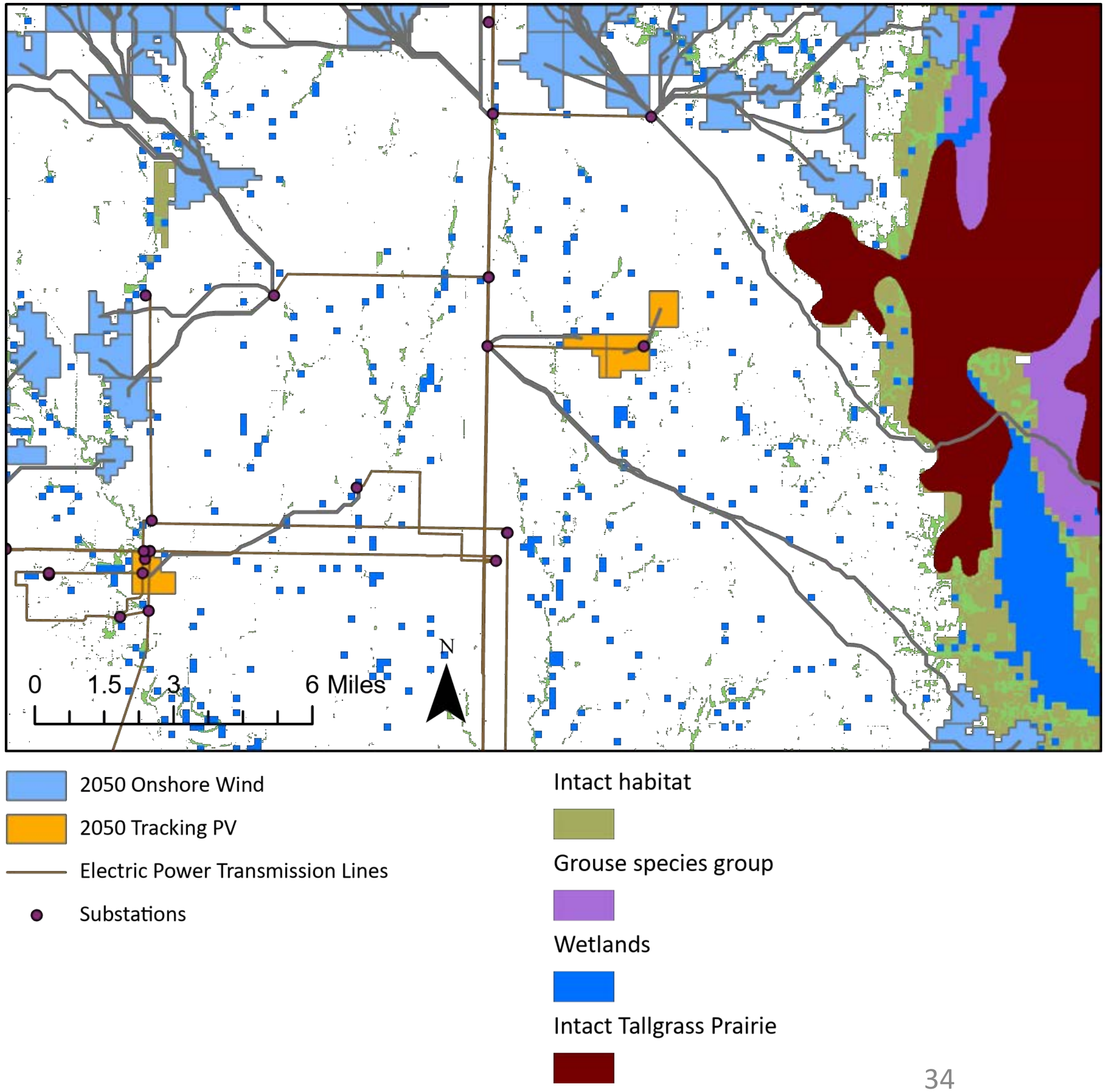
Solar PV

Variables ranked by contribution to machine learning predictive approach



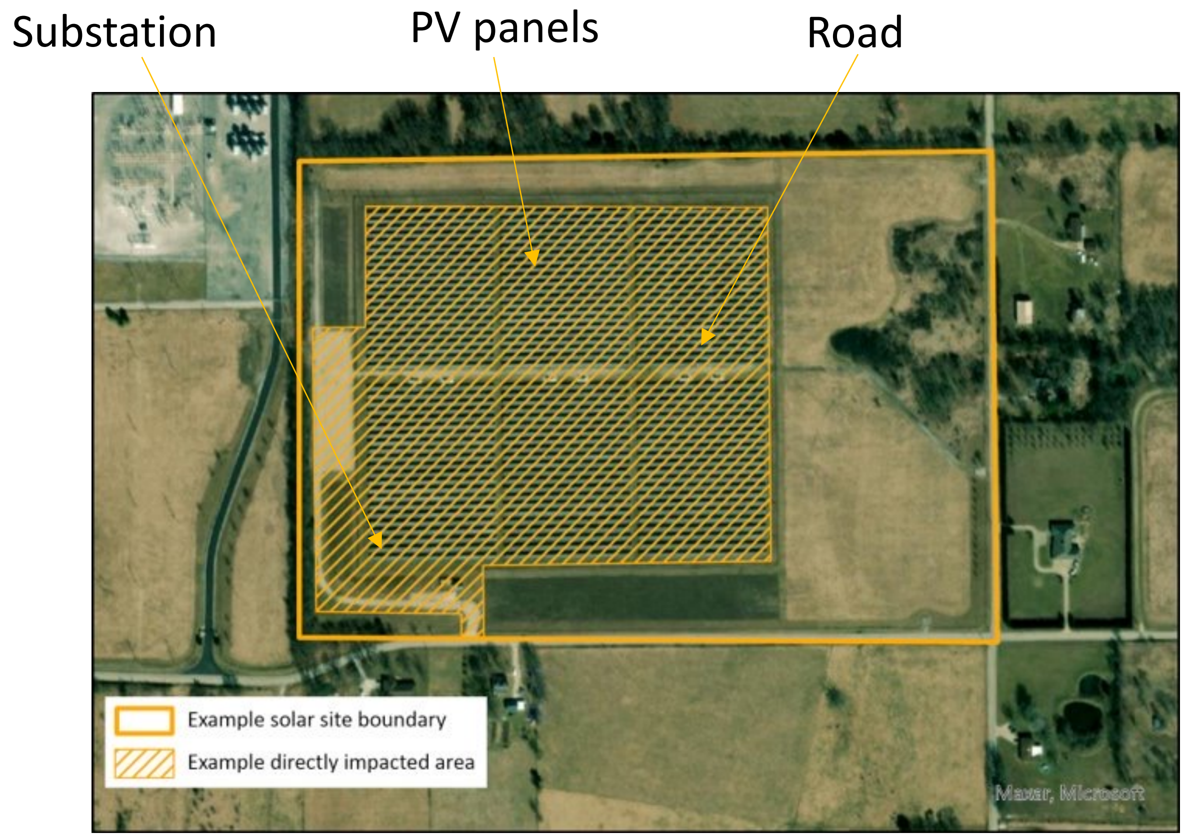
6 Portfolio Assessment

- For each technology (solar, wind, agrivoltaics, colocation of wind and solar) we use the portfolio footprint to evaluate affected area (including both site generation and transmission interconnection corridors) for the following resource types:
  - Intact landscapes
  - Resilient Connected Network
  - Intact tallgrass prairie
  - Wetlands
  - Forest
  - Bat habitat
  - Grouse species habitat
  - Whooping crane habitat
  - Tortoise species habitat
  - Productive farmland
  - Energy communities

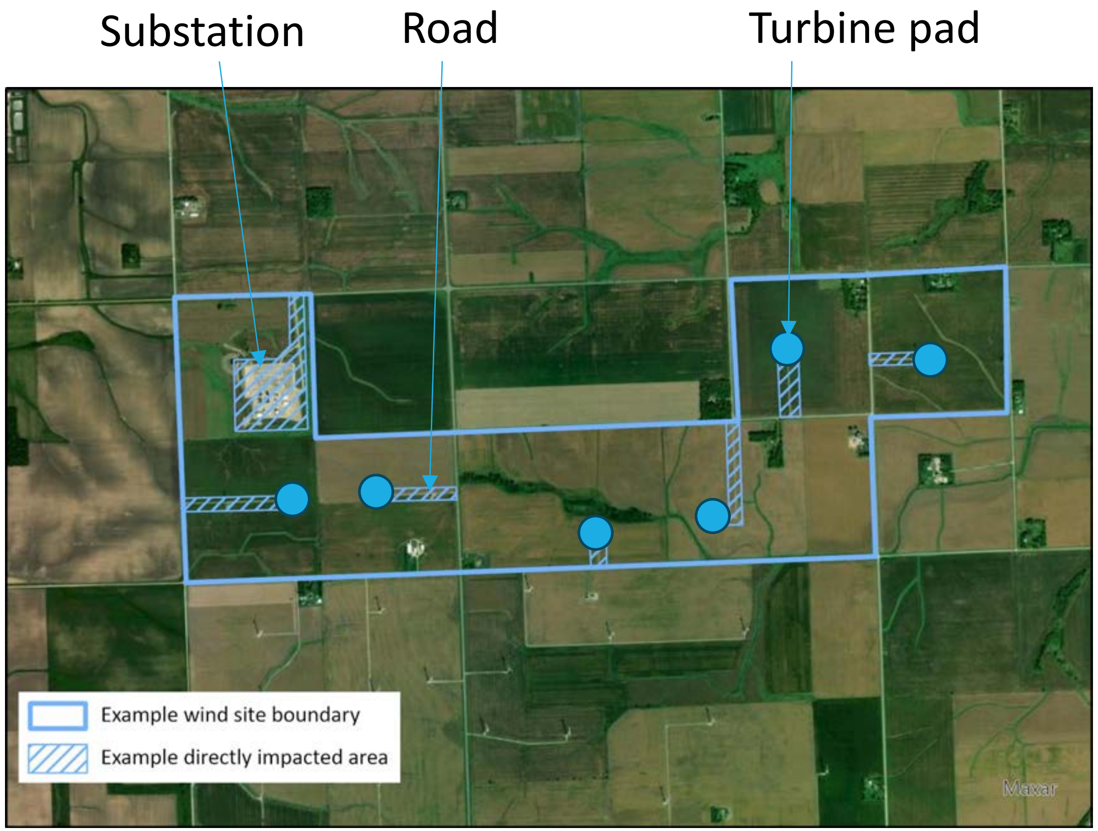


See appendix (slide 86) for references

6 Calculations include direct and total affected area for each metric and technology



Direct area = 91% of total area

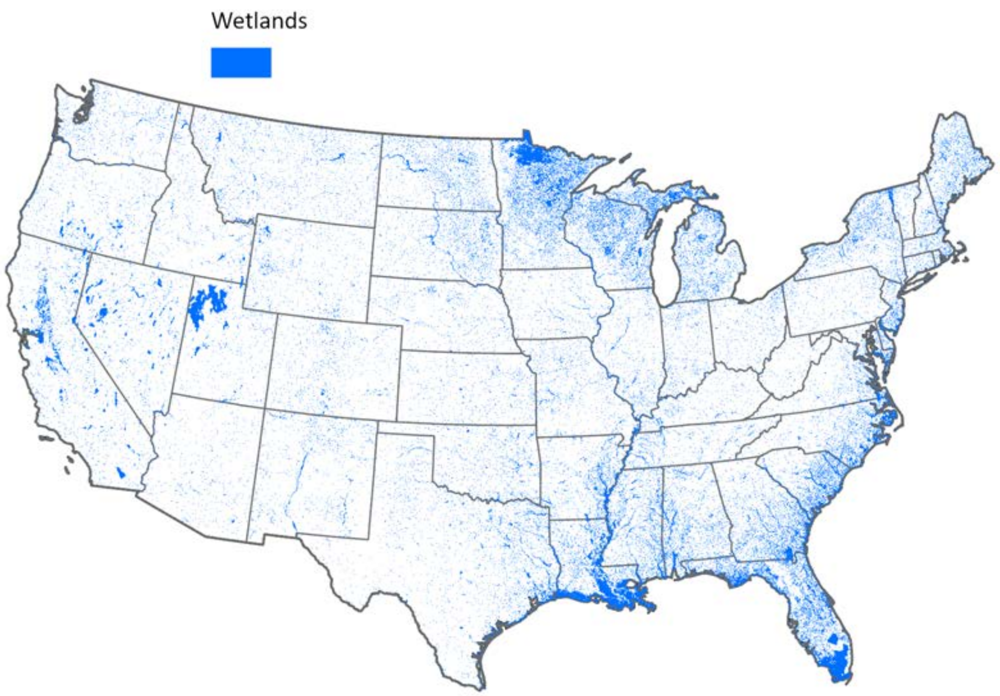


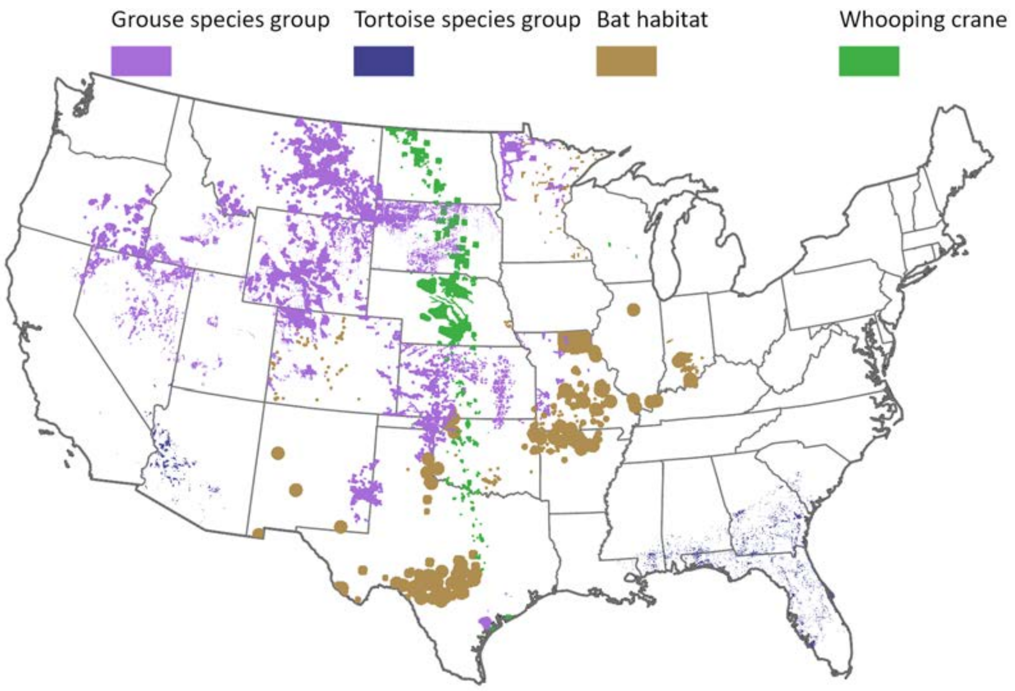
Direct area = 3% of total area

Colocation: direct area = 50% of total area

Source: Ong et al (2013) and Denholm et al (2009)

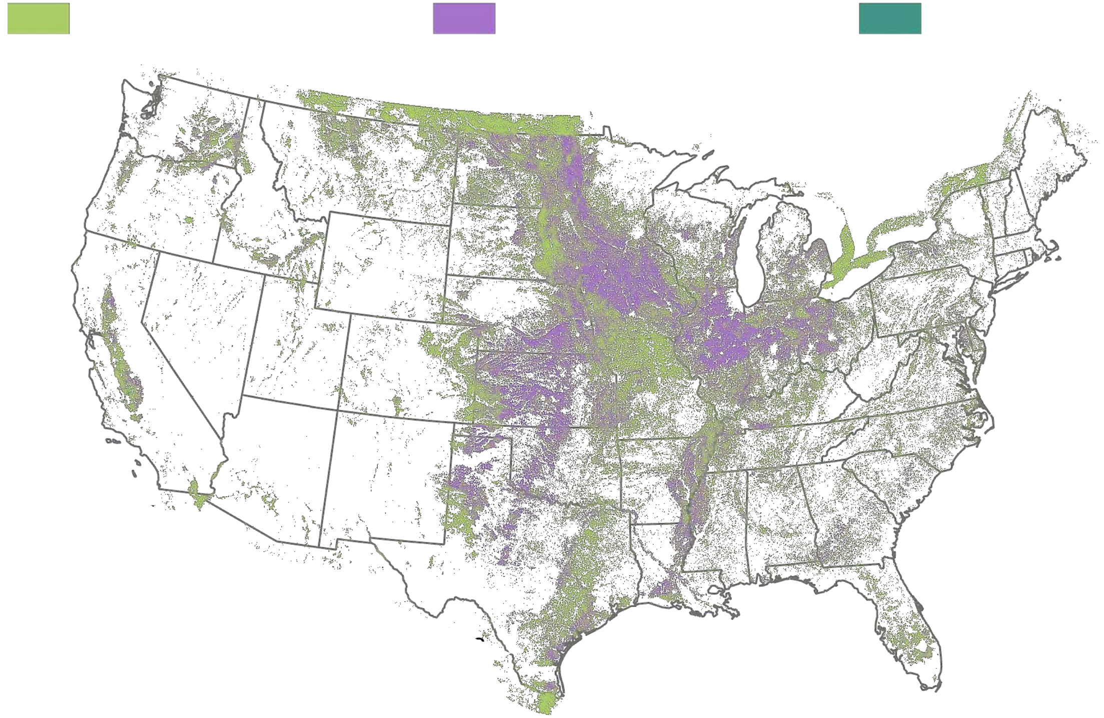
6 Portfolio Assessment - Environmental

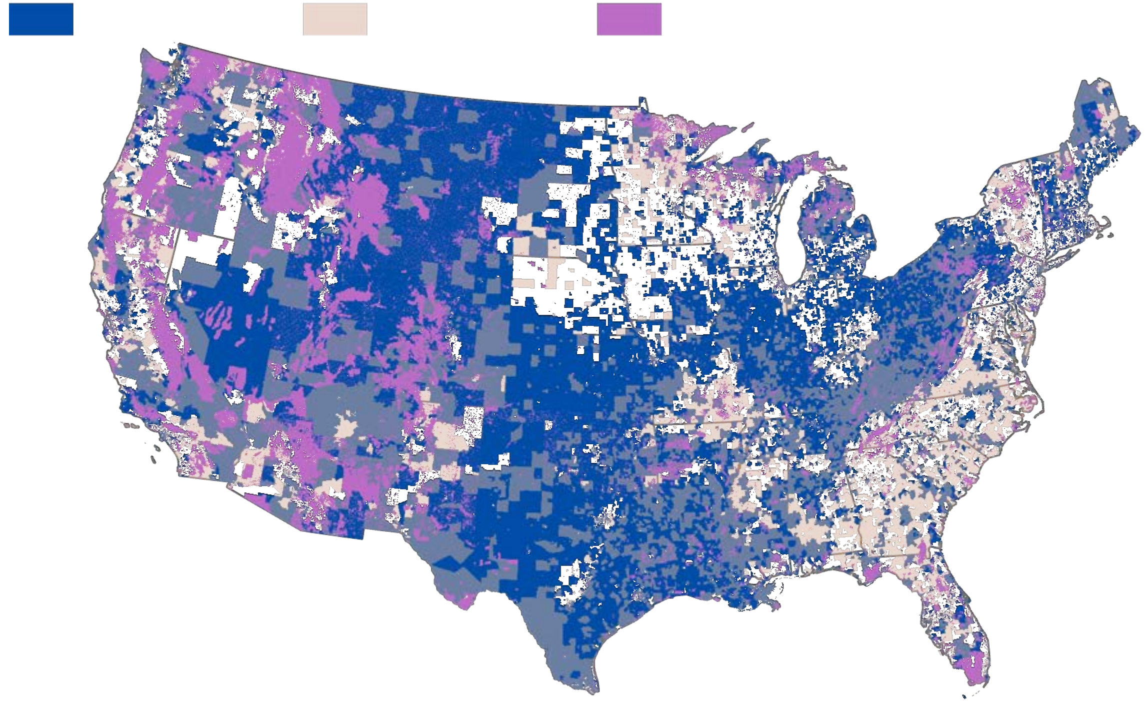




See appendix (slide 86) for references

⑥ Portfolio Assessment - Social





See appendix (slide 86) for references

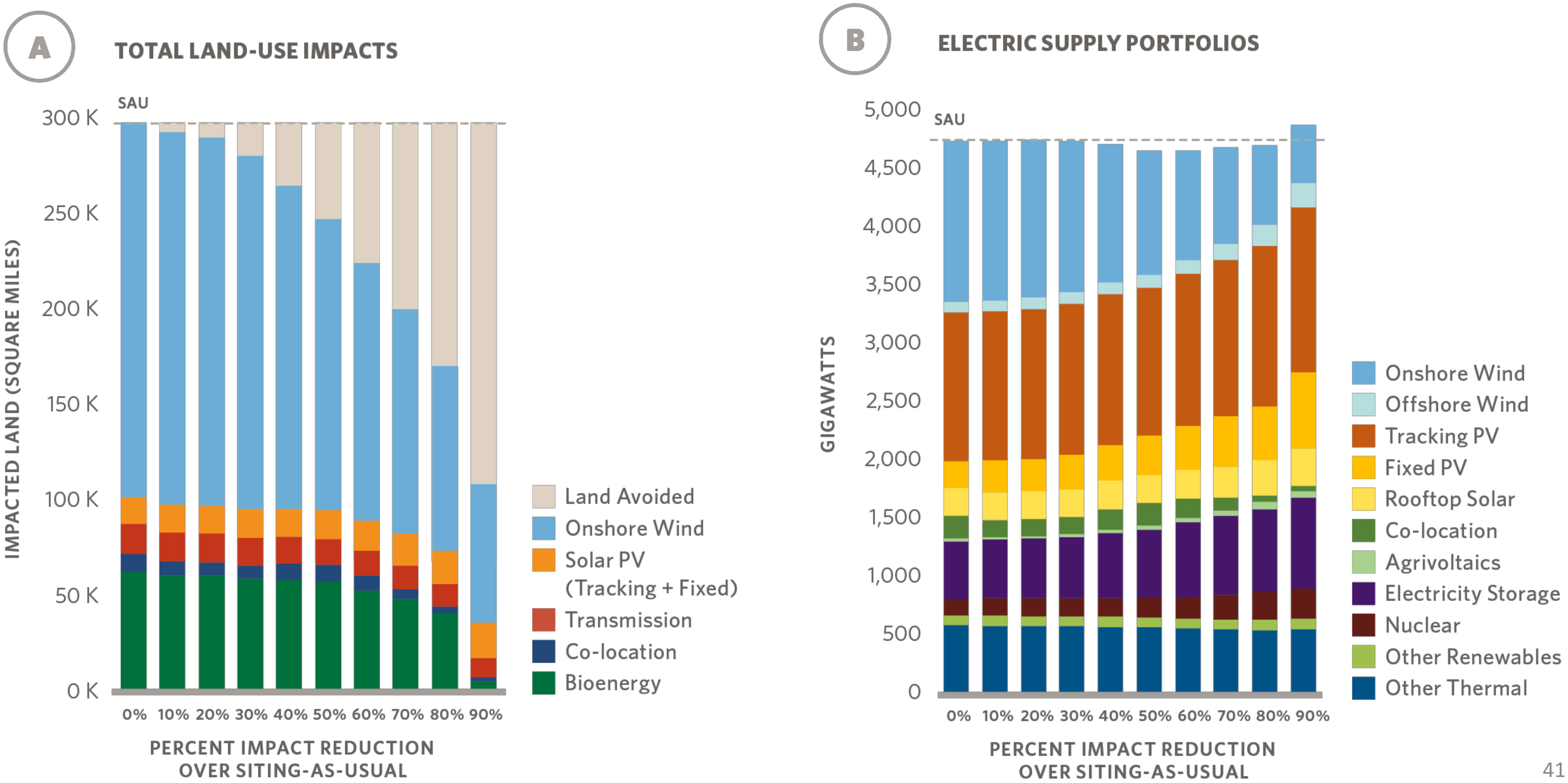
Assumptions and caveats

- Goal of this study: demonstrate a modeling approach and framework at the national level, provide a starting point for discussion
- We develop input assumptions for modeling purposes
- Other groups may make different assumptions, based on differing values, priorities
- Regionally-oriented customization, with higher granularity at the local level, is possible and expected, and local analysis should supersede simplified national results.

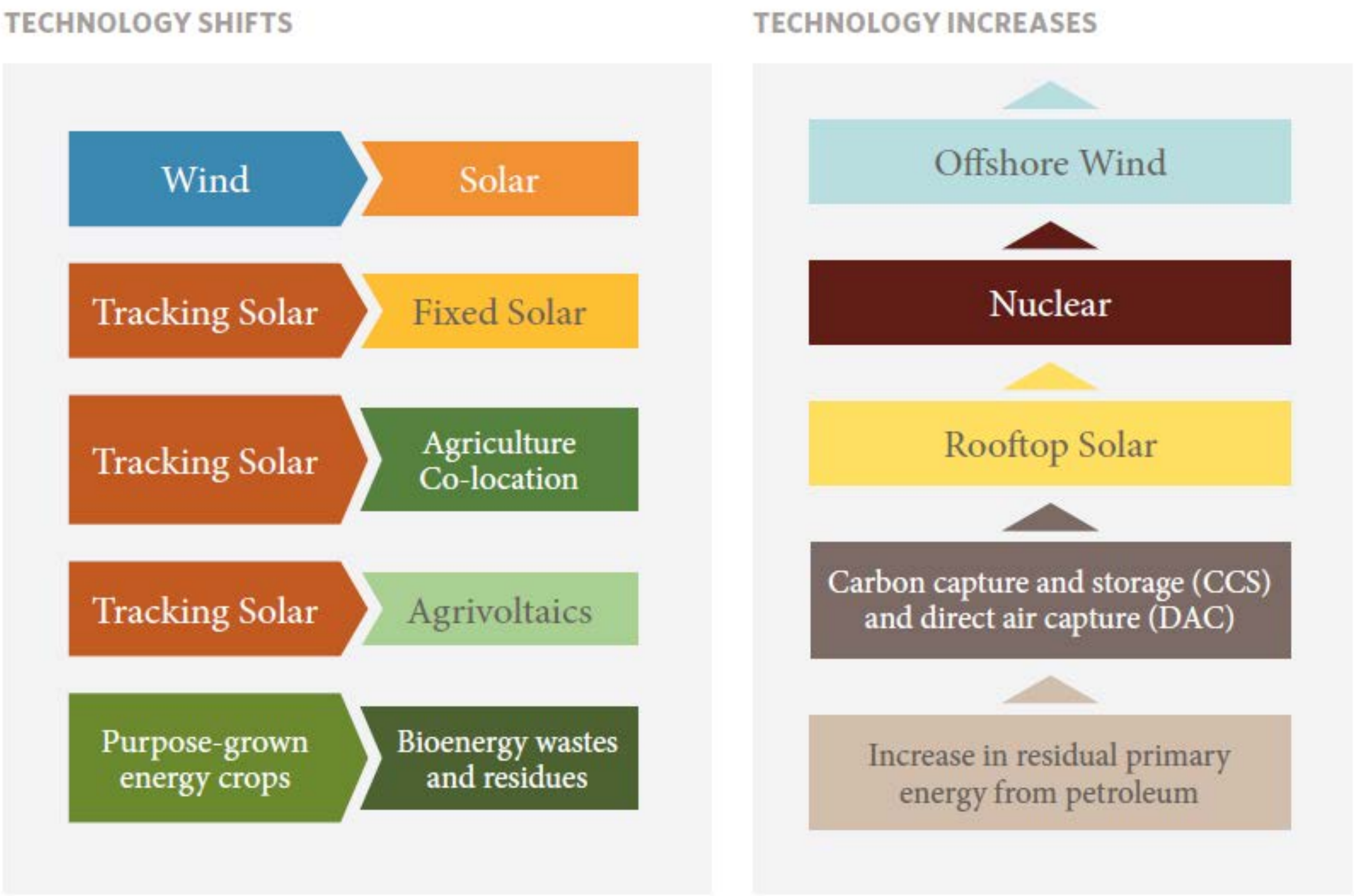
Questions on Methodology?

Power of Place-National Key Results

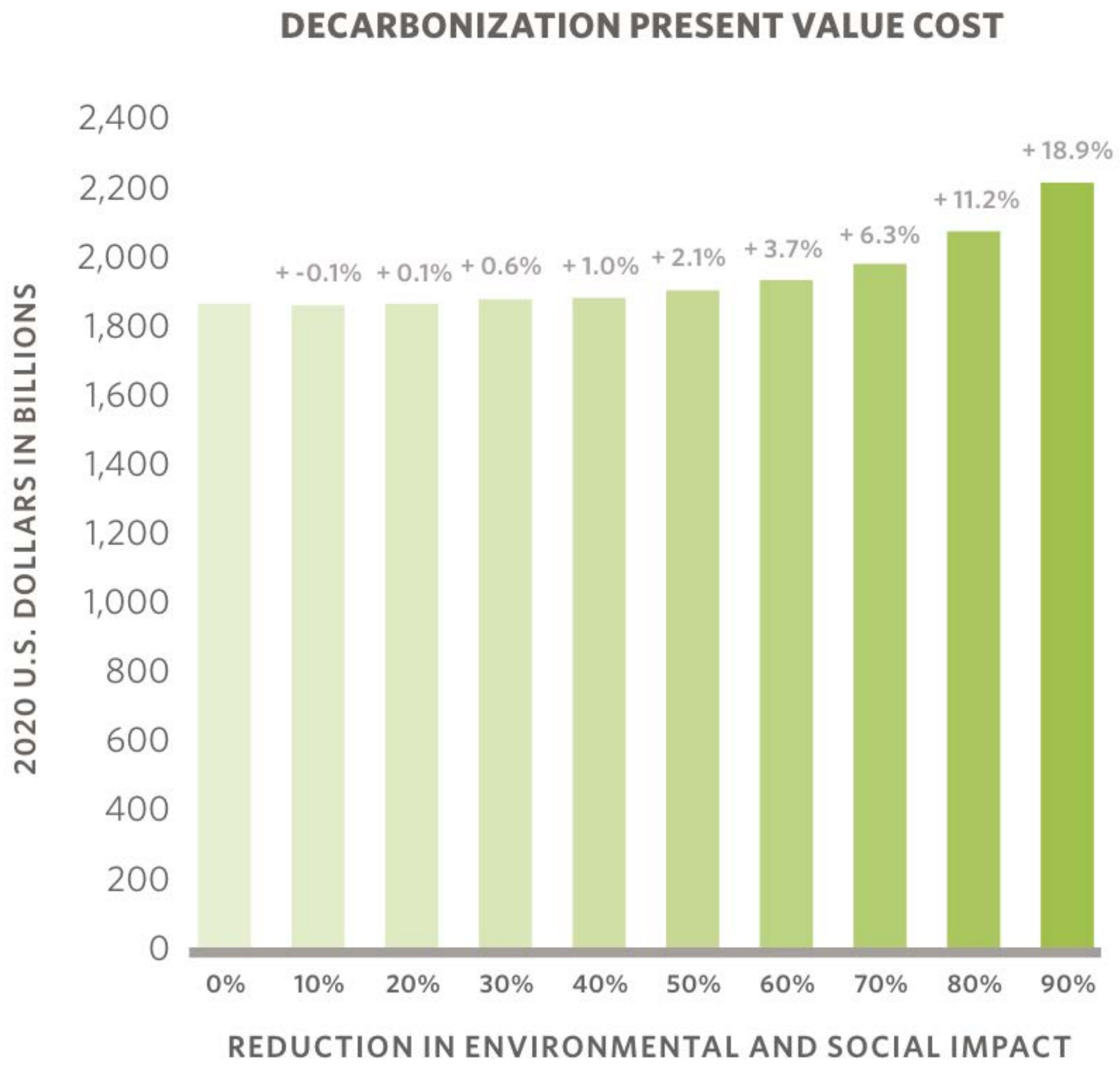
Reducing environmental and social impacts shifts clean energy portfolios



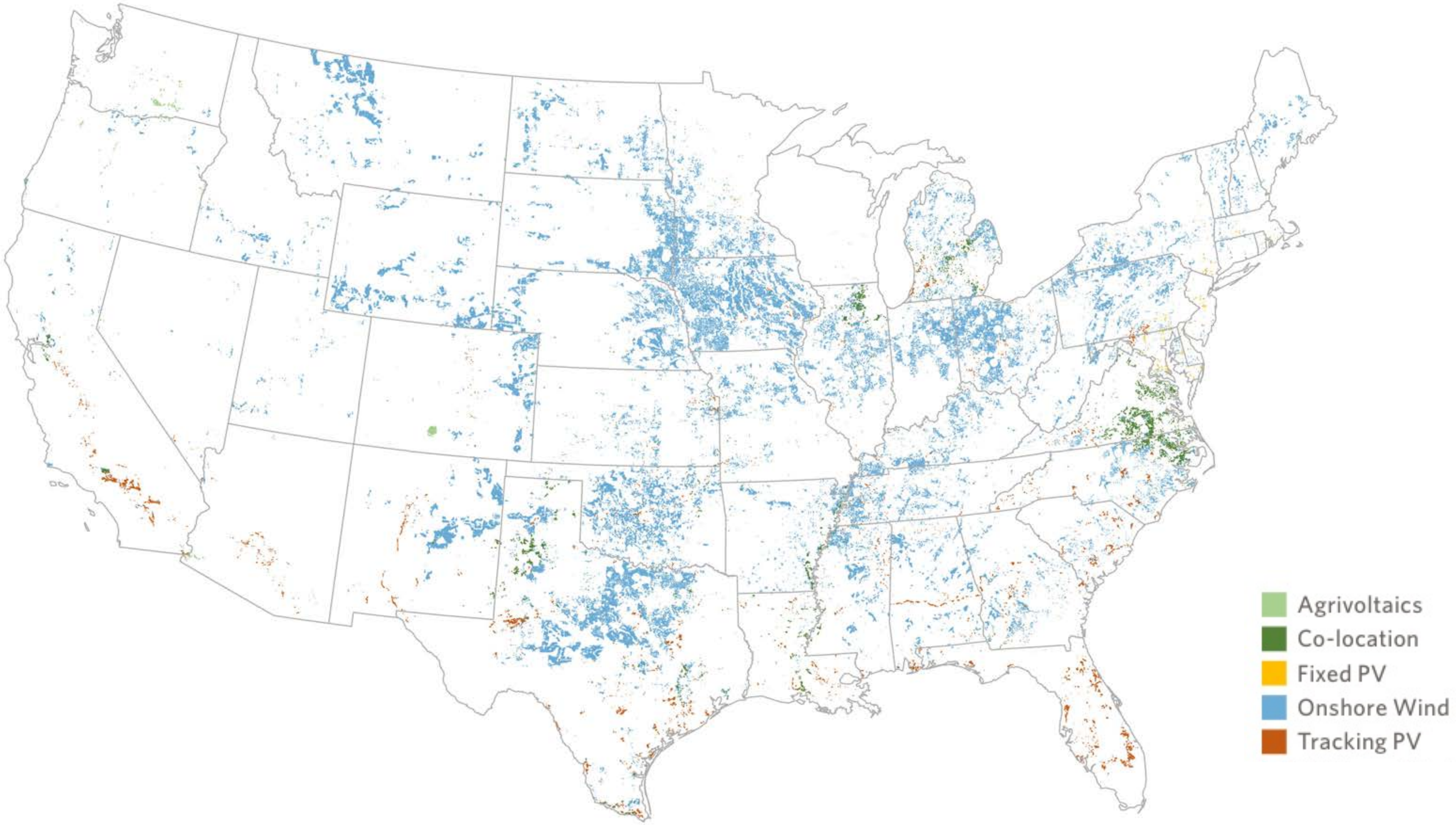
Reducing environmental and social impacts shifts clean energy portfolios



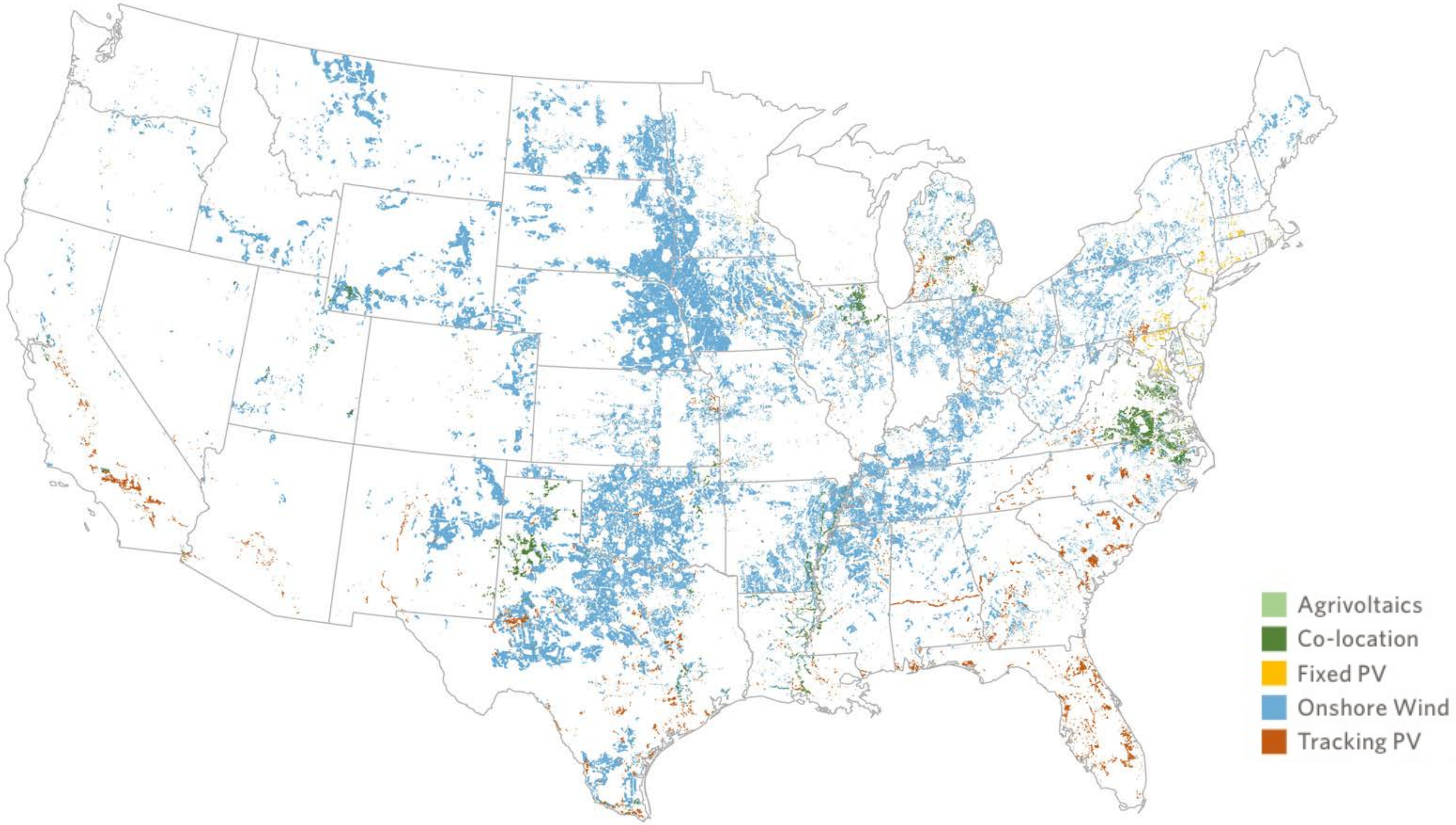
Impacts to sensitive natural and working lands and waters can be avoided at modest additional cost



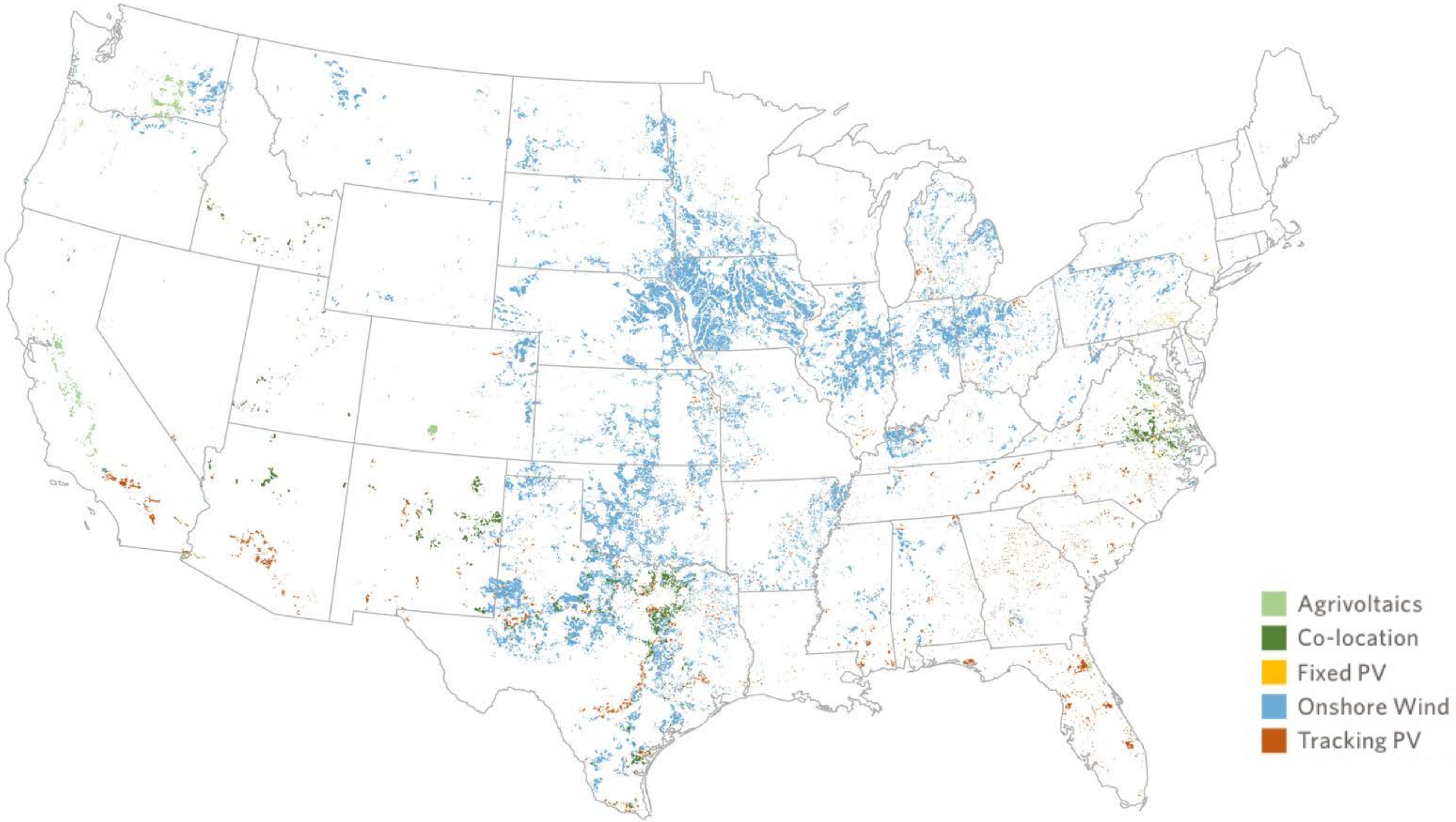
Build-out | 0% impact avoided | **2035**



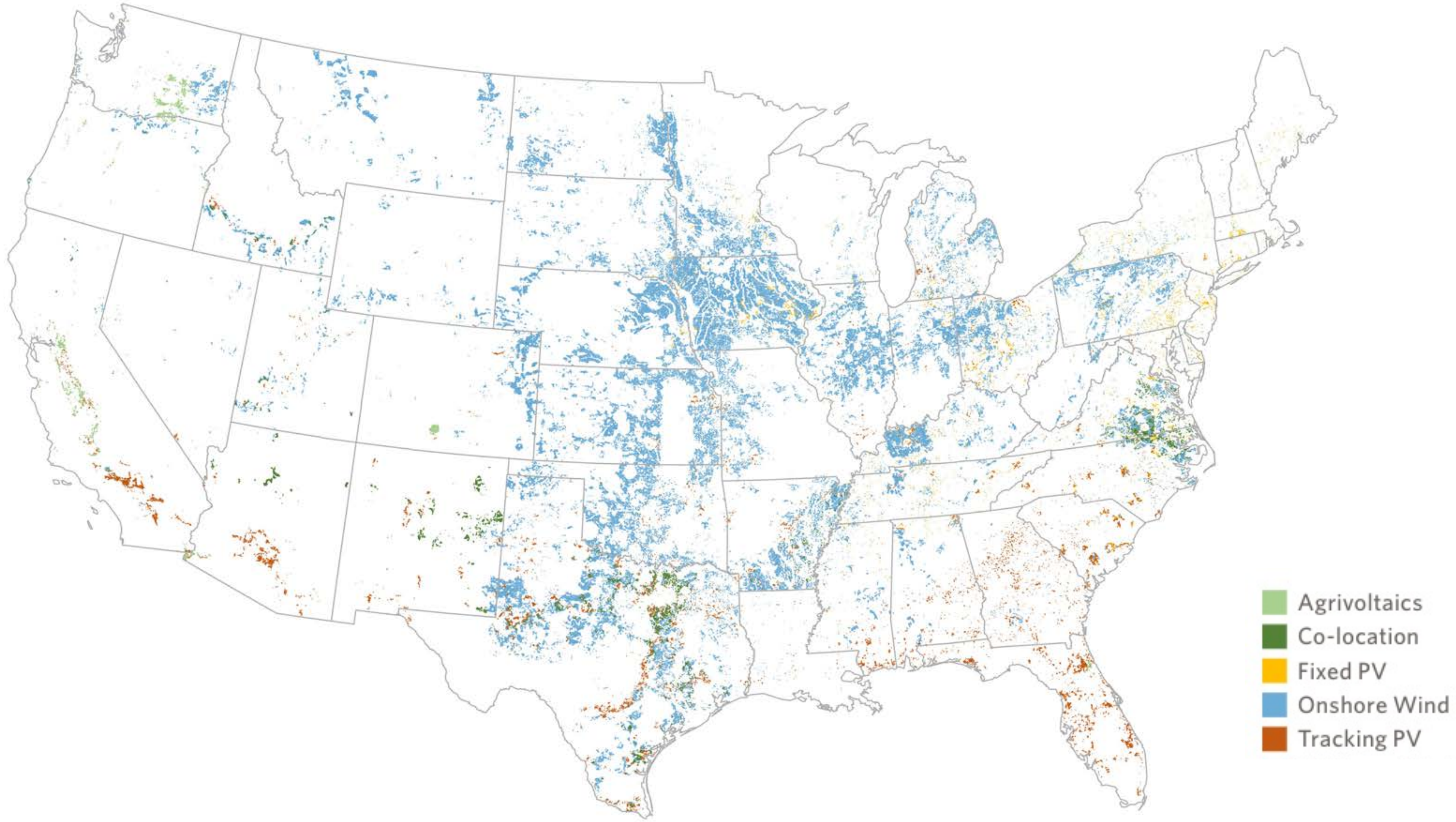
Build-out | 0% impact avoided | **2050**



Build-out | 70% impact avoided | **2035**

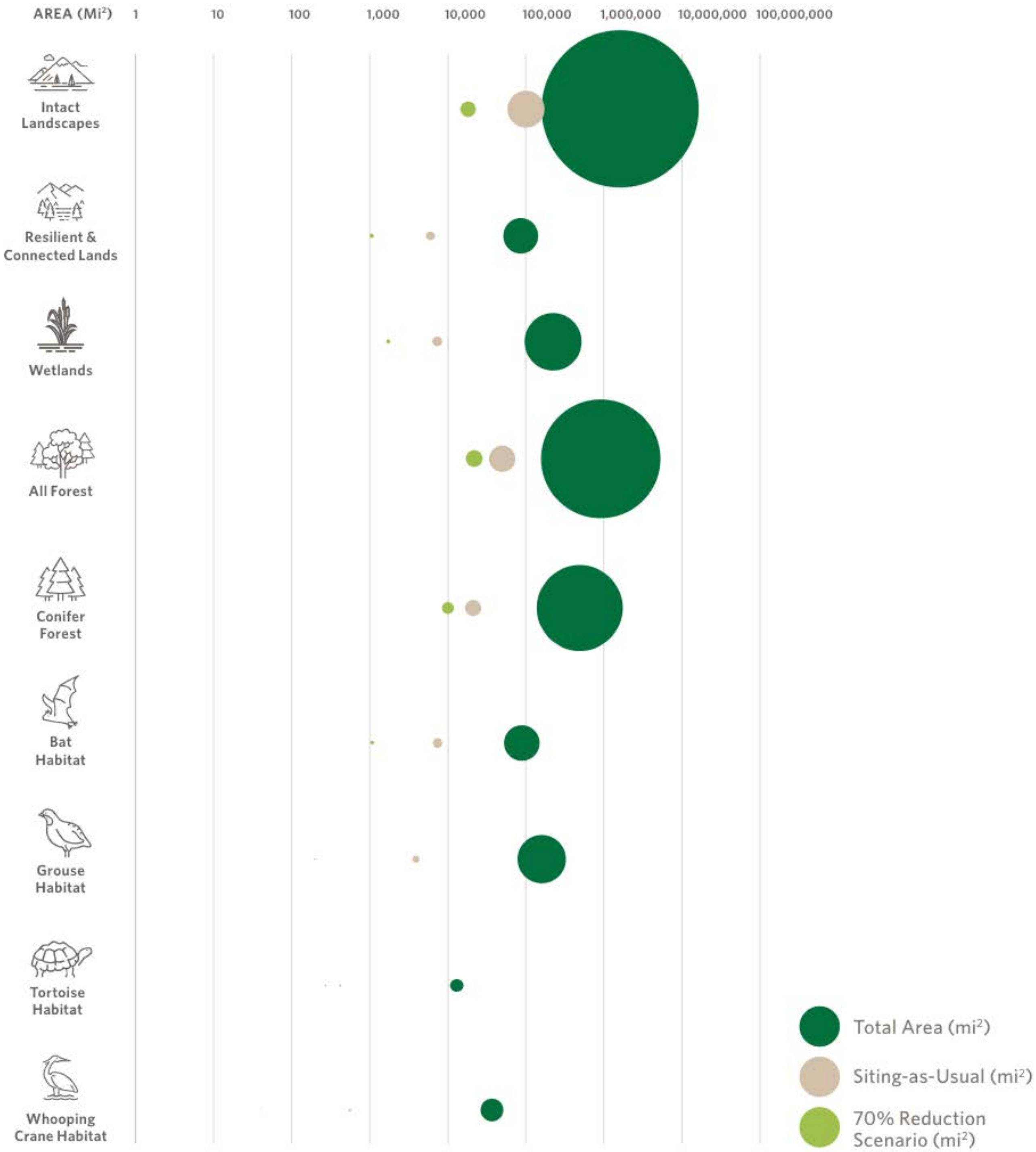


Build-out | 70% impact avoided | **2050**

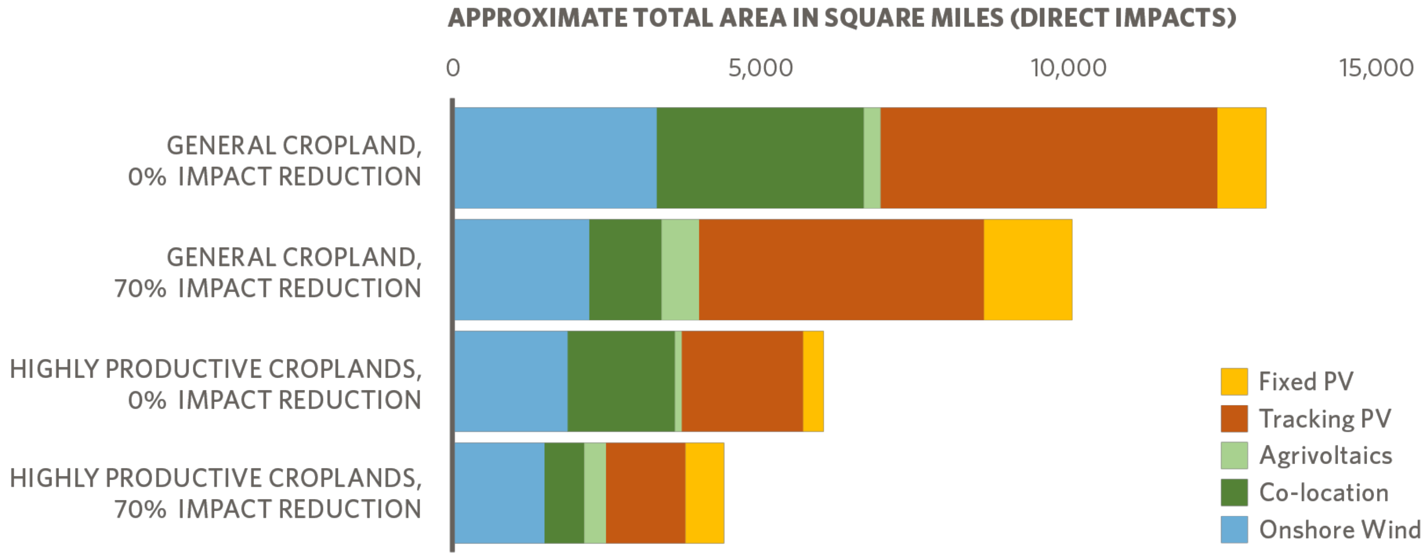


Less than 2% of different natural area types are impacted in the 70% scenario

- The possibility of impact avoidance does not mean that all impacts will necessarily be avoided.
- Careful planning is needed. This includes coordination among many entities (local, state, federal permitting authorities, transmission owners and operators, Public Utility Commissions, legislators).
- Where impacts cannot be avoided, mitigation and ecosystem restoration play critical roles.



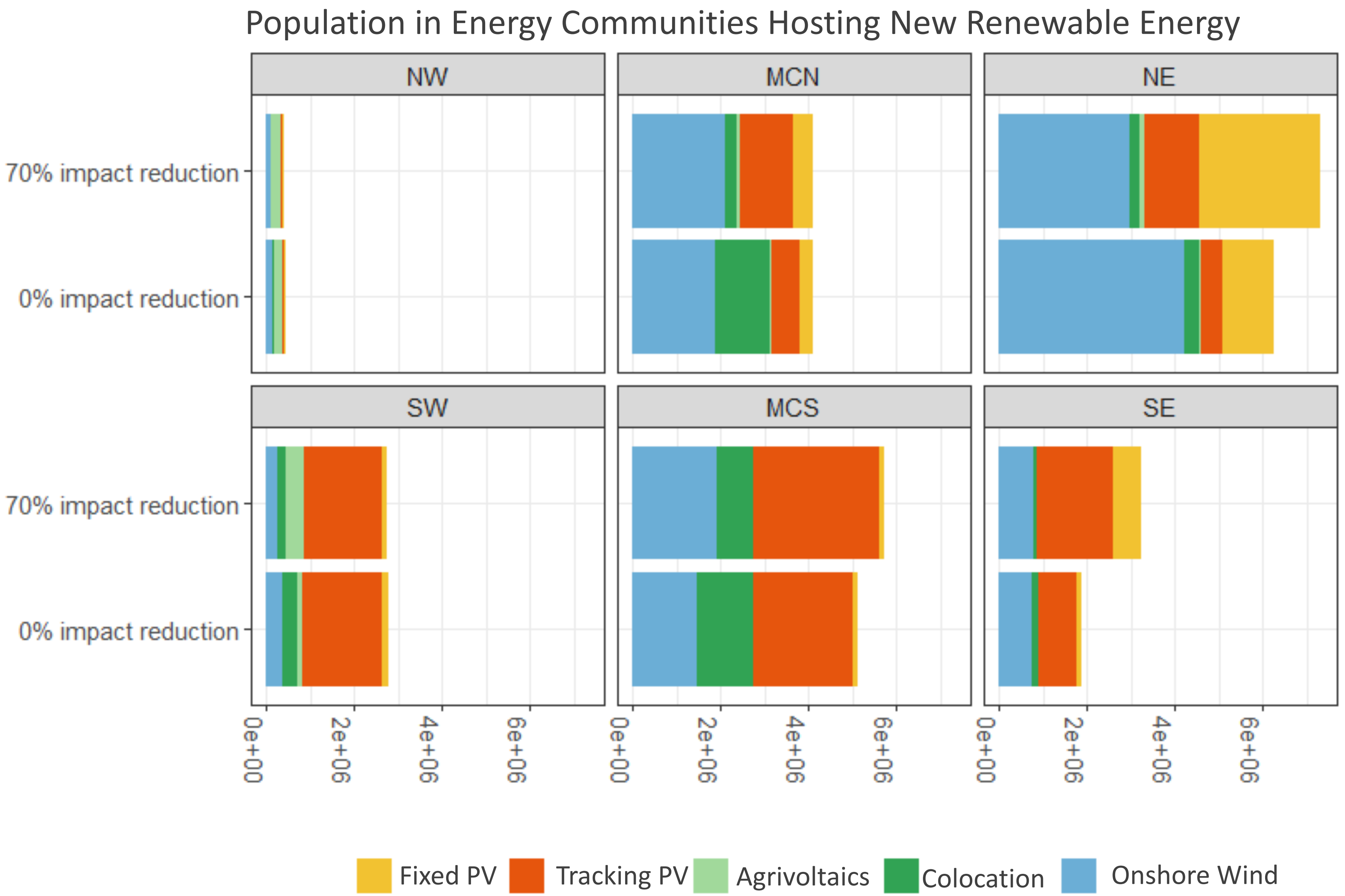
Impacts to high value croplands are modest and decline with lower impact scenarios



The following table shows the changes in direct land area in square miles for agrivoltaics and co-location under the siting-as-usual (SAU) and the 70% impact reduction scenario.

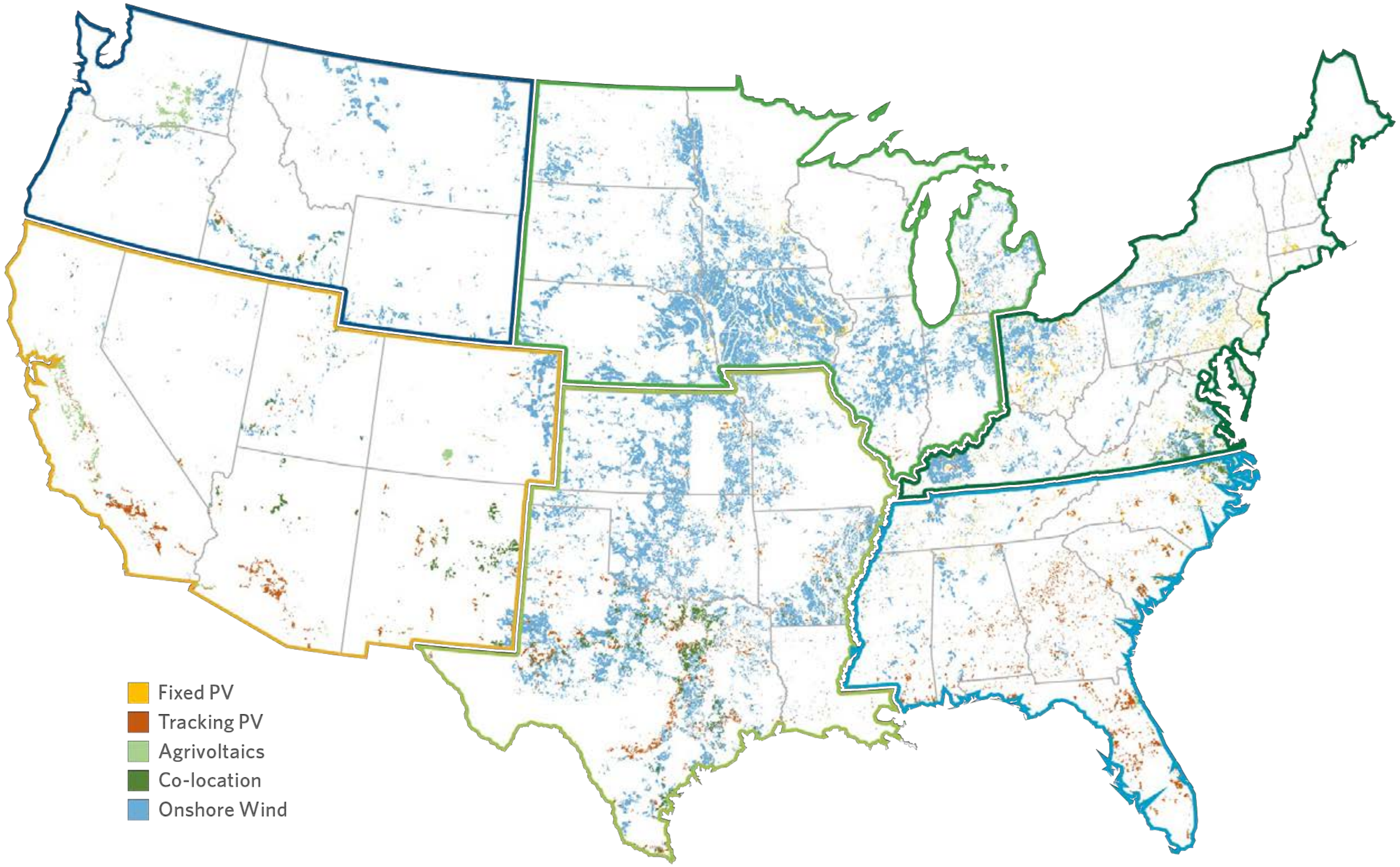
	SAU *(mi²)*	**70% REDUCTION** *(mi²)*
Agrivoltaics	216	600
Co-location	9,467	5,200

Lower impact scenarios achieve greater wind and solar driven job growth in energy communities



1.2-1.3 million new wind jobs and 10.9-13.5 million new solar jobs in Energy Communities.

Low impact siting strategies and generation technologies will vary regionally

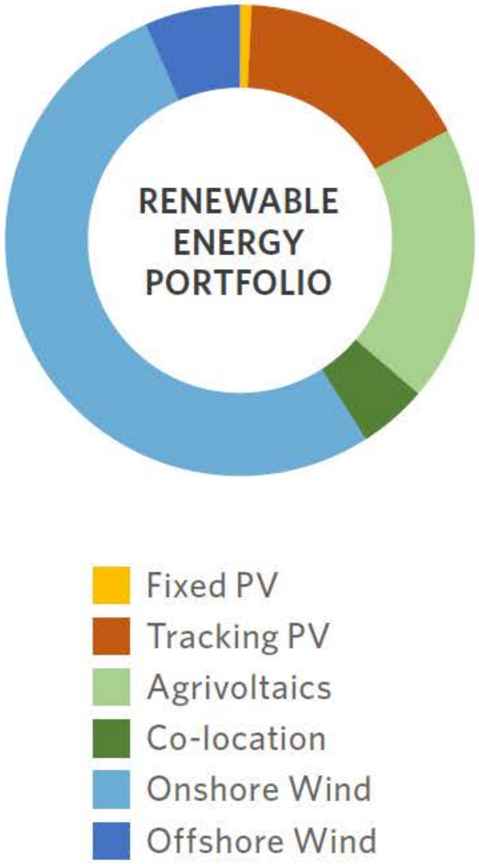


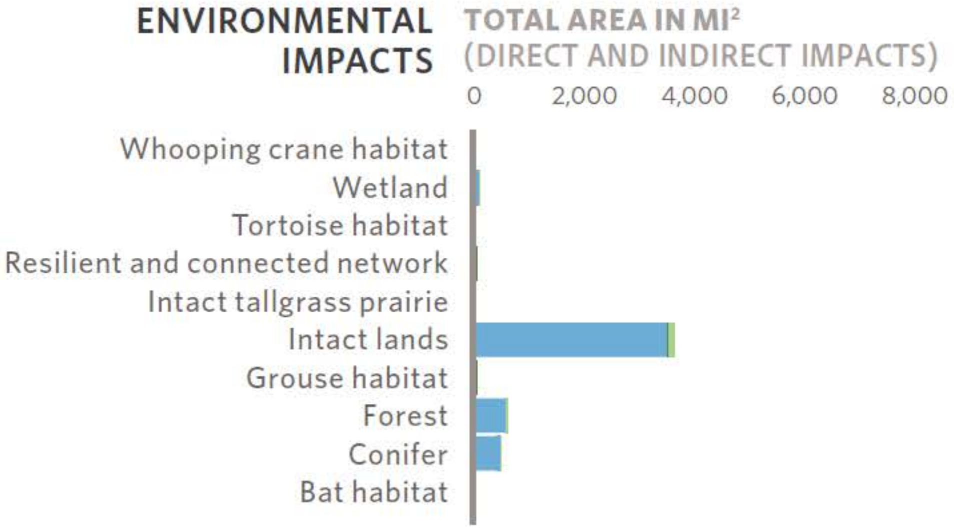
Renewable energy distribution under 70% impact reduction scenario

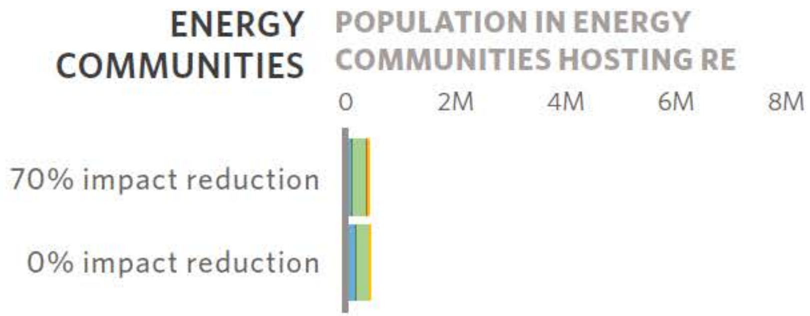
Low impact siting strategies and generation technologies will vary regionally

A

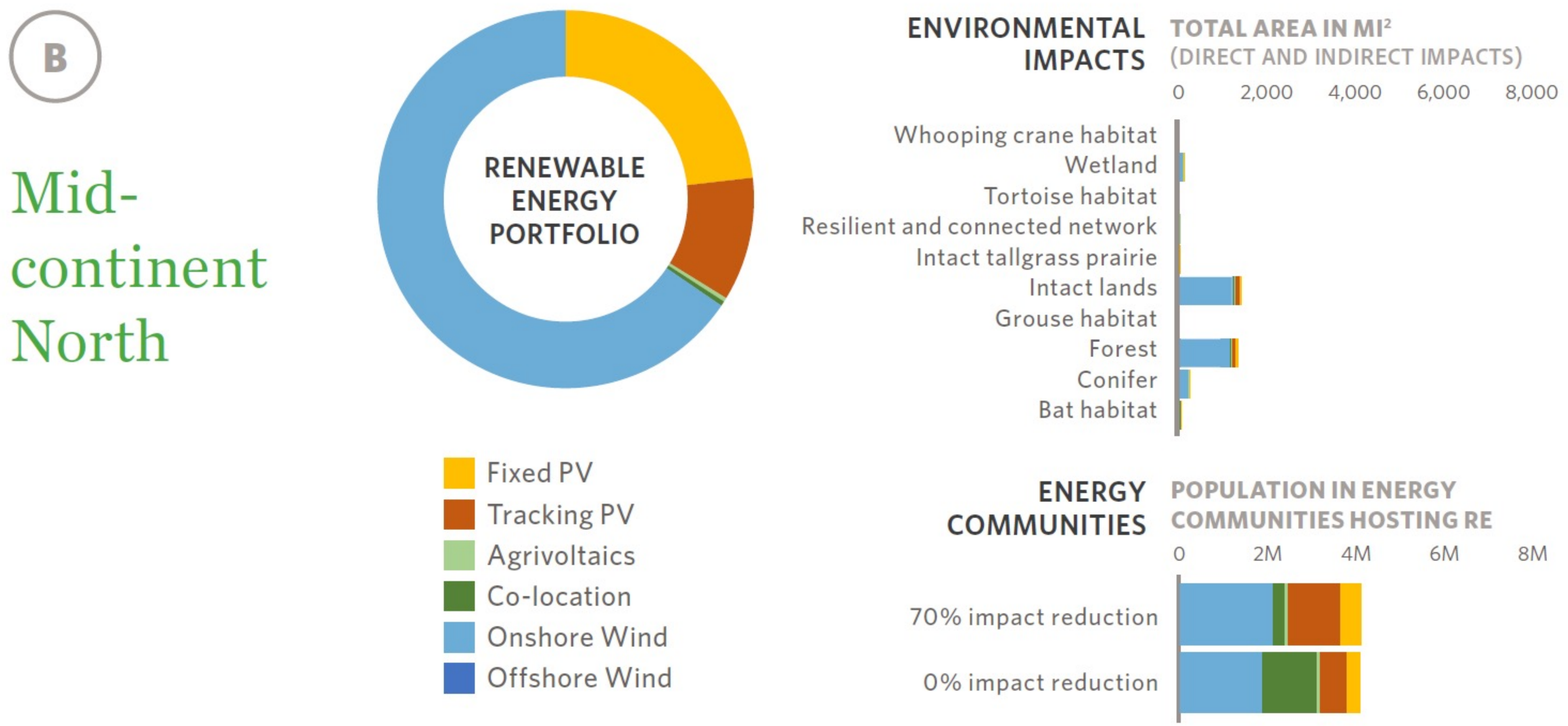
Northwest



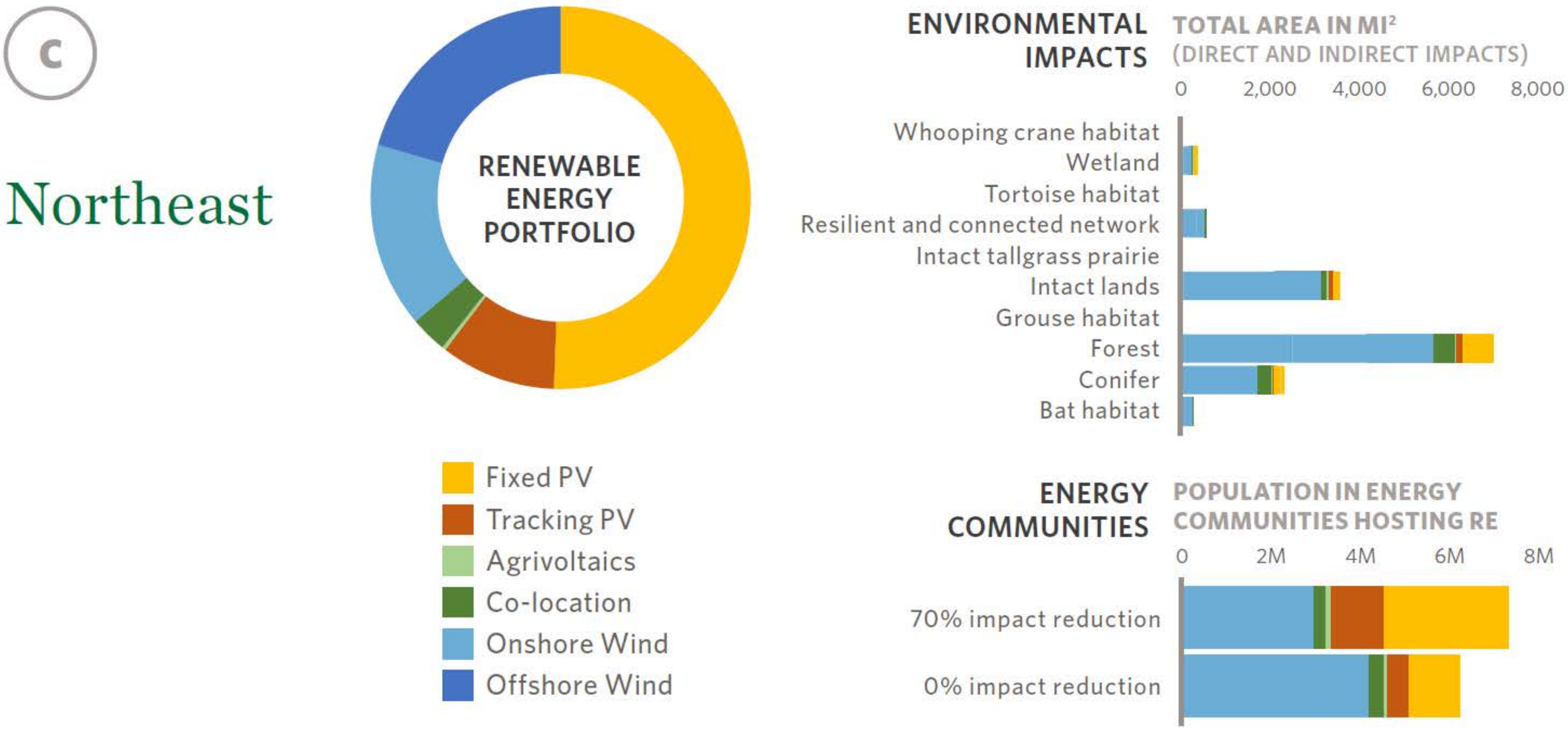




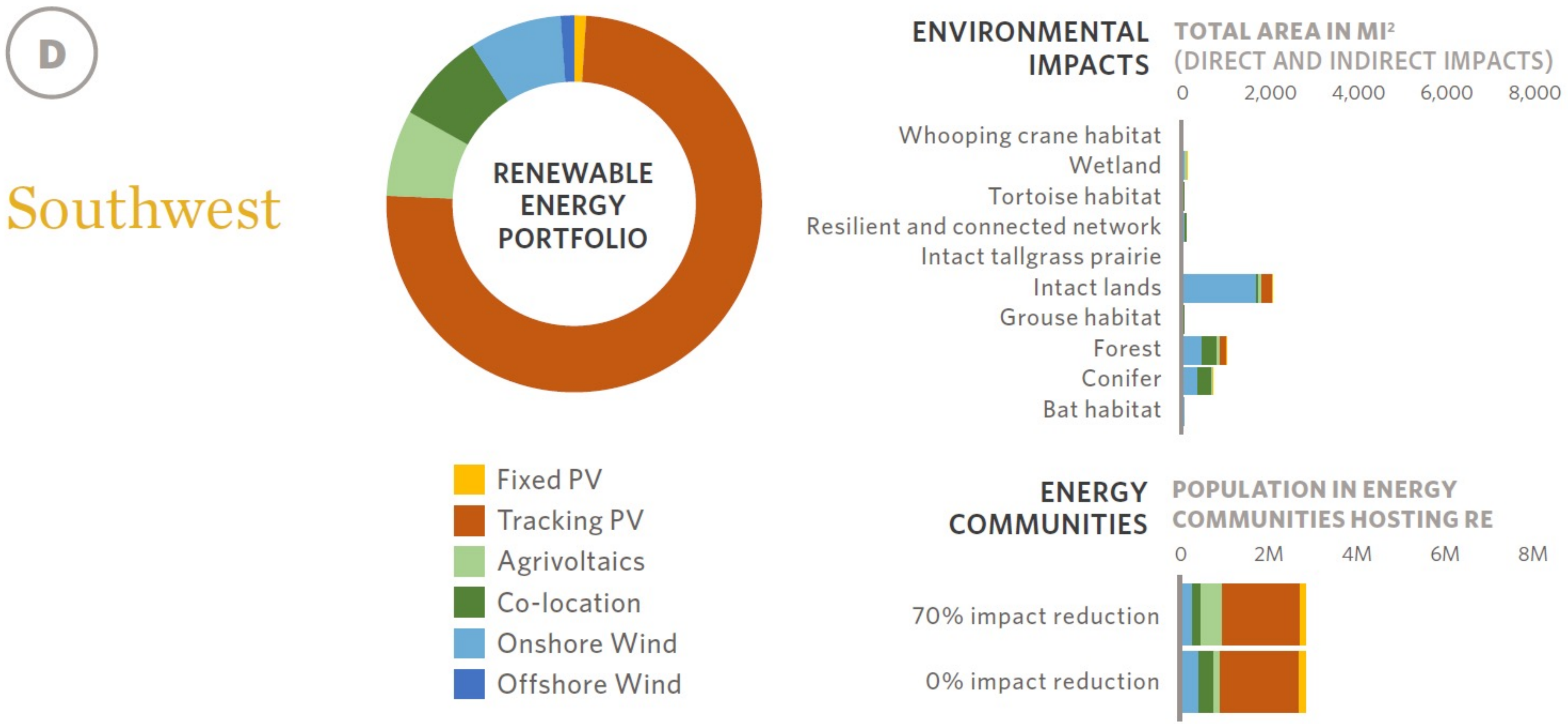
Low impact siting strategies and generation technologies will vary regionally



Low impact siting strategies and generation technologies will vary regionally



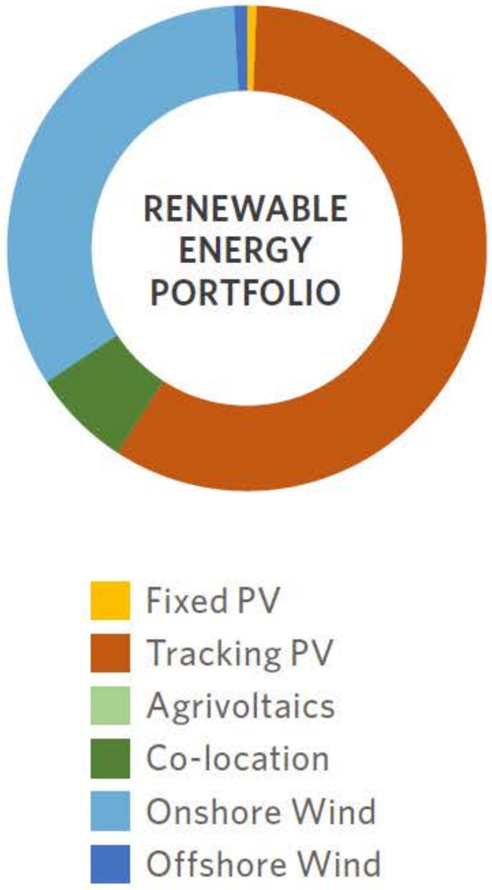
Low impact siting strategies and generation technologies will vary regionally

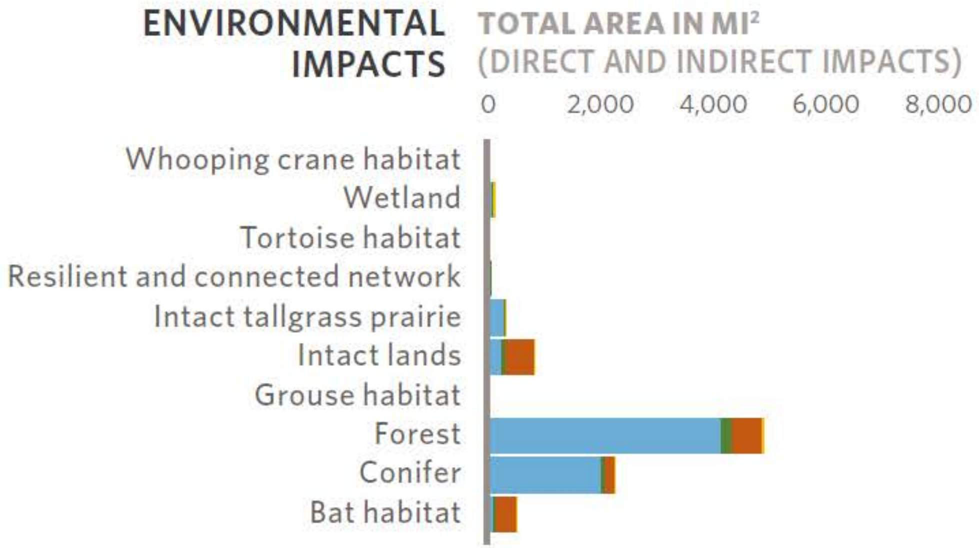


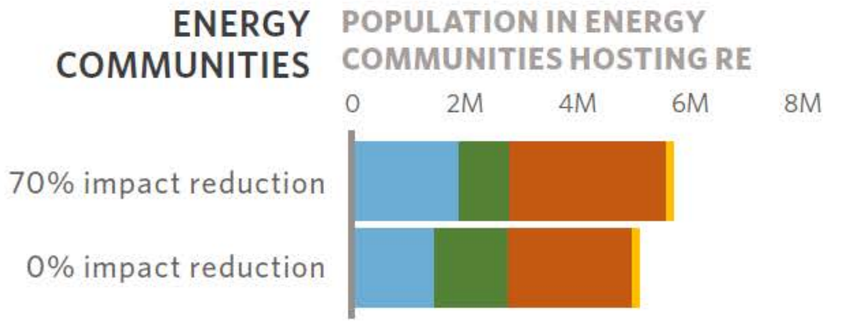
Low impact siting strategies and generation technologies will vary regionally

E

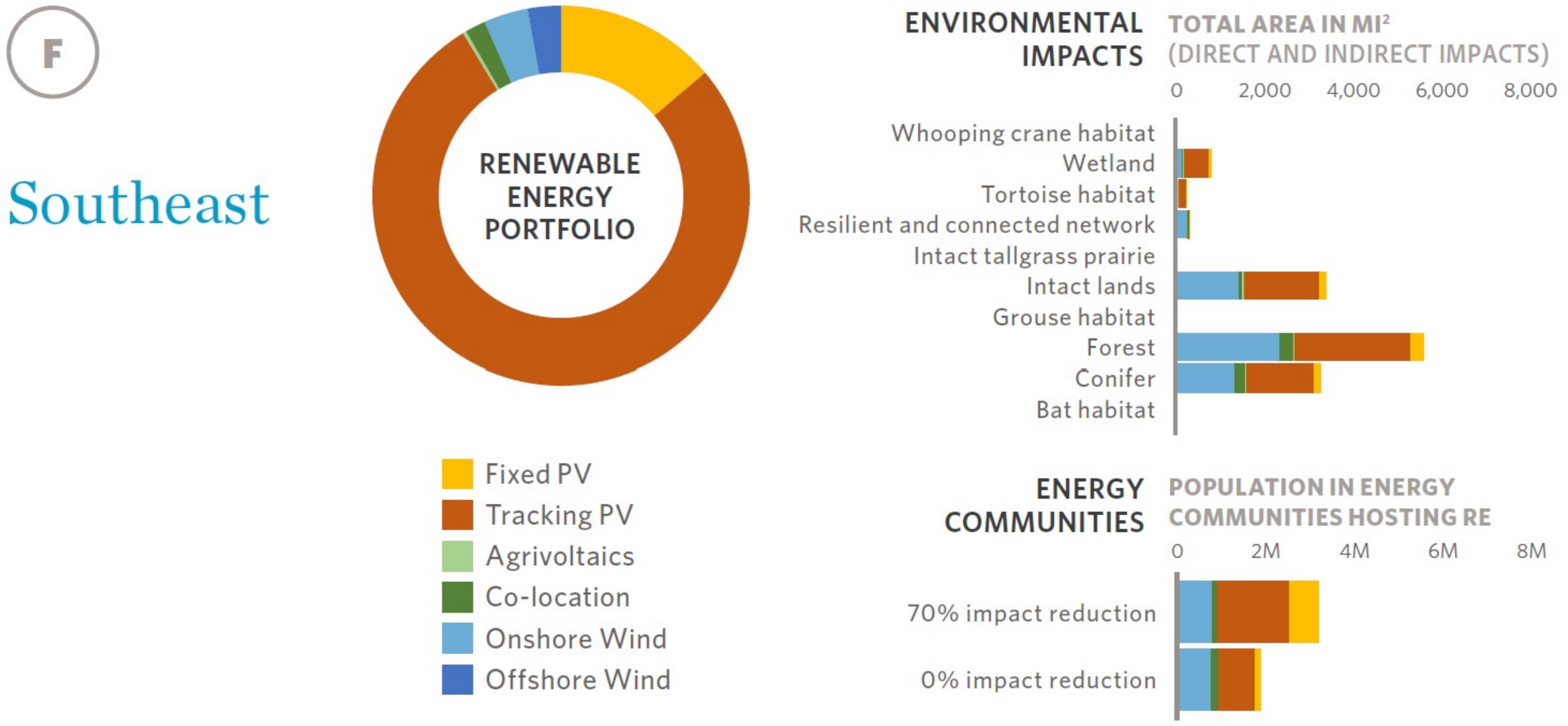
Mid-continent South



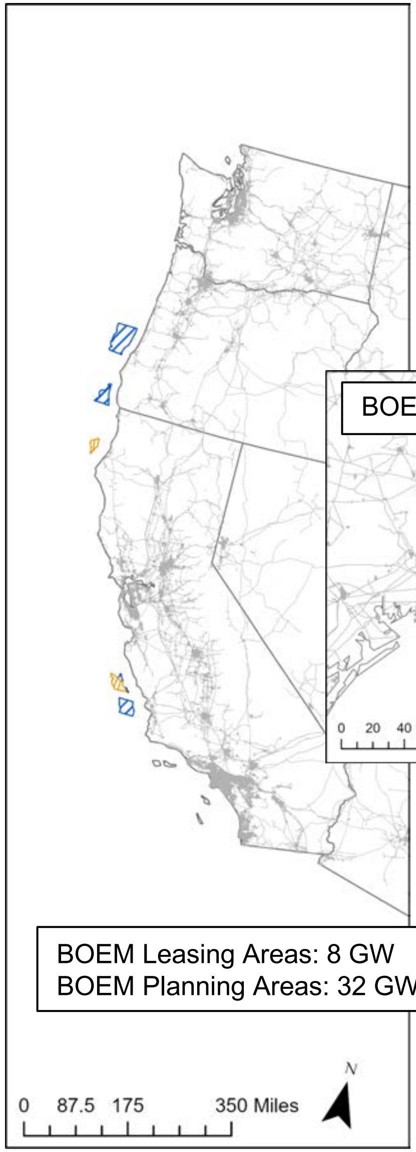


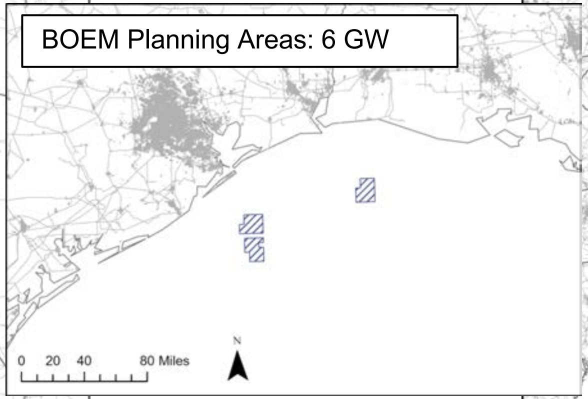


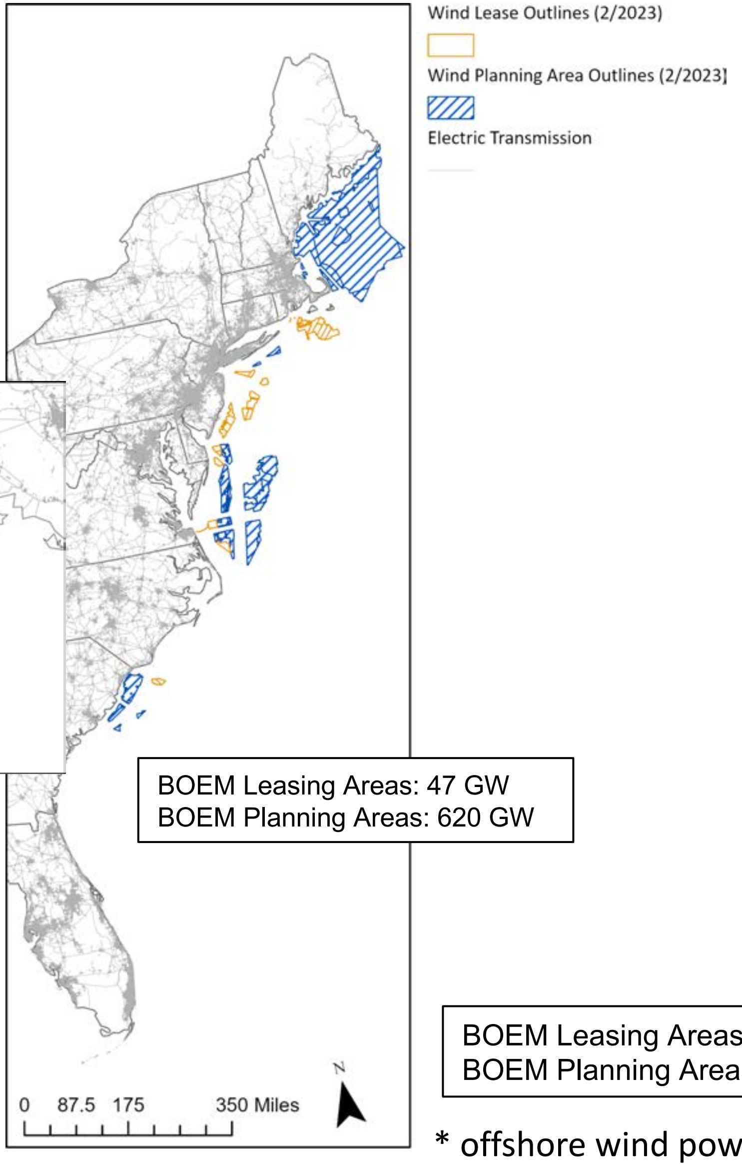
Low impact siting strategies and generation technologies will vary regionally



Federal offshore wind planning and leasing areas are continually updated by BOEM, highly sensitive to transmission and interconnection and network upgrade cost







Zone	Selected offshore wind (GW) capacity in the 70% avoidance scenario
Carolinas	23
Metropolitan New York	11
Mid-Atlantic	16
New England	29
Northern California	27
Northwest	5
Ohio Valley*	5
Southern California	3
Upstate New York*	4
Virginia	10
TOTAL	133

* selected project areas in the Great Lakes (9 GW total)

BOEM Leasing Areas (Total): 56 GW
BOEM Planning Areas (Total): 668 GW

* offshore wind power density assumption: 5 MW/km2

Modeled inter-regional and gen-tie GW-miles are reduced as impacts are reduced

- All scenarios require major expansions (2.5 to 3X current capacity) of inter-regional transmission capacity, but lower-impact scenarios require less infrastructure.

- Inter-regional transmission is reduced by ~30% between the 70% impact reduction scenario and SAU

- Because available transmission capacity can be a driving force in renewable energy development siting decisions, a well-planned transmission system can be an enabling factor in fostering low-impact buildout

REDUCTION IN ENVIRONMENTAL IMPACT	GW-MILES *inter-regional transmission*	GW-MILES *gen-tie transmission*
0%	283,000	27,000
10%	279,000	27,000
20%	272,000	26,000
30%	264,000	26,000
40%	248,000	25,000
50%	233,000	24,000
60%	219,000	23,000
70%	202,000	22,000
80%	191,000	21,000
90%	144,000	22,000

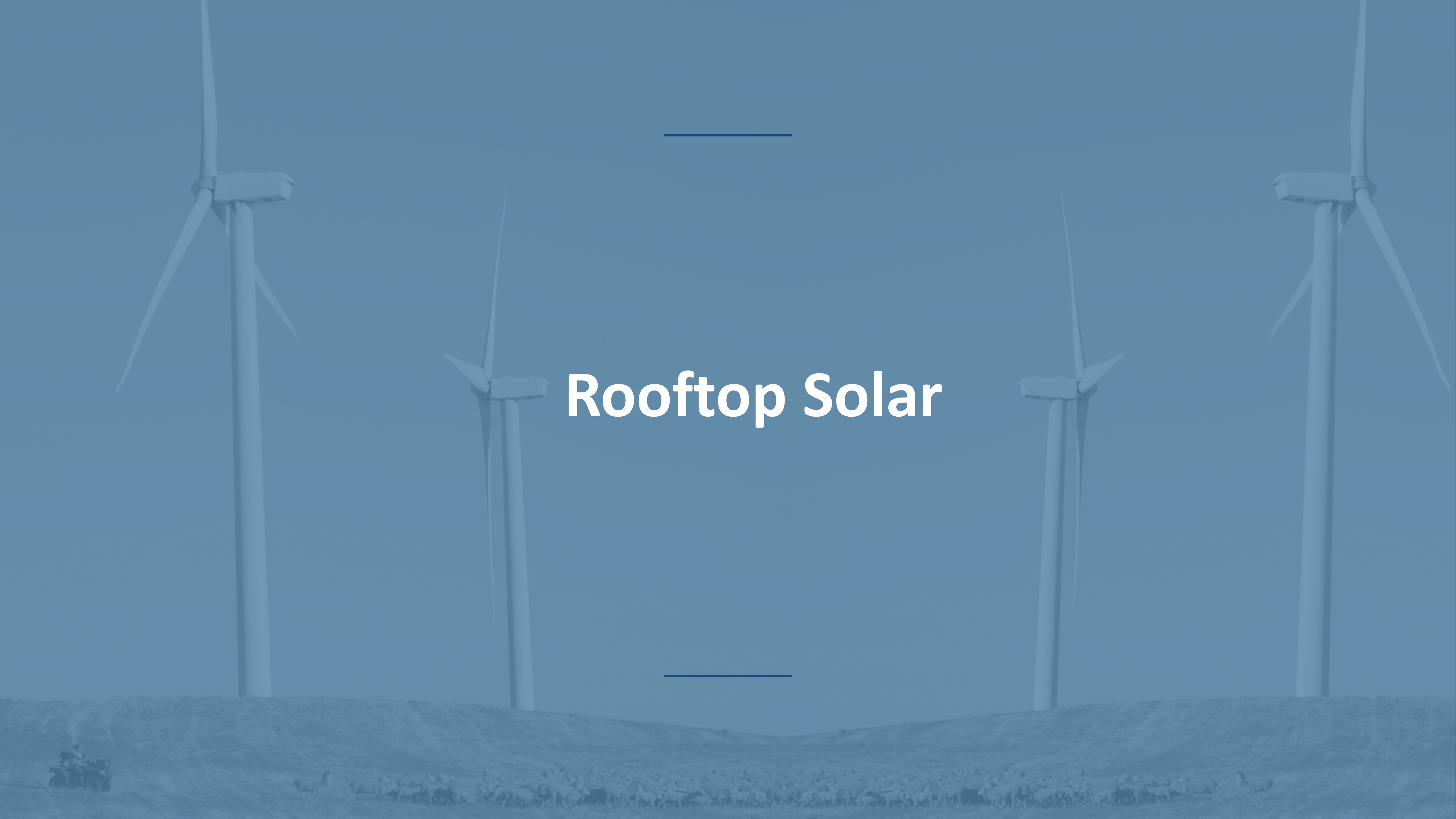
Power of Place

Planning Priorities for a Clean Energy Future.

The Nature Conservancy

Questions?

Appendix



Rooftop Solar

Rooftop solar

For comparison:

Total technical potential (contiguous U.S.): 1.1 TW

Technical potential (California): 130 GW

P. Gagnon, R. Margolis, J. Melius, C. Phillips, and R. Elmore, "Estimating rooftop solar technical potential across the US using a combination of GIS-based methods, lidar data, and statistical modeling," *Environ. Res. Lett.*, vol. 13, no. 2, p. 024027, Feb. 2018, doi: 10.1088/1748-9326/aaa554.

Zone	Sum of GW (Siting As Usual)	Sum of GW (70% reduction)
Alaska	1	1
Carolinas	12	21
Central Great Plains	2	3
Florida	16	20
Great basin	6	10
Hawaii	11	11
Metropolitan Chicago	4	4
Metropolitan New York	6	6
Michigan	5	5
Mid-Atlantic	14	16
Middle Mississippi Valley	7	7
Mississippi delta	4	4
New England	16	19
Northern California	21	22
Northern Great Plains	1	2
Northwest	4	4
Ohio valley	11	11
Rockies	5	5
Southeast	6	8
Southern California	29	33
Southern Great Plains	5	5
Southwest	8	9
Tennessee Valley	4	5
Texas	19	19
Upper Mississippi Valley	7	7
Upstate New York	4	4
Virginia	7	7
Grand Total	237	**267**

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Wu, G.C.; Jones, R.A.; Leslie, E.; Williams, J.H.; Pascale, A.; Brand, E.; Parker, S.S.; Cohen, B.S.; Fargione, J.E.; Souder, J.; Batres, M.; Gleason, M.G.; Schindel, M.H.; Stanley, C.K. Minimizing habitat conflicts in meeting net-zero energy targets in the western United States. Proc. Natl. Acad. Sci. USA 2023, 120, 4, e2204098120. https://doi.org/10.1073/pnas.2204098120.

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Fargione, J.; Kiesecker, J.; Slaats, M.J.; Olimb, S. Wind and wildlife in the Northern Great Plains: Identifying low-impact areas for wind development. PLoS ONE 2012, 7, e41468.
Hise, C.; Obermeyer, B.; Ahlering, M.; Wilkinson, J.; Fargione, J. Site Wind Right: Identifying Low-Impact Wind Development Areas in the Central United States. Land 2022, 11, 462. https://doi.org/10.3390/land11040462.
Kiesecker, J.M.; Evans, J.S.; Fargione, J.; Doherty, K.; Foresman, K.R.; Kunz, T.H.; Naugle, D.; Nibbelink, N.P.; Niemuth, N.D. Win-win for wind and wildlife: A vision to facilitate sustainable development. PLoS ONE 2011, 6, e17566.
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Peterson, J.M; Earl, J.E.; Fuhlendorf, S.D.; Elmore, D.; Haukos, D.A.; Tanner, A.M.; Carleton, S.A. Estimating response distances of lesser prairie-chickens to anthropogenic features during long-distance movements. Ecosphere 2020, 11, e03202.	Telemetry study indicated lesser prairie chickens avoided tall structures (towers, transmission lines) during long distance movements.
Łopucki, R.; Klich, D.; Gielarek, S. Do terrestrial animals avoid areas close to turbines in functioning wind farms in agricultural landscapes? Environ. Monit. Assess. 2017, 189-343.	Tracking study suggests roe deer and European hare avoided wind farm interiors in Poland.
M. Bolinger and G. Bolinger, "Land Requirements for Utility-Scale PV: An Empirical Update on Power and Energy Density," IEEE Journal of Photovoltaics, vol. 12, no. 2, pp. 589–594, Mar. 2022, doi: 10.1109/JPHOTOV.2021.3136805.	Land area requirements for solar PV
B. P. Bryant *et al.*, "Shaping Land Use Change and Ecosystem Restoration in a Water-Stressed Agricultural Landscape to Achieve Multiple Benefits," *Frontiers in Sustainable Food Systems*, vol. 4, p. 138, 2020, doi: 10.3389/fsufs.2020.00138.	Marginal farmland in California
P. Denholm, M. Hand, M. Jackson, and S. Ong,Land-Use Requirements of Modern WindPower Plants in the United States, Aug. 2009. [Online]. Available:https://www.nrel.gov/docs/fy09osti/45834.pdf(visited on 08/03/2020).	Direct vs. Indirect land use assumptions for wind
S. Ong, C. Campbell, P. Denholm, R. Margolis, and G. Heath,Land-Use Requirementsfor Solar Power Plants in the United States, Jun. 2013. [Online]. Available:https://www.nrel.gov/docs/fy13osti/56290.pdf(visited on 08/03/2020).	Direct vs. Indirect land use assumptions for PV
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D. Ludwig *et al.*, "Evaluation of an onsite integrated hybrid PV-Wind power plant," *AIMSE*, vol. 8, no. 5, Art. no. energy-08-05-988, 2020, doi: 10.3934/energy.2020.5.988.	Colocation assumptions
V. Ramasamy, D. Feldman, J. Desai, and R. Margolis, "U.S. Solar Photovoltaic System and Energy Storage Cost Benchmarks: Q1 2021," NREL/TP-7A40-80694, 1829460, MainId:77478, Nov. 2021. doi: 10.2172/1829460.	Fixed vs. Tracking cost assumptions

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Offshore Wind Modeling Assumptions

Offshore wind modeling assumptions
Power of Place West

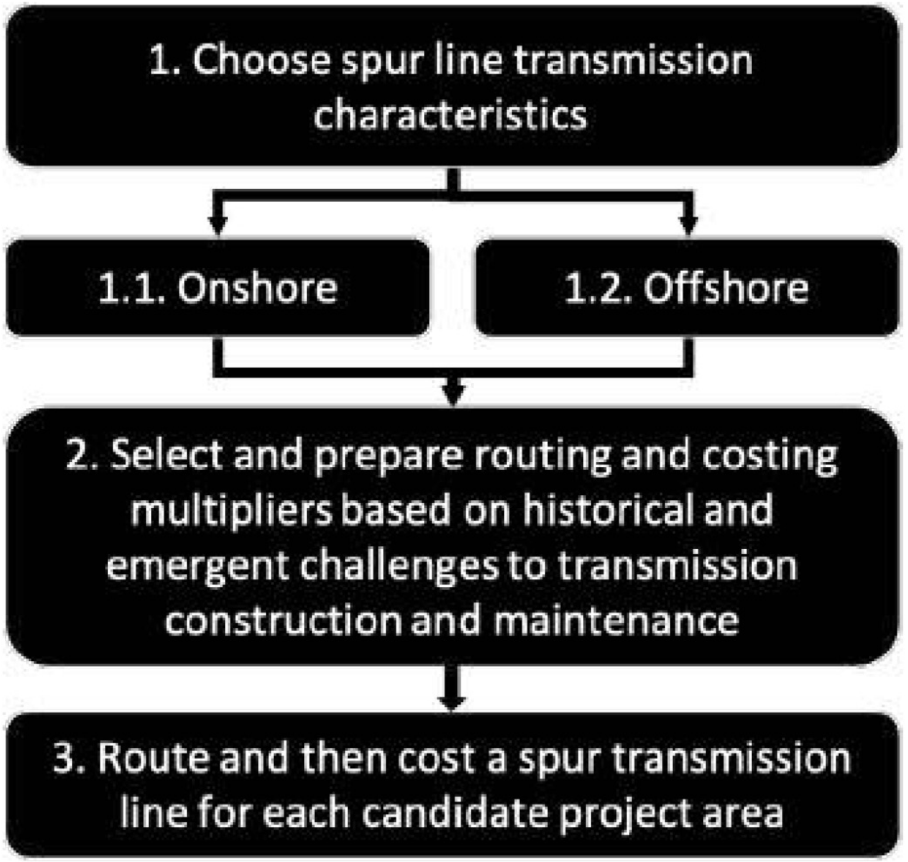
Parameter	Unit	Value
Turbine model	MW	NREL 7 MW offshore reference turbine power curve (from NREL System Advisory Model)
Hub height	m	100
Power density	MW/km2	5 The Maritime Spatial Planning of the European Commission finds that in the Baltic and North Sea regions there is an average power density between 5.5 and 6 MW/Km2. They find that this broadly supports estimations of between 5 - 5.4 MW/Km2.
Meteorological data	na	Marine regions: NREL WIND Toolkit Offshore Summary Dataset Great Lakes: Global Wind Atlas
Energy production estimate method	na	7 year average weilbull parameters
Assumed energy losses	na	Wake effects loss of about 8.75%. Other losses included availability (5.5%), turbine performance (3.95%), and environmental (2.39%).
Sea floor depth assumption	m	For values < 50m, assume fixed foundation. For values > 50m, assume floating foundation
Inner study area boundary	na	Minimum distance from shore: 5-8 km
Outer study area boundary	Nautical miles	50, except where BOEM Designated Wind Planning Areas exceed; in these locations BOEM boundaries supersede (Gulf of Maine and others)
Avoidance areas	na	Techno-economic exclusions from DOE National Transmission Study and areas presently excluded by law (Category 1)
Interconnection cost calculation method	$/kW-mi	Proximity analysis performed, to identify subsea cable routing from turbines to nearest substation with voltage >= 115 kV. Base costs: NREL ATB 2020, Beiter et al (2020) (NREL/TP-5000-77384) and NYD of Public Service Staff, New York State Energy Research and Development Authority Staff, TB Group, P Consulting, Initial Report on the New York Power Grid Study Technical report (New York State Public Service Commission 2021).

Offshore Wind Supporting Information

- Power density: The amount of power that can be generated by hub height 100 m; IEC Class I, per square kilometer under peak conditions
- Maritime Spatial Planning of the European Commission
  - The Maritime Spatial Planning finds that in the Baltic and North Sea regions there is an average power density between 5.5 and 6 MW/Km2. They find that this broadly supports estimations of between 5 - 5.4 MW/Km2.
- BVG and WindEurope
  - The report finds a power density of 5.36 MW/Km2 for all of Europe
- 5 MW/Km2 is a conservative estimate

Transmission Modeling Assumptions

Transmission Least-Cost Path Modeling Framework



Wu et al 2021, https://www.pnas.org/doi/10.1073/pnas.2204098120

Transmission Cost Assumptions

Table S5. B&V Transmission cost calculator configuration and base costs

Configuration	Re-conductor 230 kilovolt (kV)	Re-conductor 345kV	Re-conductor 500kV	Co-locate 500kV	New 500kVd HVAC	New 500kV HVDC
Calculator configuration	230 kV double circuit, ACSR, Lattice, >10 miles, reconductor	345 kV double circuit, ACSR, Lattice, >10 miles, reconductor	500 kV double circuit, ACSR, Lattice, >10 miles, reconductor	500 kV double circuit, ACSR, Lattice, >10 miles, new	500 kV double circuit, ACSR, Lattice, >10 miles, new	500 kV HVDC, ACSR, Lattice, >10 miles, new
Base cost in USD2018/mile	664,127	1,262,297	2,131,048	3,278,535	3,278,535	1,639,820
ROW width in feet	150	200	250	NA	250	200

Transmission Cost Assumptions (Interconnection spur lines)

Table S8. Spur line parameters for line and substation cost estimates

Parameter	Setting
Voltage class	230 kV
Number of circuits	single
Conductor type	ACSR
Tower structure	lattice (adjusted later to pole using GIS population density layer (33))
Line length	> 10 miles (expedient simplification)
Build type	new
Right-of-way (ROW) width	125 feet
Include land costs for ROW	yes
AFUDC/Overhead costs	17.5% (implemented as a GIS multiplier layer)
Substation handling	one substation for all lines, plus one additional substation for every 161 km after first 161 km
Circuit breaker type	breaker and a half
Number of Line/XFMR positions	2
HVDC Converter	no
Transformer type	115/230 kV
MVA rating per transformer	200
Number of transformers	1
SVC MVAR rating	1
Shunt reactor MVAR rating	1
Series capacitor MVAR rating	1

Agrivoltaic Assumptions

Agrivoltaic sources

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- Dinesh H, Pearce JM. The potential of agrivoltaic systems. Renewable and Sustainable Energy Reviews. 2016 Feb 1;54:299–308. [**lettuce**]
- Weselek A, Ehmann A, Zikeli S, Lewandowski I, Schindele S, Högy P. Agrophotovoltaic systems: applications, challenges, and opportunities. A review. Agron Sustain Dev. 2019 Jun 19;39(4):35. [**winter wheat, maize, tomato, watermelon, rice, clover grass, celeraic, potato**]
- Cho J, Park SM, Park AR, Lee OC, Nam G, Ra IH. Application of Photovoltaic Systems for Agriculture: A Study on the Relationship between Power Generation and Farming for the Improvement of Photovoltaic Applications in Agriculture. Energies. 2020 Sep 15;13(18):4815. [**grapes**]
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- Liu W, Liu L, Guan C, Zhang F, Li M, Lv H, et al. A novel agricultural photovoltaic system based on solar spectrum separation. Solar Energy. 2018 Mar;162:84–94. [lettuce, cucumber, spinach]
- Valle B, Simonneau T, Sourd F, Pechier P, Hamard P, Frisson T, et al. Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops. Applied Energy. 2017 Nov;206:1495–507. [**lettuce**]
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References (Social and Environmental datasets)

Generalized Area Types

Area Type	Description	Source	URL
Administratively protected areas (Environmental Category 2)	Administratively protected under current policy	Wu et al 2023, WECC Environmental Data Task Force, BLM West-Wide Wind Mapping Project	https://www.pnas.org/doi/10.1073/pnas.2204098120
High conservation value areas (Environmental Category 3)	Land with high conservation value that may not be currently protected	Wu et al 2023, Wu et al 2023, WECC Environmental Data Task Force, BLM West-Wide Wind Mapping Project	https://www.pnas.org/doi/10.1073/pnas.2204098120
Wetlands	National Wetlands Inventory (NWI)	USFWS National Wetlands Inventory	https://www.fws.gov/program/national-wetlands-inventory
Forests	Areas where the existing vegetation type life form is classified as tree	Landfire 2020	https://landfire.gov/evt.php
Conifer forest	Areas where the existing vegetation type physiognomy is conifer or conifer-hardwood	Landfire 2020	https://landfire.gov/evt.php
Shrublands	Areas where the existing vegetation type life form is classified as shrub	Landfire 2020	https://landfire.gov/evt.php
Grasslands	Areas where the existing vegetation type life form is classified as herbaceous	Landfire 2020	https://landfire.gov/evt.php
Resilient and connected network	A subset of The Nature Conservancy's Resilient Connected Network, including only Prioritized Network areas with Resilient, Concentrated Flow (Climate Informed), Recognized Biodiversity	The Nature Conservancy Resilient, Connected, Network	https://www.conservationgateway.org/ConservationPractices/ClimateChange/Pages/RCN-Downloads.aspx
Intact lands	Areas largely undisturbed by human modification. HMI < 0.082, except where modified per Hise et al 2022 (central U.S.)	Theobald Human Modification Index, others	https://datadryad.org/stash/dataset/doi:10.5061/dryad.n5tb2rbs1, https://www.mdpi.com/2073-445X/11/4/462
Intact tallgrass prairie	Landscapes in the eastern Great Plains with largely intact natural vegetation	Ostlie, W. Untilled Landscapes of the Great Plains; The Nature Conservancy: Minneapolis, MN, USA, 2003.	

Focal Species

Area Type	Description	Source	URL
Grouse habitat (e.g., sage grouse and prairie chicken)	Habitat with conservation importance for grouse and prairie chicken species	Hise et al 2022, Wu et al 2023	https://www.mdpi.com/2073-445X/11/4/462, https://www.pnas.org/doi/10.1073/pnas.2204098120
Sensitive desert species habitat (e.g., desert and gopher tortoises)	Habitat with conservation importance for imperiled tortoise species	Wu et al 2023, USGS Southeast gopher tortoise habitat mode	https://www.pnas.org/doi/10.1073/pnas.2204098120, https://www.sciencebase.gov/catalog/item/5d0d4ba0e4b0941bde52a306
Sensitive whooping crane habitat	Key whooping crane stopover sites	Hise et al 2022	https://www.mdpi.com/2073-445X/11/4/462
Bat habitat	Key bat roosting areas in the central U.S. per Hise et al 2022, USFWS critical habitat for threatened and endangered species	Hise et al 2022	https://www.fws.gov/endangered/what-we-do/critical-habitats.html

Social Datasets

Area Type	Description	Source	URL
Energy Communities	Brownfields [not mapped], areas with significant fossil fuel employment, and areas with retired coal power plants	2022 Inflation Reduction Act	https://www.congress.gov/117/bills/hr5376/BILLS-117hr5376enr.pdf
Low-Income Communities	Areas with high poverty rates according to the U.S. Census	2022 Inflation Reduction Act	https://www.congress.gov/117/bills/hr5376/BILLS-117hr5376enr.pdf
Croplands (general)	Vegetation of agricultural lands, including row crops, intensive pastures, orchards, vineyards, plowed or harvested fallow fields, rice paddies, and farm ponds	Landfire 2020	https://landfire.gov/evt.php
Productive farmland	Productive Versatile Resilient farmland (value = 0.53 on a scale of 0-1)	American Farmland Trust "Farms Under Threat" Report	https://farmlandinfo.org/publications/farms-under-threat-the-state-of-the-states/ https://farmlandinfo.org/wp-content/uploads/sites/2/2020/05/AFT_FUT_PVR_Fact_Sheet.pdf
Marginal farmland	Challenging soil' based on USDA Gridded Soil Survey Geographic Database	USDA Gridded Soil Survey Geographic Database	https://www.nrcs.usda.gov/resources/data-and-reports/gridded-soil-survey-geographic-gssurgo-database