Princeton's Net-Zero America Study
Annex D: Solar and Wind Generation Transitions

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1 Introduction

A national 2050 net-zero greenhouse gas emissions target will require substantial deployment of new utility-scale wind and solar photovoltaic (PV) electric power generation resources. One component of the *Net-Zero America* (NZA) study was to identify a plausible map of this deployment by applying the Optimal Renewable Buildout (ORB) framework [1] and Multi-Criteria Analysis for Planning Renewable Energy (MAPRE) [2] geoprocessing tools to convert a potential resource portfolio produced at a low-resolution, 14-region scale by a macro-energy systems optimization model (the RIO model; see Annex A) into a higher-resolution set of selected sites, presented in a geographically-explicit format for visual inspection. The resulting maps depict a set of hypothetical utility-scale wind and solar deployment patterns from 2020 to 2050 under a least-cost siting approach subject to a range of land use constraint assumptions. Specifically, the site selection algorithm chooses individual areas for wind and solar project deployment from amongst a set of 'candidate project areas' that pass a land use screening process. Sites are selected until the regional wind and solar energy supply levels specified by the macro-energy systems optimization model are satisfied while minimizing the levelized cost of energy. This approach incorporates resource quality (location-specific wind speed and solar irradiance), capital cost, transmission cost, and risk of siting conflict (using a range of assumed land use exclusions as a proxy).

This study expands upon methods set forth in prior studies [1] [3] [4] [5] [6], in the following ways: 1) it brings together existing publicly available datasets in a new configuration, with refinements; 2) it expands the geographic extent of these prior studies from the western United States to include all of the lower 48 states; 3) it tests and refines existing methods at this greater geographic extent; 4) it extends renewable resource siting consideration beyond utility-scale solar photovoltaic and onshore wind to include potential offshore wind resources; 5) it begins to characterize the range of possible land-use outcomes at a national scale with two "bookend" scenarios: base land use assumptions, vs. constrained land use assumptions.

Base land use assumptions (BLUA) include a set of techno-economic and environmental land use exclusions represented by sixty GIS data layers. Constrained land use assumptions (CLUA) apply additional land use exclusions to restrict the siting of renewable resources away from intact landscapes and prime farmland and towards landscapes which have already experienced more significant human modification. By minimizing siting of new utility-scale wind and solar generation in intact landscapes, the CLUA cases identify a path to achieve a net-zero 2050 greenhouse gas emissions target that minimizes the loss of intact landscapes and creates opportunities to preserve areas suited for environmental protection, restoration, and adaptation in the context of climate change. A summary of assumptions used in the BLUA and CLUA cases is provided in Table 1. A comprehensive list of site suitability input assumptions is provided in Appendix A Table 7.

We perform this high-resolution siting analysis or "downscaling" for the regional results generated by Evolved Energy Research (EER) for three of the five core scenarios in the Net-Zero America study: E+, a scenario with minimal supply side constraints and a high degree of end-use electrification, E+ RE-, a scenario with the same high end-use electrification that constrains the rate of wind and solar capacity additions, and E+ RE+, a scenario with the same high end-use electrification and a restriction to 100% renewable energy supplies (with no nuclear, no fossil fuel use, and no geologic sequestration of CO_2 by 2050). Additionally, we perform downscaling for the no-new-policies reference scenario, REF, to provide a comparison for each of the net-zero emissions pathways. The siting process described herein is performed for both E+ and RE+ scenarios under the BLUA and CLUA cases, and for RE- and REF under BLUA, resulting in six different series of

Table 1: Site suitability overview

Input Assumption	Solar	Onshore Wind	Offshore Wind
Spatial Resolution of raw resource data (km) [7] [8] [9]	10	2	3
Average Power Density (MW/km2)	45	2.7	5 (fixed) 8 (floating)
Slope	10 deg	19 deg	na
Intactness (Theobald Human Modification Index)	HMI $\leq$ 0.082 for CLUA only		na
Population Density	$\geq$ 100 people/km^2 excluded	$\geq$ 100 people/km^2 excluded	na
Urban Areas buffer (km)	0.5	1	Exclude $\pm$ 20deg N and S of major ports
Water Bodies buffer (km)	0.25	0.25	na
Military Installations buffer (km)	1	1	1
Active Mines buffer (km)	1	1	na
Airports and Runways buffer (km)	1	3	na
Railways buffer (km)	0.25	0.25	na
Prime soils	Not allowed	Allowed (BLUA); Not allowed (CLUA)	na
FEMA 1% annual flood hazard areas	Not allowed	Not allowed	na
Areas of critical environmental concern	Not allowed	Not allowed	Exclude GAP Status 1
National parks and recreation areas	Not allowed	Not allowed	Exclude national sanctuaries
Wild and scenic rivers	Not allowed	Not allowed	na
National Wildlife refuges and wetlands	Not allowed	Not allowed	na
State parks, forests, and wilderness	Not allowed	Not allowed	na
BLM high and moderate sensitivity areas	Not allowed	Not allowed	na
NOAA shipping lanes	na	na	Exclude
Submarine cables	na	na	Exclude areas $\leq 250m$
Military Marine Danger Zones	na	na	Exclude areas $\leq 5000m$
BOEM offshore wind leasing and planning areas	na	na	CLUA limited to these areas only

maps and data covering the evolution of wind and solar deployment from 2020 to 2050 in five-year intervals (see Appendix B for a complete set of maps and results).

Both the BLUA and CLUA cases under the E+ scenario demonstrate that adequate land area exists to deploy sufficient new utility-scale renewable energy resources to meet a national net-zero 2050 greenhouse gas emissions target, while minimizing development on intact landscapes. The results are consistent with a strategy that mitigates a number of key drivers of biodiversity loss, including changes in land and sea use, climate change, and pollution, per the IPBES Global Assessment Report on Biodiversity and Ecosystem Services [10]. While we find sufficient land areas exist, the cumulative impacts of wind and solar siting, development considerations not captured in the screening methods used herein, and other challenges may impede the scale of wind and solar capacity deployment in this scenario in practice. However, as the E+ scenario uses only a portion of all lands that pass BLUA and CLUA site suitability screens, there may be sufficient flexibility to reconfigure siting in ways that can address and minimize these challenges and/or achieve other important socio-economic goals beyond the least-cost objective employed in this siting algorithm. Future work to explore these challenges and opportunities would be valuable.

We also find that both the BLUA and CLUA cases under the RE+ scenario encounter deployment shortfalls in some regions while land remained available elsewhere, indicating the need for a different spatial distribution of resources from the distribution designated by the NREL supply curve accessed by the EER model. The greater level of wind and solar capacity in the RE+ case also utilizes a larger fraction of the total available lands in BLUA and CLUA cases, including more than 100% of available onshore wind sites in the CLUA case, indicating substantially reduced flexibility in alternative siting configurations relative to E+.

The RE- case utilizes a much smaller portion of available areas for wind and solar siting. However, this scenario entails the greatest use of carbon capture, transport, and storage of any scenario and the largest deployment of new nuclear power, each of which entail their own siting challenges and constraints (see Annexes E and I).

2 Methods

Utility-scale solar photovoltaic (PV), onshore wind, and offshore wind Candidate Project Areas (CPAs) are identified in a 4km x 4km grid, through a site suitability analysis conducted using the Multi-Criteria Analysis for Planning Renewable Energy (MAPRE) [2] tool. Post-processing steps then generate additional CPA characteristics such as simplified transmission and generation costs, merge MAPRE generated CPAs with existing and planned projects identified by the United States Energy Information Administration (EIA) [11] and eliminate CPAs that exceed the slope and population density thresholds listed in Table 1. The "Optimal Renewable Buildout" (ORB) framework [1] is then employed to select CPAs in each region in order of increasing simplified Levelized Cost of Energy (LCOE), to meet the scenario-specific cumulative five-year portfolio generation targets set by the Regional Investment and Operations (RIO) model developed by Evolved Energy Research (see Annex A). Ordered selection of CPAs results in a portfolio of selected sites for each scenario, land use case, and time period. Figure 1 presents a high level methodological overview of the workflow. For a more detailed methodological flow diagram see Appendix A Table 21.

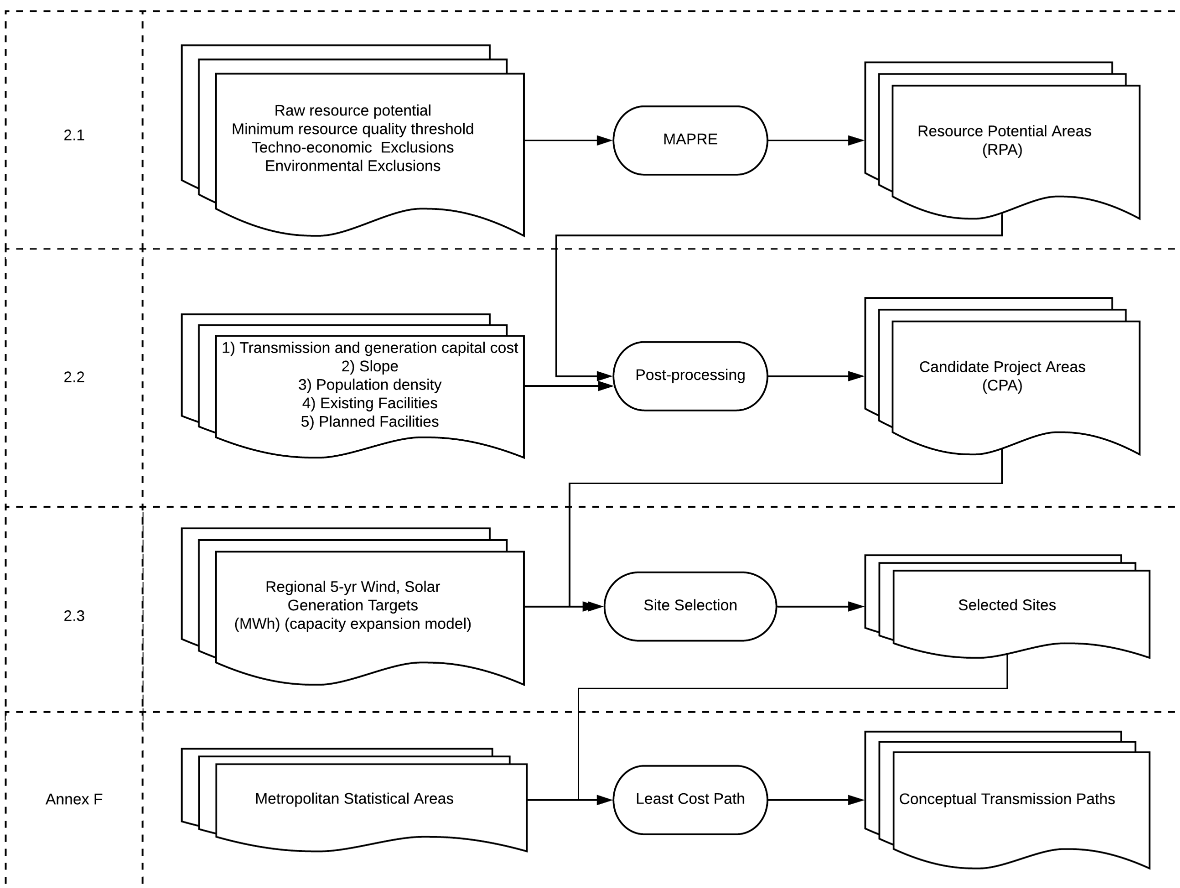


Figure 1: Overview of methods

A detailed description of the first three steps of the process shown in Figure 1 are described in this methods section. The determination of final transmission costs and routes is detailed in Annex F.

2.1 Candidate Project Area Identification

To identify initial CPAs, resource potential and site suitability datasets were gathered and pre-processed as inputs to the MAPRE tool [2] [12].[1] MAPRE tools have been used to identify renewable resource CPAs for IRENA East Africa SEAREZ and The Nature Conservancy Power of Place projects [13] [14]. Input data sets used in the characterization of raw resource potential are summarized in Table 6. For a detailed listing of the data sets included in site suitability analyses, see Table 7.

BLUA site suitability screens were selected based on the applicable renewable resource type (PV, onshore wind, offshore wind). The CLUA site suitability screens added further development constraints by excluding areas with intact landscapes, as measured by the human modification index (HMI) [15],[2] and by limiting offshore wind resources only to areas already approved for offshore wind development by federal and state authorities. For a summary of resource type and land use assumption combinations see Table 7.

CPA data sets are produced as the output of the site suitability analysis run using MAPRE script tool B based on the applicable site suitability screens. CPAs arising from CLUA site suitability assessments are a subset of the BLUA assessment.

For each CPA, nameplate capacity of the applicable renewable resource is estimated based on the CPA shape area and a standard assumed power density set forth in Table 2.

For solar power, we empirically estimate the national mean power density from the USGS National Solar Array dataset [16], based on the subset remaining after the following facilities are removed: 1) plants that do not have an AC nameplate rating; or that have an AC nameplate rating, but an DC:AC ratio of less than 1.1;[3] 2) power density $\leq$ 10 or $\geq$ 100 MW/ km^2 (ac);[4] and 3) where power densities based on nameplate capacities reported in the USGS dataset [16] and EIA Form 860 [11] differ by $>$ 5 MW/km^2[5]. See methodological notes in Figures 22, 23, and 24.

For wind power, we calculate national weighted average power density from the USGS US Wind Turbine Data Base [17]. Existing facilities with the following characteristics are included in the sample: 1) commercial operation date in 2017 or later; 2) nameplate capacity $\geq$20 MW (ac); 3) power density $>$ 1 MW/km^2 (to remove outliers).

[1]It should be noted that our analysis customizes the estimation of LCOE in a post-processing step rather than use the base LCOE calculator in the MAPRE Script B tool.

[2]In Theobald's HMI analysis [15], North America is analyzed at 1000m spatial resolution, and each 1000m cell is assigned an HMI value ranging from 0.0 to 1.0, where 0.0 is no human modification and 1.0 is full or complete human modification. Types of human modification include urban and built-up land, agriculture and biological harvesting of forests, energy production and mining, transportation and service corridors, human intrusions, natural system modifications, and pollution. CLUA scenarios exclude highly intact landscapes with HMI values $\leq$ 0.082.

[3]Because the timeframe of this analysis is 2020-2050, and because industry trends indicate increasing inverter loading ratios over time, the lower DC:AC ratios of the historic dataset were deemed irrelevant. Higher DC:AC ratios are anticipated going forward.

[4]These cutoffs are arbitrary and result in the removal of the bottom 1 percent and top 7 percent of projects in the USGS database.

[5]We chose to compare power density rather than reported total capacities as it allowed a little more flexibility in capacity discrepancies in larger systems - of which there are fewer in the data set, while not allowing relatively large reported discrepancies between small systems. This $>$ 5 MW/km^2 cutoff is arbitrary. Some discrepancy between the USGS and EIA estimated power densities of larger systems is allowed as the nameplate AC rating relies completely on the de-rating factor used by the company/person reporting the system. Allowed ac/dc de-rating factor range from between 1.1 to 2.4.

Table 2: Wind and solar power densities

Technology	Power Density (MW/km^2)
Solar	45.0
Onshore wind	2.7
Offshore wind	5.0 (fixed); 8.0 (floating)

The mean power densities calculated for this study were compared to the values reported in prior studies [18]. Prior studies have estimated solar power densities ranging from 6.6 MW/km^2 [19], to 27.8 MW/km^2 [20], and 48 MW/km^2 [21]. Our estimate is on the high end of the range, but considered reasonable due to recent industry trends such as increasing nameplate power rating for photovoltaic panels [22]. Previous studies have estimated wind power density to be 3.0 ± 1.7 MW/km^2 [23]. Our wind power density is comparable, if on the low end. This is consistent with the industry trend of declining specific power in American wind facilities [24], as manufacturers seek to maximize annual energy production on low wind-speed sites, thereby increasing rotor diameter and decreasing nameplate specific power. For offshore wind, fixed turbine power density is assumed to be 5.0 MW/km2 and floating turbine power density is 8.0 MW/km, as prior studies indicate a range of 3.1 to 18.7 (see Borrmann et al 2018 [18], [25], [26]).

Nameplate capacity is translated to annual generation using raw resource potential data sources summarized in Table 6. The following technical assumptions underlie the raw resource capacity factor estimates:

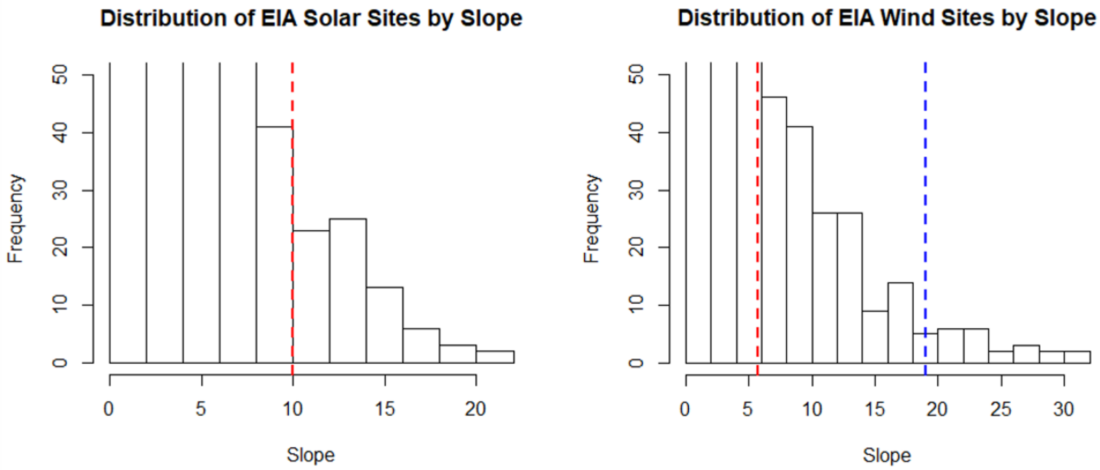
- Solar photovoltaic: Ground Mount Single-Axis Tracking Configuration, DC/AC Ratio = 1.35, Average Annual Soiling Losses = 3%, Module Mismatch Losses = 2%, Diode and Connection, Losses = 0.5%, DC Wiring Losses = 2%, AC Wiring Losses = 1%, Availability Losses = 1%

- Onshore wind: Hub height = 100m. ERGIS power curves. Wake losses range from 0-5% depending on number of adjacent turbines. Cut-in wind speed = 5 m/s. Cut-out wind speed = 20-25 m/s depending on turbine class.

- Offshore wind: Hub height = 140m. Turbine type varies, based on bathymetry. For locations with seafloor depths $<$ 50m, fixed foundations are assumed. For locations with seafloor depths $>=$ 50m, floating turbine foundations are assumed.

2.2 Post-processing

CPAs with slopes and population densities exceeding cut-offs shown in Table 1 are removed as a first step in post-processing. CPAs are then adjusted again to allow for more realistic development patterns, which account for the relative difficulty of acquiring parcels and siting projects in higher population density areas. Attributes such as capital cost, transmission cost, and population density are then calculated for remaining CPAs using map algebra based on the input datasets summarized in Table 6 and Table 8. Cost attributes are then used to estimate LCOE for each CPA. As a final step in CPA post-processing before site selection, CPA locations are compared with the locations reported in the EIA data [11][27], and an attribute is added to CPAs to enable the tracking and inclusion of existing and planned projects during site selection.



(a) Solar (b) Wind

Figure 2: Distribution of existing and planned solar facilities by slope

2.2.1 Select and apply slope cut-offs for solar PV and wind

In initial iterations, the NZA team selected general slope cut-offs of 10° for solar PV and 5.7° for wind based on communications with experts. Slope thresholds were then calibrated in later iterations by comparing initial cut-offs with the distribution of existing and planned facilities in the EIA datasets [11][27] as shown in 2. After finding that a solar slope cut-off of 10° only removed 1.3% of all existing and planned solar PV facilities, it was decided to keep that threshold and adjust the wind cut-off from 5.7° to 19°, a threshold which excludes a similar % of all existing and planned onshore wind facilities.

All solar PV CPAs with a slope of greater than 10°, and all wind CPAs with a slope of greater than 19° were excluded from the remainder of the analysis.

2.2.2 Adjustment of CPAs to account for the relative difficulty of acquiring parcels and siting projects in offshore and higher population density areas

For population density, we adjusted the land utilization rates (or the percent of CPAs that passed land use screens that were assumed to be available for development) to be inversely proportional to population density. These adjustments resulted in more realistic development patterns, accounting for the relative difficulty of acquiring parcels and siting projects in higher population density areas. However, the functional form selected here is somewhat arbitrary, and future research would be productive to determine a more empirically grounded set of parameters. See Table 3 for summary of population density assumptions, after calibration adjustments.

Similarly, for offshore wind, we sought to simulate practical realities by including designated offshore wind leasing areas and wind planning areas identified by the U.S. Bureau of Ocean Energy Management (BOEM) without modification. For BLUA scenarios, we included additional offshore wind CPAs outside of designated leasing and planning areas, but removed 40% of these CPAs (in a randomly scattered distribution), in order to indicate uncertainty and incompleteness of publicly available marine spatial planning information in many offshore U.S. regions. For CLUA scenarios, we did not include any CPAs outside of designated offshore wind leasing and planning areas.

Table 3: Population density thresholds

	Population Density Bins (person/km^2)	Percent Removal per Bin
Solar	0-4	0%
	4-12	25%
	12-25	88%
	25+	94%
Wind	0-4	0%
	4-12	87.5%
	12-25	94%
	25+	97%

2.2.3 Estimation of LCOE

CPAs are sorted in order of increasing LCOE, summarized below (per Masters, 2004 [28]).

$$LCOE = annualPayments/annualGeneration$$

Where:

$AnnualPayments = ProjectCapitalCost \times CRF(0.04, 20)$

CRF, or annual capital recovery factor, is a function of interest rate (assumed here to be 4%) and loan term (assumed here to be 20 years, resulting in CRF = 0.0736)

$LCOE = (ProjectCapitalCost \times CRF)/AnnualGeneration$

Attributes for each CPA are calculated as follows:

$CPANameplateCapacity$ (MW ac) = $ShapeArea$ (km^2) $\times PowerDensity$ (MW ac/km^2, varies by technology)

$CPAAnnualGeneration$ (MWh) = $NameplateCapacity \times 8760$ (hrs/yr) $\times CapacityFactor$ (%)

$CPACapitalCost = GenerationCapitalCost + TransmissionCapitalCost$

$GenerationCapitalCost(\$) = NameplateCapacity$ (MW) $\times GenericTechnologyCapitalCost$ (\$/MW, varies by region)

Transmission capital cost is determined by the minimum of two options. Option 1 is to connect from the CPA to the nearest 161 kV or greater substation, and from this substation to the nearest load center with population $> 750,000$. Option 2 is to connect directly to the nearest load center with population $> 750,000$. Both options are calculated based on the calculated straight-line Euclidean distance for all CPAs and the least cost option is selected. Least-cost-path distance is calculated in a later stage, described in Annex F. [6]

Option 1) $TxCostLoad = [dLoad$ (km) $\times SpurLineCost$ (\$/MW-mi)] $\times$ $NameplateCapacity$ (MW)
/[1.60934(kmPerMi)]

Option 2) $TxCostSubLoad = [dSub$ (km)$\times SpurLineCost$ (\$/MW-mi)$+dSubLoad$(km) $\times HVLineCost$ (\$/MW-mi)] $\times$ $NameplateCapacity$ (MW)/[1.60934(kmPerMi)]

Table 4: Transmission capital cost assumptions, summarized by voltage level and region. All values (USD2018\$/MW-mi). Source: [29]

Region	Spur Line Cost (230 kV)	HV Line Cost (kV varies by region: 345, 500, 765 kV)
Desert Southwest	1448	4181
California	2948	5574
Texas	1448	4181
Florida	1448	4395
Upper Midwest	1045	4395
New England	3752	5574
Pacific Northwest	1448	4181
New York	3216	5574
Mid-Atlantic and Great Lakes	1260	4985
Rocky Mountains	1448	4181
Lower Midwest	965	4073
Louisiana and Ozarks	2586	4726
Southeast	1314	5038
Utah Nevada	1448	4181

2.3 Site Selection and post-site selection adjustments

After CPAs are sorted by LCOE in ascending order, a site selection algorithm is used to identify a portfolio of selected sites in five year increments, for each technology, for each region (see Figure 3, and for each scenario's portfolio. Within a region, selected sites are associated with the nearest metropolitan statistical area with population $\geq$ 750,000 people (see Figure 4).

[6] Site selection is based on the LCOE including straight line interconnection cost. For the purposes of generating final cost numbers and routes for visualization, least cost path analysis for transmission is performed, as detailed in Annex F. Future work could expand upon this siting algorithm to include minimum cost surfaces for spur line routing and cost estimates, which could impact least-cost site selection.

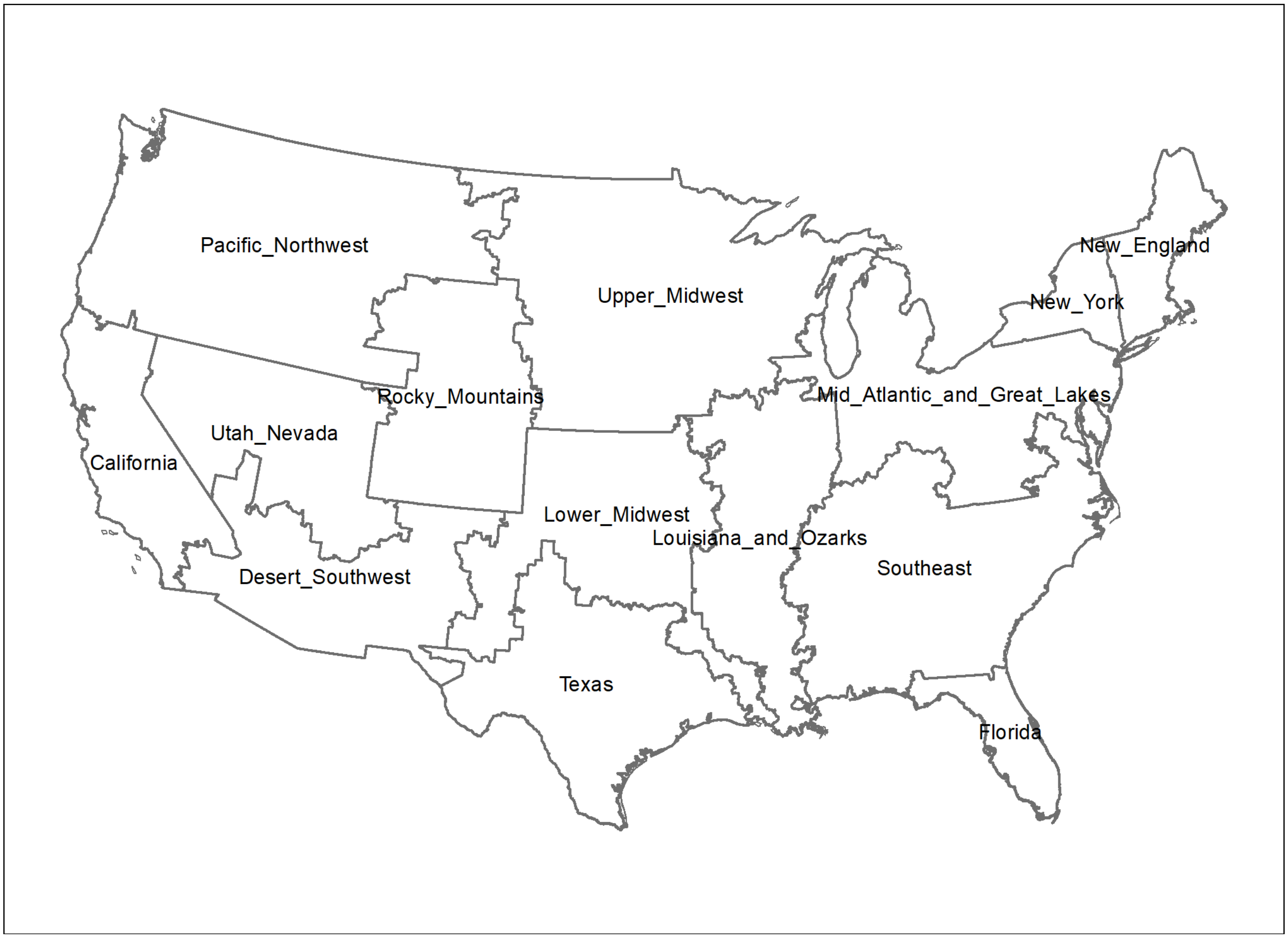


Figure 3: Regions modeled

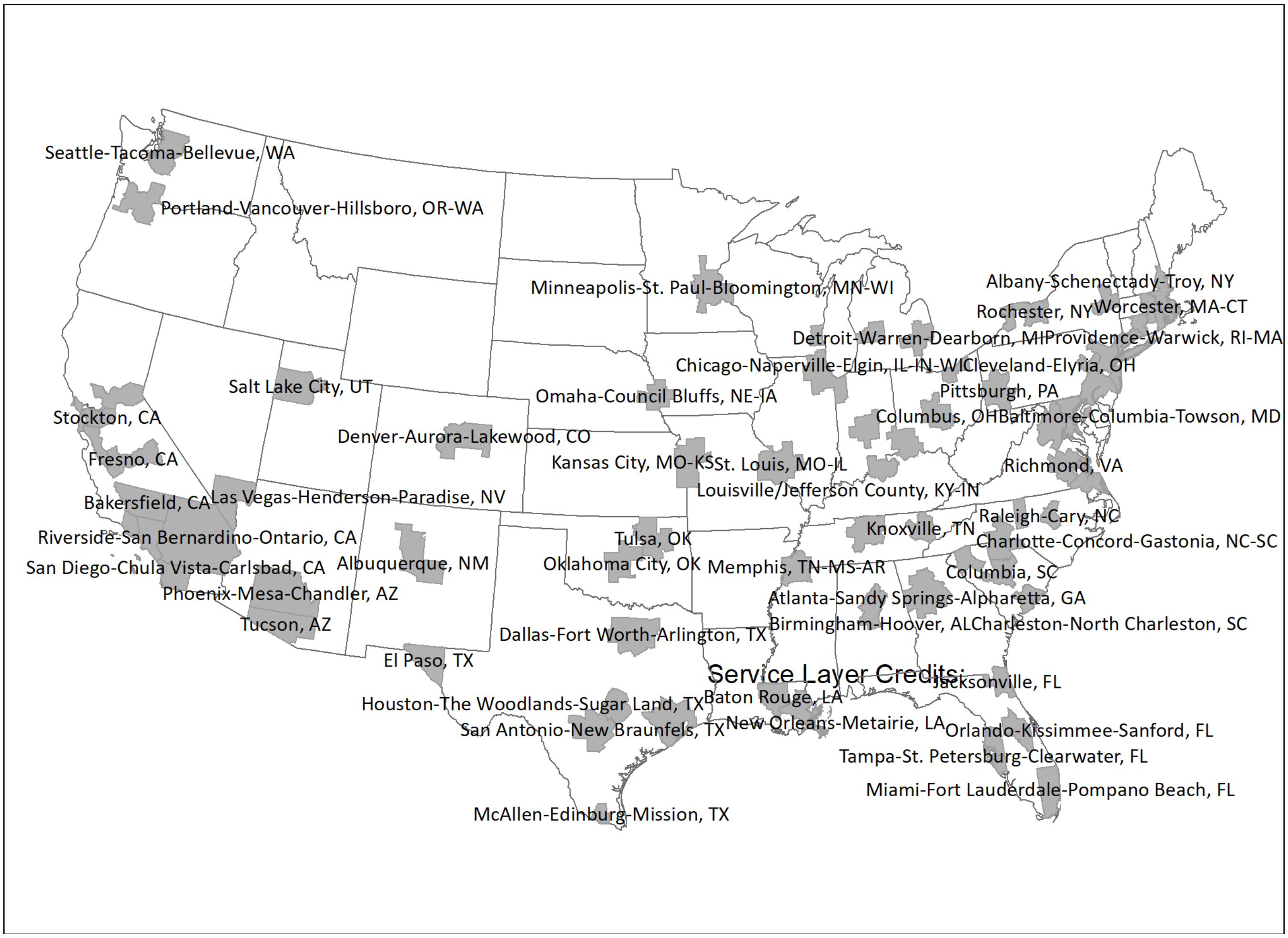


Figure 4: Metropolitan statistical areas with population $\geq$ 750,000

Sites are selected in five year increments, in order of increasing LCOE, for each of the 14 regions, as a function of renewable resource quality, annual estimated generation, generation capital cost, transmission distance, and transmission cost. Additional sites are selected cumulatively, until regional wind and solar RIO targets are satisfied. Existing and planned facilities are selected first.[7] For summaries of existing and planned facilities per region, see Table 9.

The resulting sites are adjusted again in post-processing after site selection. Post-processing steps include solar discount factor correction, to show more realistic hypothetical facility boundaries. Because solar lands were discounted in pre-processing (an 80% discount factor was applied), this meant that 80% of land area had to be removed in post-processing, in order to show only the 20% footprint of solar facilities. Additionally, in post-processing, we assume that 91% of solar facility area is directly impacted by equipment or infrastructure ([20]), and 1% of wind facility area is directly impacted by equipment or infrastructure ([23]).

Where regional energy shortfalls occur compared to the RIO portfolio, additional supplemental sites are selected in post-processing. For CLUA scenarios, this means selecting additional wind CPAs from the BLUA set, where insufficient CPAs exist in the region's CLUA set to satisfy the portfolio. For solar, shortfalls are addressed by allowing the model to select more than 20% of the CLUA case solar CPAs in a given region.

Onshore wind shortfalls only occur in constrained scenarios. These are filled by adding BLUA sites. In the case of offshore wind, shortfalls occur in the Mid-Atlantic and Great Lakes (MAGL) region in CLUA for both E+ and RE+ and even in the BLUA scenario for RE+. This regional offshore wind shortfall is not filled, but simply noted. It highlights potential future improvements to power density and siting assumptions in the capacity expansion model input assumptions and the potential need to reconfigure deployment of offshore wind to other adjacent regions.

3 Results

3.1 Site Suitability

For site suitability exclusions, see Figure 5. Each group of combined exclusions (techno-economic, base environmental exclusions, and constrained environmental exclusions) consists of contributing datasets, summarized in Table 7. Light grey areas visible in these figures represent remaining candidate project areas (CPAs) after exclusions are applied.

[7] Existing and planned facility shapes are removed from CPA dataset, and regional targets are decremented by the regional existing and planned facility amount; then sites are selected from the CPA dataset; then existing and planned facilities are added to the selected sites in the earliest five-year time increment

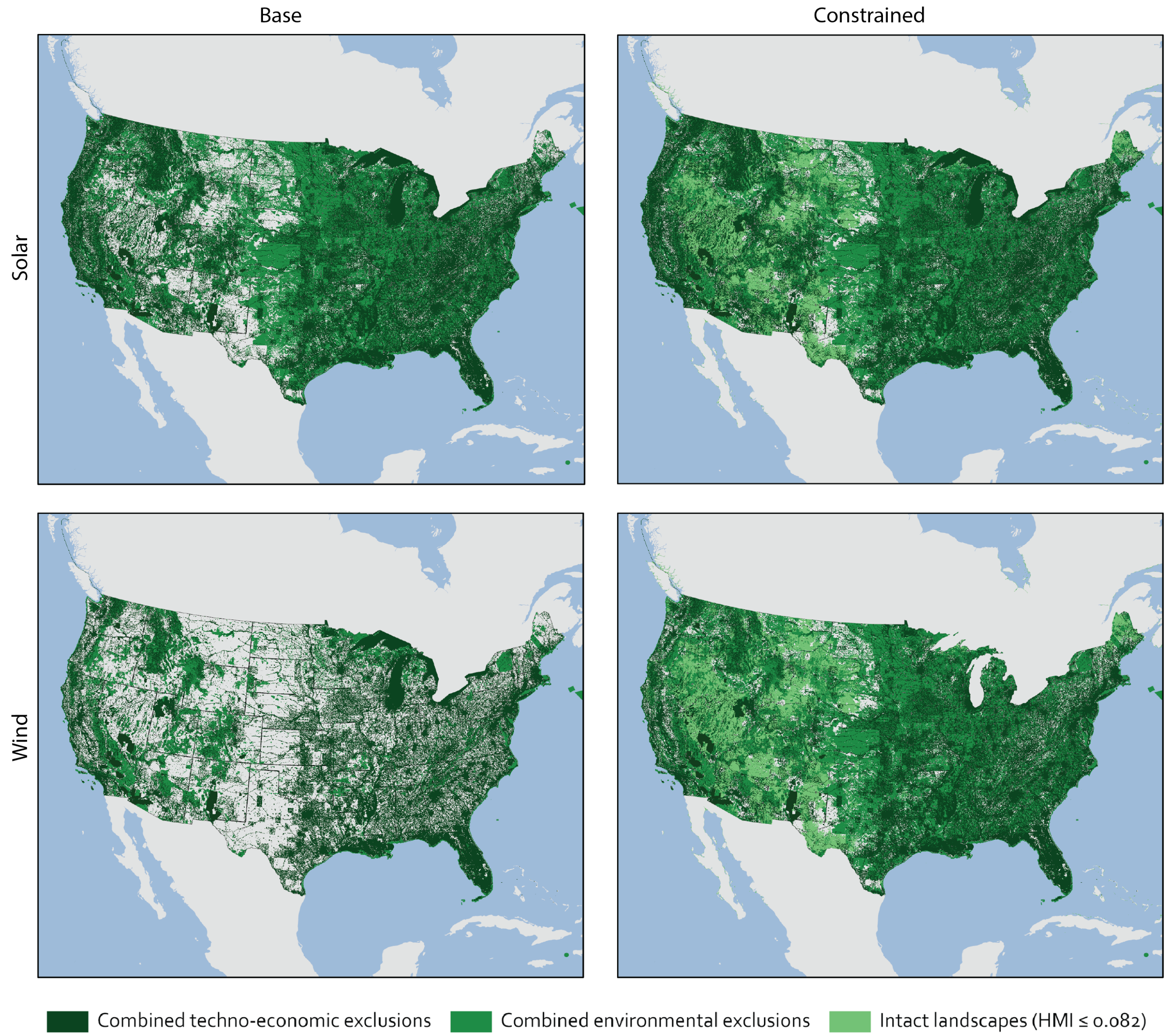


Figure 5: Site suitability factors

3.2 Candidate Project Areas

As shown in Figure 6, total solar CPA area is 3,030,656 km^2 under BLUA, and 1,464,830 km^2 under CLUA. Total wind CPA area is 4,473,379 km^2 under BLUA, and 996,242 km^2 under CLUA. Total offshore wind CPA area is 238,930 km^2 under BLUA, and 25,576 km^2 under CLUA.

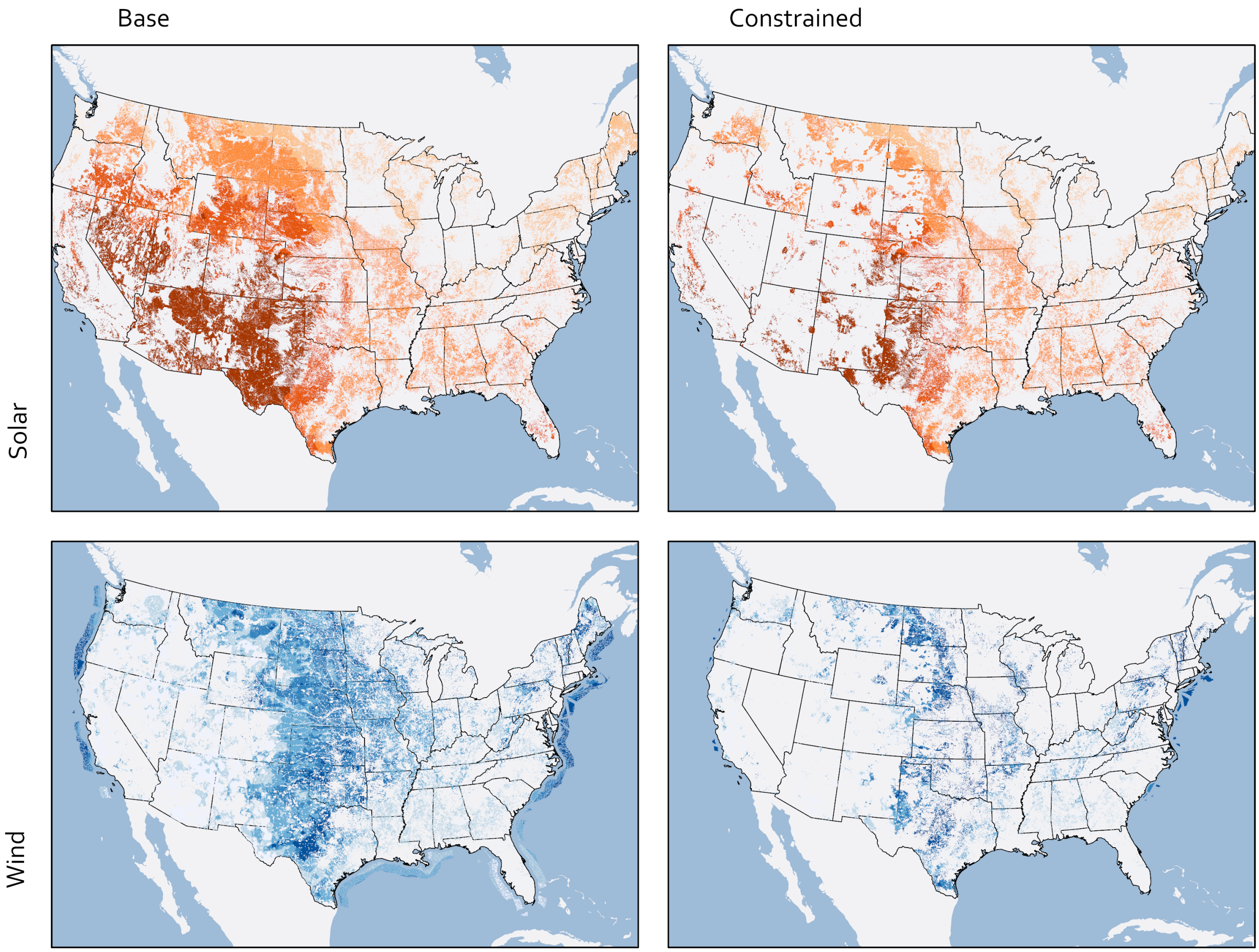


Figure 6: Candidate Project Areas (CPA)

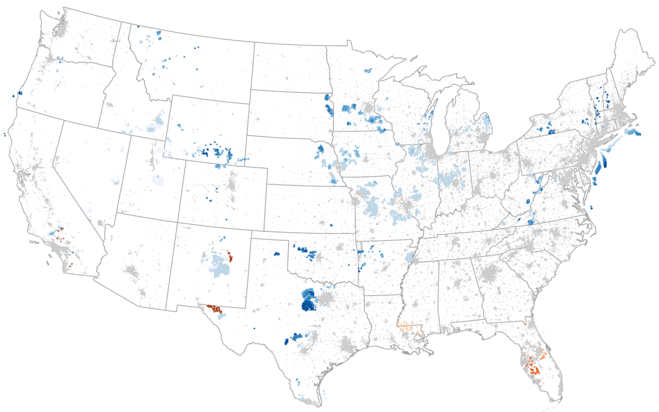
3.3 Selected Sites: Results

As shown in Figure 7, the total area of solar sites selected for the REF Scenario is 3,048 km^2, and 14,240 km^2 for the RE- scenario (0.1% and 0.5% of CPA area respectively). For comparison, total area of wind selected sites is 141,559 km^2 for REF, and 244,339 km^2 for RE- (3% and 5% of CPA area respectively). Total area of offshore wind selected sites is 7,875 km^2 for REF, and 5,691 km^2 for RE- (3% and 2% of CPA area respectively).

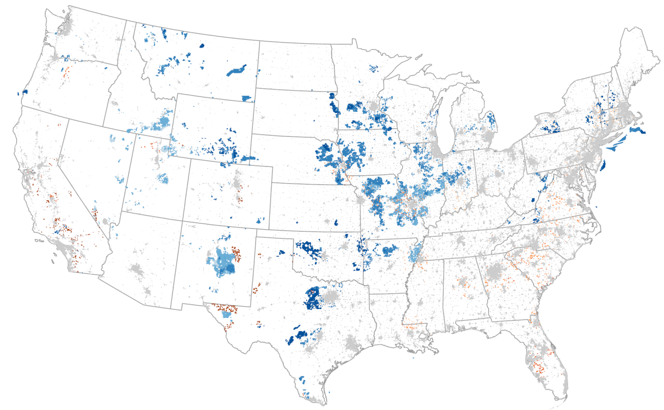
As shown in Figure 8, the total area of solar sites selected for the E+ Scenario is 38,317 km^2 under BLUA, and 37,818 km^2 under CLUA (1% and 3% of CPA area respectively). For comparison, total area of wind selected sites is 551,140 km^2 under BLUA, and 563,824 km^2 under CLUA (18% and 57% of CPA area respectively). Total area of offshore wind selected sites is 33,077 km^2 under BLUA, and 35,080 km^2 under CLUA (14% and 137% of CPA area respectively). As offshore wind exceeds available area in CLUA for the E+ case, additional sites are selected from the BLUA CPAs until the required energy is provided to each model region.

As shown in Figure 9, the total area of solar sites selected for the RE+ Scenario is 65,945 km^2 under BLUA, and 65,583 km^2 under CLUA (3% and 4% of CPA area respectively). For comparison, total area of wind selected sites is 1,008,975 km^2 under BLUA, and 563,824 km^2 under CLUA (34%

and 57% of CPA area respectively). Total area of offshore wind selected sites is 63,829 km^2 under BLUA, and 63,486 km^2 under CLUA (27% and 248% of CPA area respectively). As offshore wind exceeds available area in CLUA for the RE+ scenario, additional sites are selected from the BLUA CPAs until the required energy is provided to each model region.

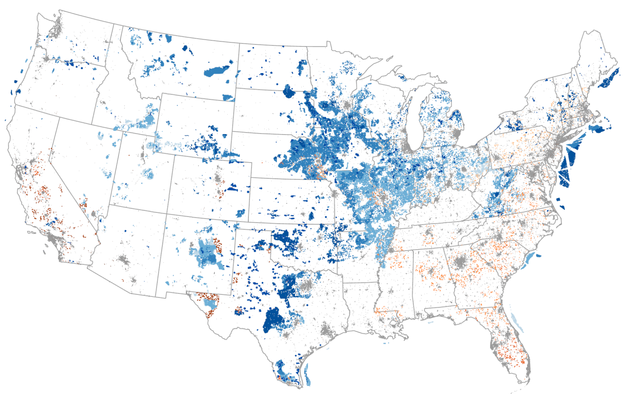


(a) REF (Reference) scenario, Base land use assumptions (BLUA)

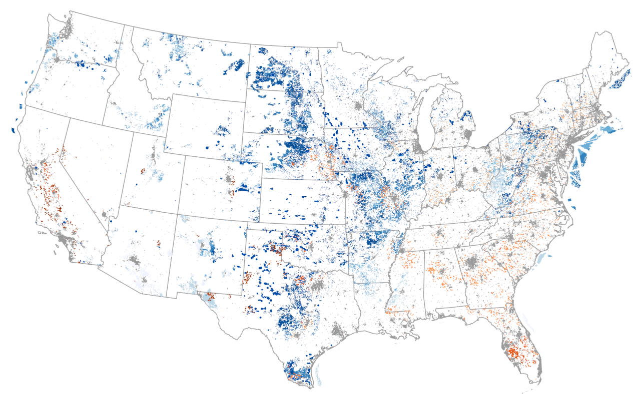


(b) RE- (Renewables-constrained) scenario, BLUA

Figure 7: 2050 Selected sites REF and RE-, BLUA.

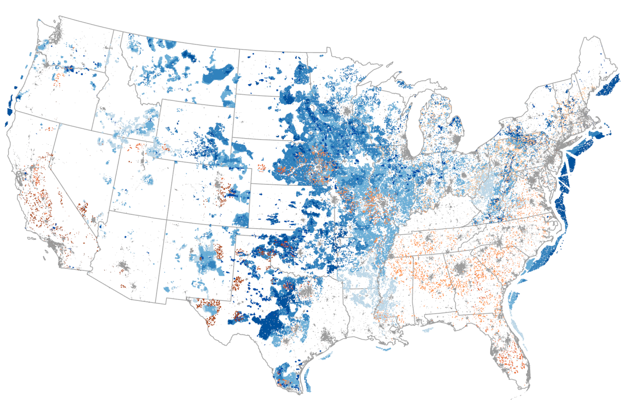


(a) E+ scenario, Base land use assumptions (BLUA)

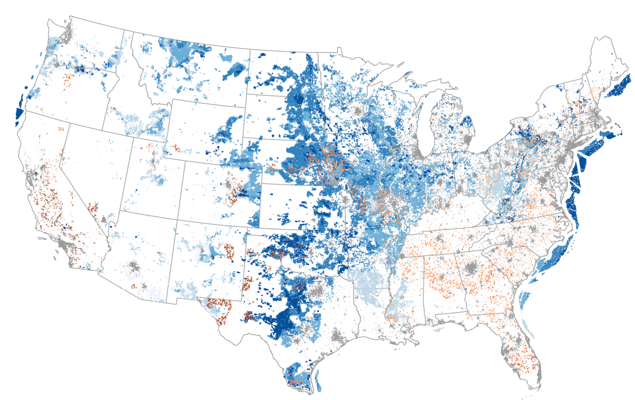


(b) E+ scenario, Constrained land use assumptions (CLUA)

Figure 8: 2050 Selected sites E+ BLUA and CLUA.

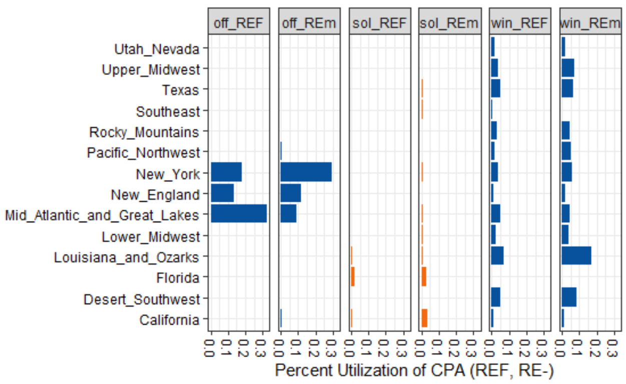


(a) RE+ (100% renewables) scenario, Base land use assumptions (BLUA)

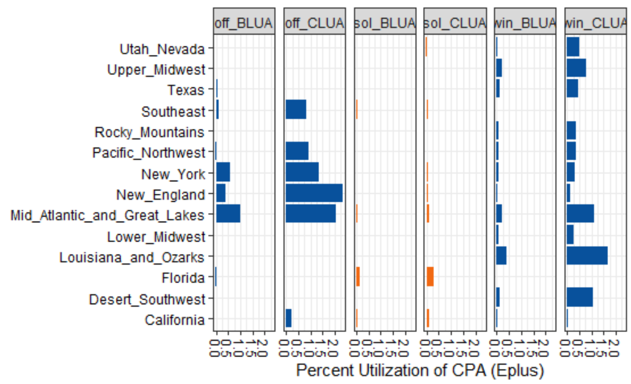


(b) RE+ (100% renewables) scenario, Constrained land use assumptions (CLUA)

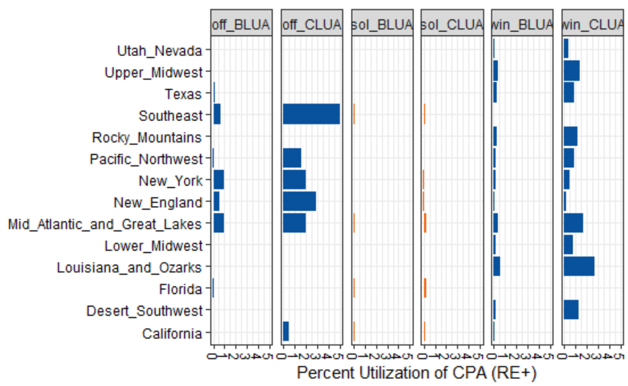
Figure 9: 2050 Selected sites E+ RE+ BLUA and CLUA.



(a) REF and RE-



(b) E+



(c) RE+

Figure 10: 2050 Utilization of Candidate Project Area

For offshore wind siting analysis, simplifying assumptions were made to account for uncertainty. Forty percent of offshore wind CPAs were removed, and areas within 20 degrees north and south of major ports were also removed. Designated Bureau of Ocean Energy Management (BOEM) offshore wind leasing areas were prioritized, but were not adequate to fill the need, as shown in Figure 11.

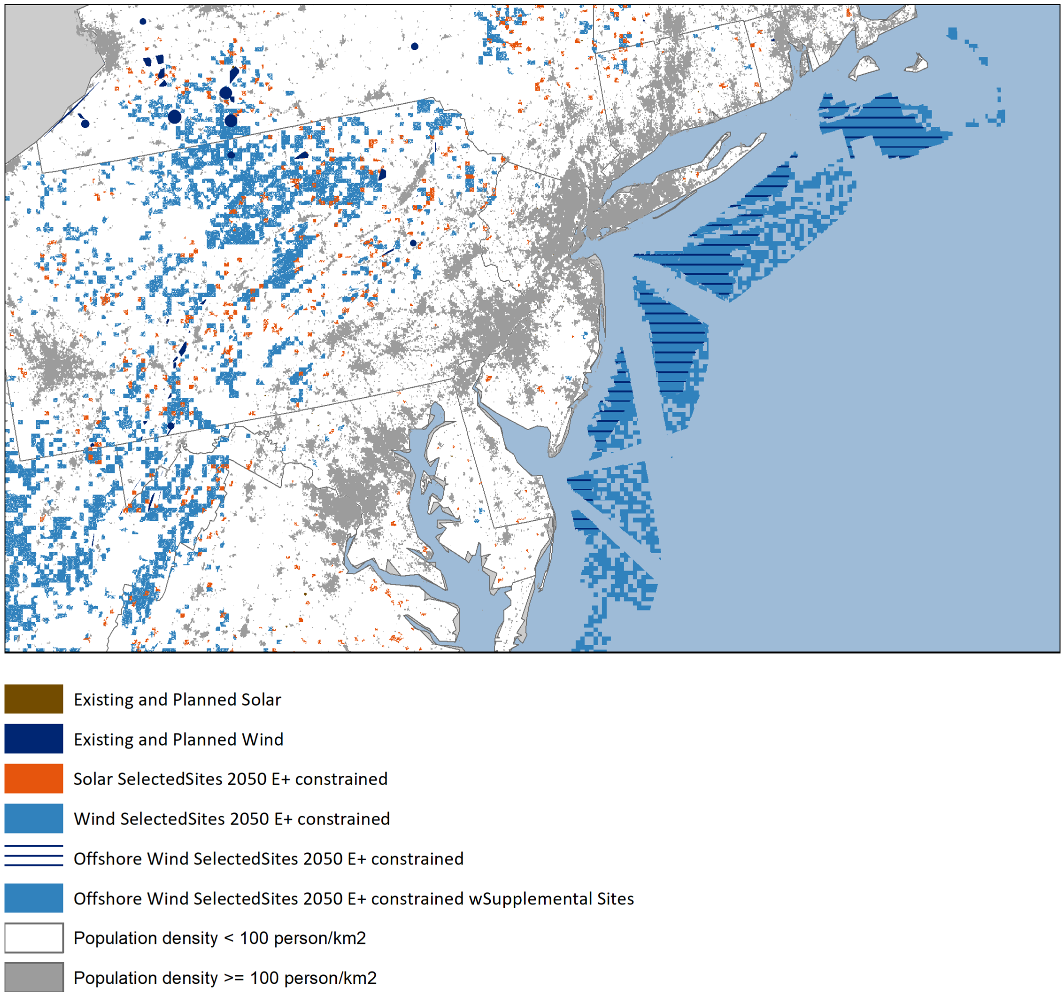
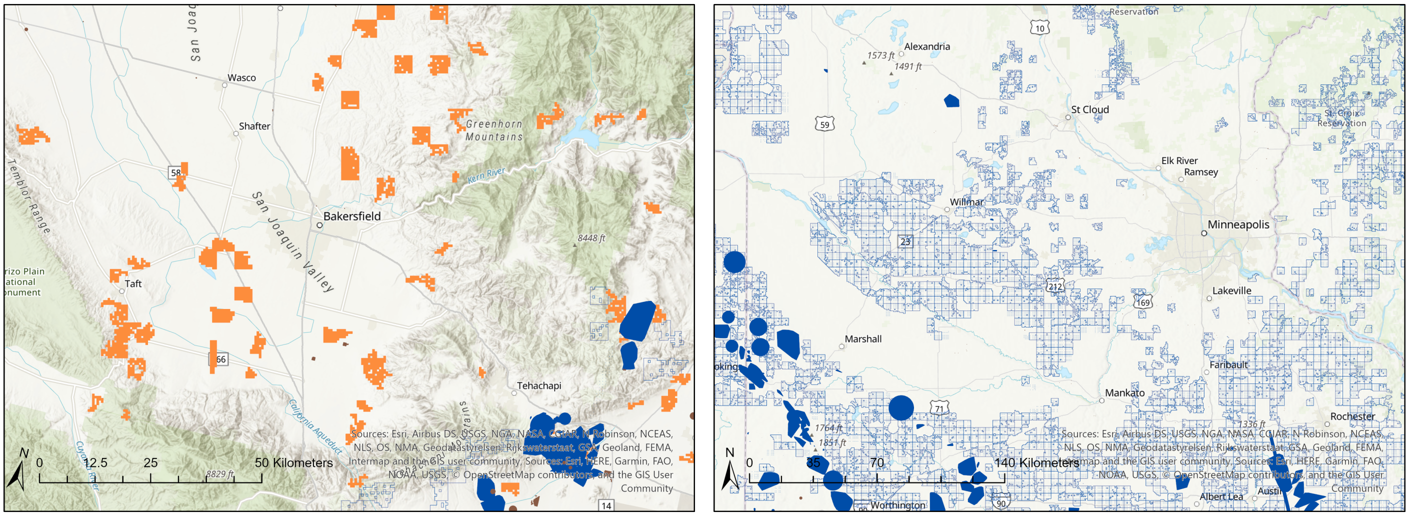


Figure 11: Selected sites for Mid-Atlantic and southern New England region. CLUA offshore wind sites are shown in dark blue stripes, and supplemental BLUA offshore wind selected sites shown in lighter blue, with 40% of sites unavailable due to uncertainty in far offshore siting considerations.

Distance to load centers was included in the transmission cost, and thus sites with good resource quality in close proximity to load centers were favored, as shown in Figure 12.



(a) Bakersfield (b) Minneapolis, MN

Figure 12: Distribution of selected sites in two areas: Bakersfield California and Minneapolis Minnesota. Selected sites are inversely proportional to population density, and largely consistent with patterns of existing solar and wind facilities (dark brown and dark blue).

3.4 Affected Land Cover Types: REF and RE- Scenarios

For the REF Scenario, wind selected sites occur primarily on agricultural land cover types (cultivated crops and hay/pasture lands), and solar occurs primarily on shrub and scrub land cover types, with percent of total area for each technology as follows.

The majority of wind selected sites occur on agricultural land (cultivated crops and hay/pasture lands) (45% of total wind selected site area). The next most common land cover types for wind are forest (21%) and shrub/scrub land (14%).

The majority of solar selected sites occur on shrub/scrub land (31% of total solar selected site area). The next most common land cover types for solar are cultivated crop and pasture land (29%), and forest 15%.

3.5 Affected Land Cover Types: E+ Scenario

As shown in Figure 14, for the E+ Scenario, wind selected sites occur primarily on agricultural land (cultivated crops and hay/pasture lands, 48% and 33% respectively for BLUA and CLUA), forest (18% and 26%) and shrub/scrub land (15% and 16%). Solar selected sites occur primarily on forest (38% and 37%), cultivated crop and pasture land (25% and 28%), and shrub/scrub land (17% and 12%).

3.6 Affected Land Cover Types: RE+ Scenario

As shown in Figure 15, for the RE+ Scenario, wind selected sites occur primarily on agricultural land (cultivated crops and hay/pasture lands, 42% and 35% respectively for BLUA and CLUA), herbaceous (grassland) (17% and 23%) and shrub/scrub land (15% and 17%). Solar selected sites occur primarily on forest (29% and 30%), cultivated crop and pasture land (25% and 27%), and shrub/scrub land (17% and 13%).

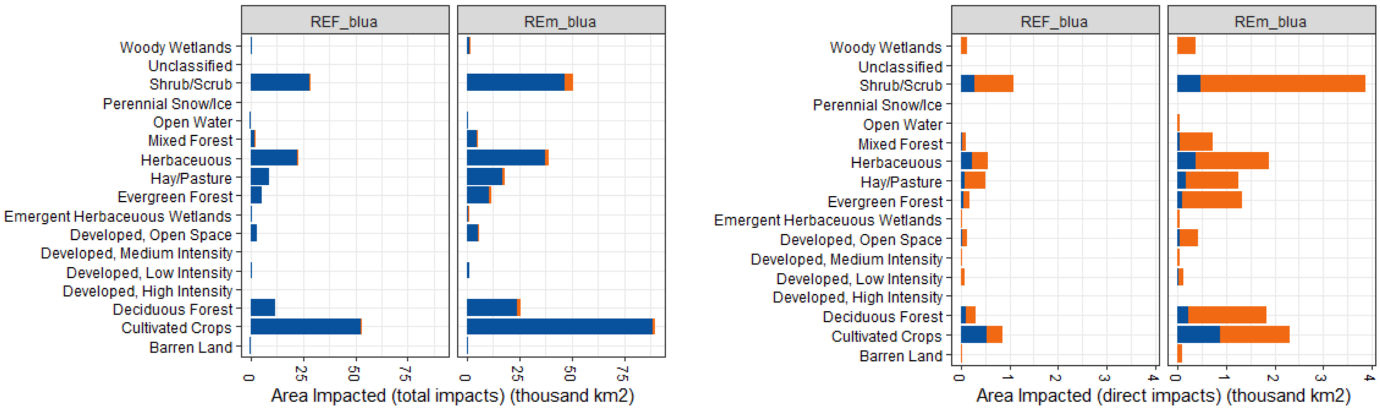


Figure 13: Land cover types affected (REF and RE- scenarios, km^2) by solar (orange) and onshore wind (blue) development.

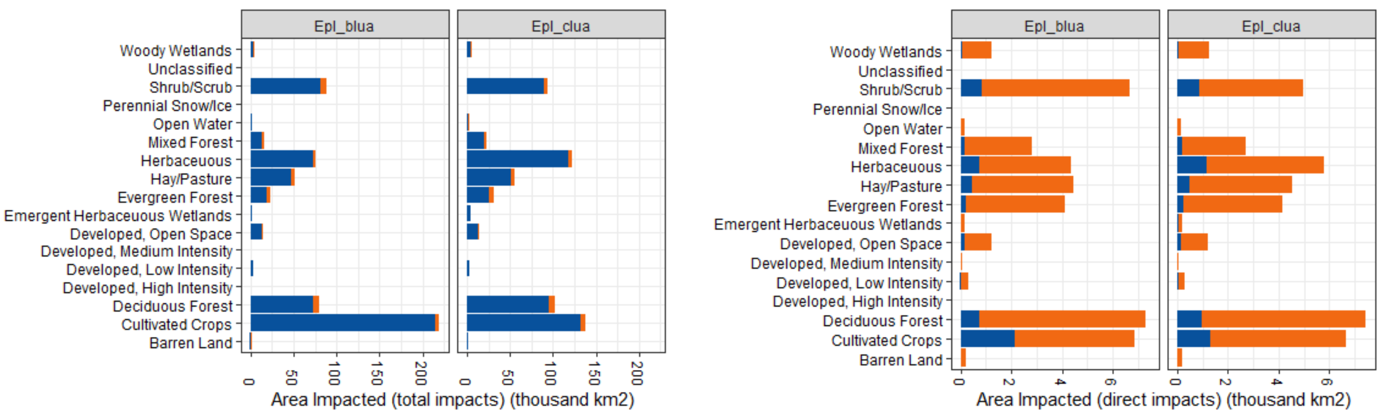


Figure 14: Land cover types affected (E+ scenario, km^2) by solar (orange) and onshore wind (blue) development.

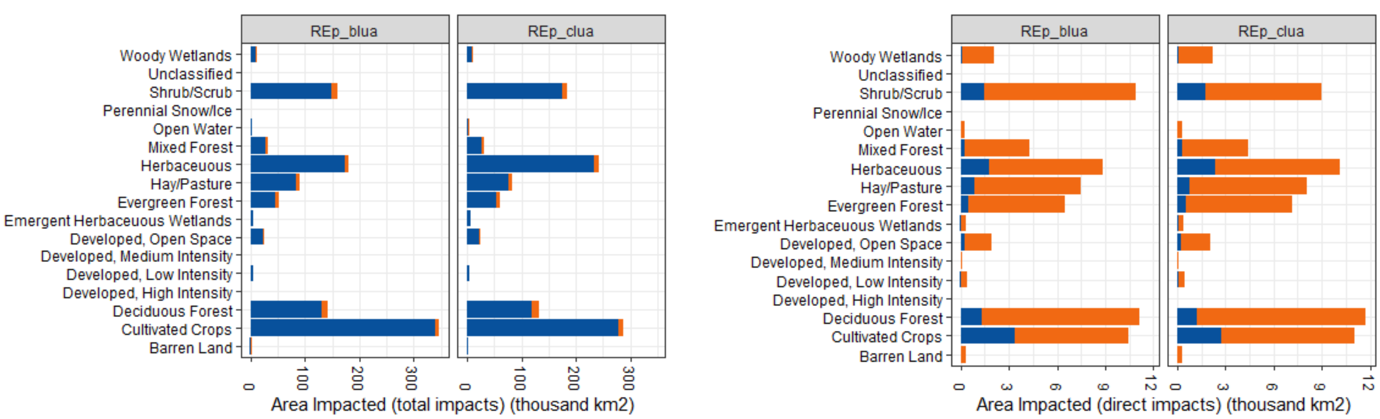


Figure 15: Land cover types affected (RE+ scenario, km^2) by solar (orange) and onshore wind (blue) development.

4 Land Cover Type Discussion

Figure 13 shows that the direct impacts for both wind and solar (turbine foundations, solar array mounting structures, roads, cable and electrical equipment) are much smaller than total impacts (entire facility boundary). However, the difference between direct and total impact varies by technology. Direct impacts for wind facilities are much smaller than direct impacts for solar facilities (Figure 13).

As can be seen in Figure 15, the majority of wind facilities occur on agricultural land, due to the compatibility of wind power with agricultural land uses. For all scenarios, changing from base to constrained land use assumptions results in a shift away from agricultural land cover types toward shrub, scrub, and grassland (herbaceous) or forested lands. This is due to the prime farmland exclusion, which occurs under constrained land-use assumptions only (and not under base land use assumptions), and restricts wind development on agricultural lands. This assumption would merit further investigation in future work. Historically, some jurisdictions have limited energy development on prime farmland (California, New York, New Jersey, and Oregon for example), but treatment of agricultural land varies widely across jurisdictions, and ideally capacity expansion models should not preclude development where viable opportunities exist.

Conversely, the constrained land use assumptions tend to result in a shift from solar development from shrub/scrub land to cultivated crop lands. This reflects the exclusion of areas of low human modification (low HMI) in the constrained case. Prime farm lands are excluded for solar development in both base and constrained land availability, so the increase in cultivated lands in CLUA scenarios for E+ and RE+ reflects non-prime soils.

Similarly, the treatment of forested land would merit further investigation in future work. Forested land cover types were not treated as an exclusion under base or constrained modeling assumptions for this study. In practice, however, there is likely to be additional cost for construction on forested sites. In practice, it is not uncommon to see wind facilities on forested ridgelines for high-wind-speed sites, but solar facilities on forested land are less common. While applying a construction cost adder for forested land was beyond the scope of this study, it may be beneficial in future work.

4.1 Land Cover Type Discussion: Trends Over Time

Figure 16 shows changes in land cover types affected over time. It can be seen that, under current study assumptions, the majority of total area affected by new wind and solar facilities occurs in Midwestern states and Texas. The majority of the affected areas in these states are agricultural and shrub/scrub land. While the total area affected in northeastern states is small, the directly impacted land as a percent of state area is large, and it is primarily forested land cover type (due to predominance of forest landcover type in the northeast, and increased reliance on solar instead of wind in this region).

Under current study assumptions, site suitability criteria do not change over time, but this topic is worth exploring in future work. Examples of site suitability criteria likely to change over time include the following:

> Population density: as urban areas expand, population density will increase, and siting conflict may become more common in densely populated areas.

Military and airspace considerations: as wind turbine deployment increases, the density of wind facilities in proximity to airfields and radar facilities may increase, driving an increase in siting conflicts.

Sensitive habitats and ecosystems: as the impacts of climate change continue to grow, climate refugia for certain species may grow in importance. Future protections for climate refugia to help prevent biodiversity loss may change the "protected areas" designation in the site suitability criteria.

Transmission congestion: changes in the cost of power imports and exports from region to region will likely drive significant changes in the spatial pattern of infrastructure deployment.

Agricultural land compatibility: in locations where groundwater supplies are overdrawn, conversion from agriculture to renewable energy production may become a more economically attractive option for landowners.

Wildfire: as wildfire risk increases with climate change, it may become more challenging to site high voltage transmission lines in high fire-risk-areas.

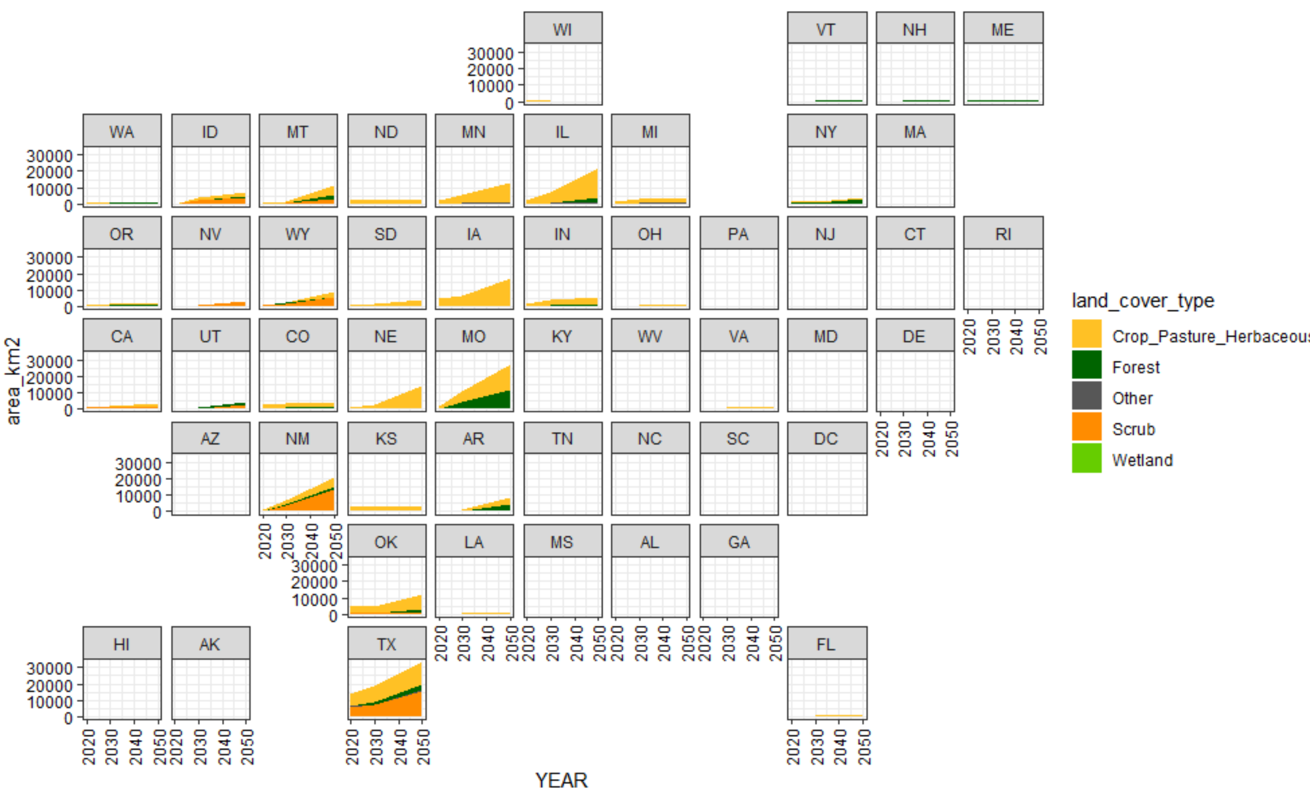


Figure 16: Land cover types affected by state (E+ scenario, base land use assumptions, total impacted land) (km^2).

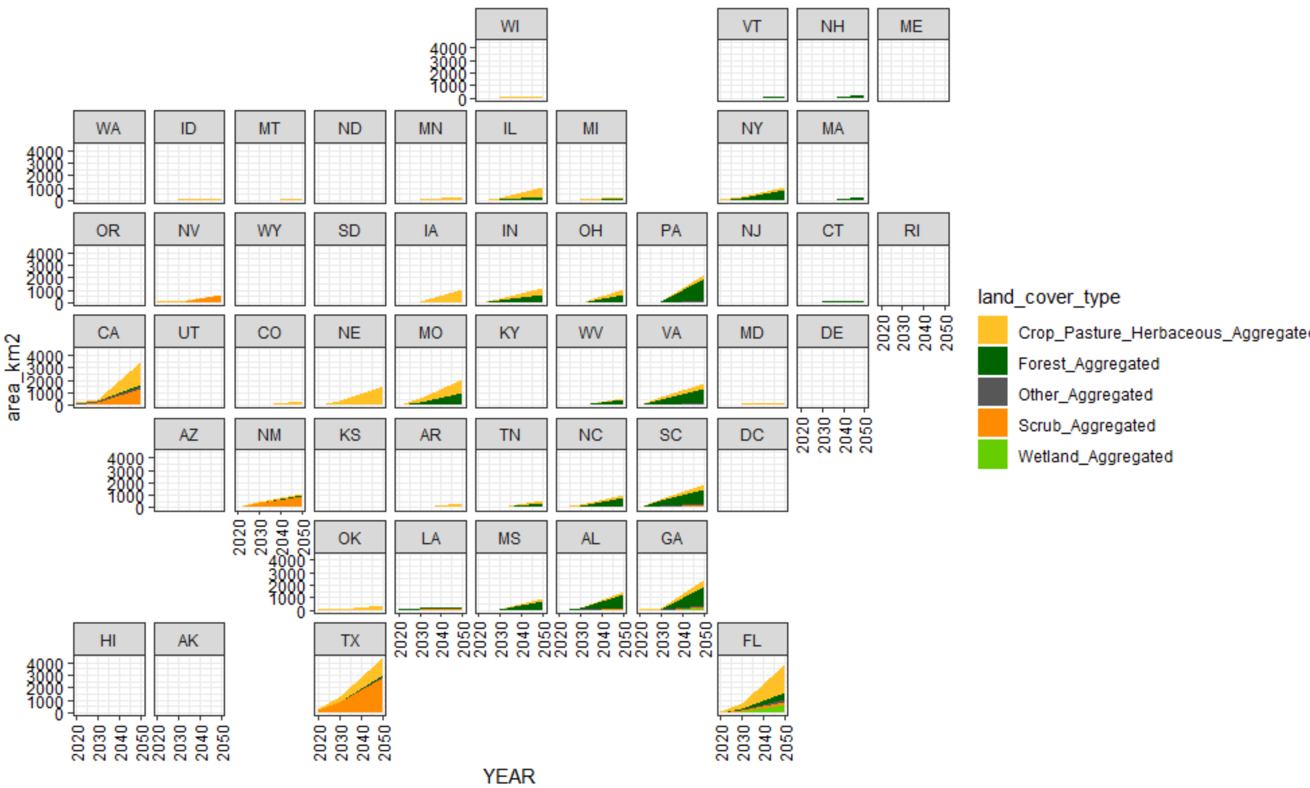


Figure 17: Land cover types affected by state (E+ scenario, base land use assumptions, directly impacted land only) (km^2).

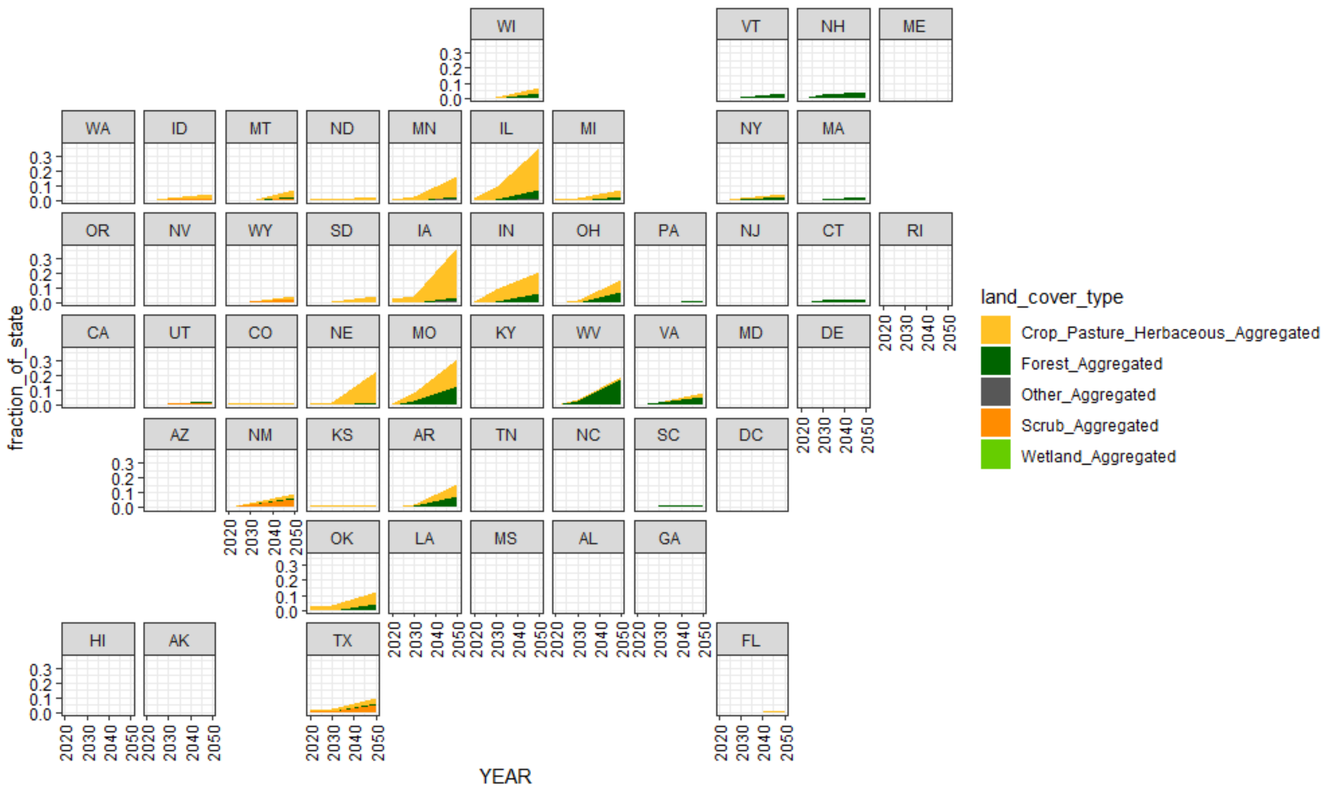


Figure 18: Land cover types affected by state (E+ scenario, base land use assumptions, total impacted land, as fraction of state area).

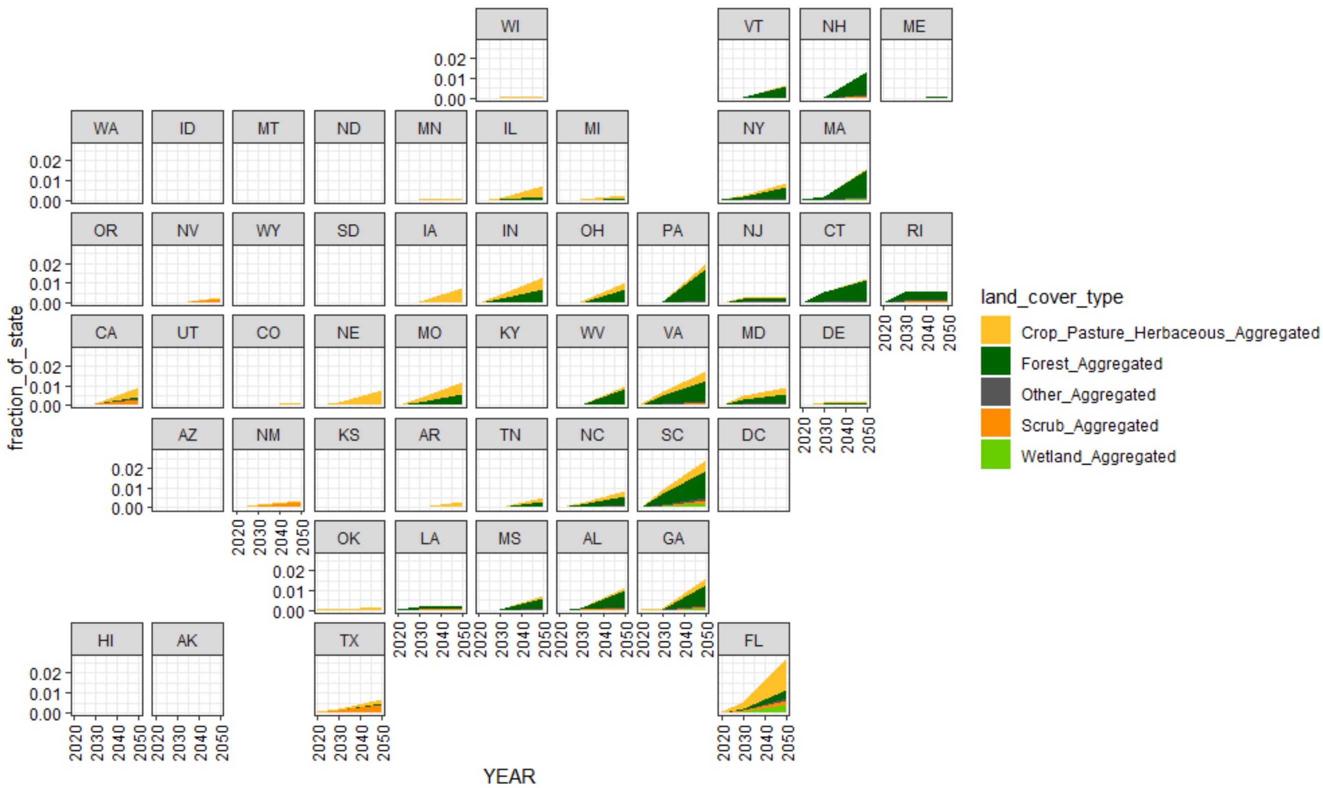
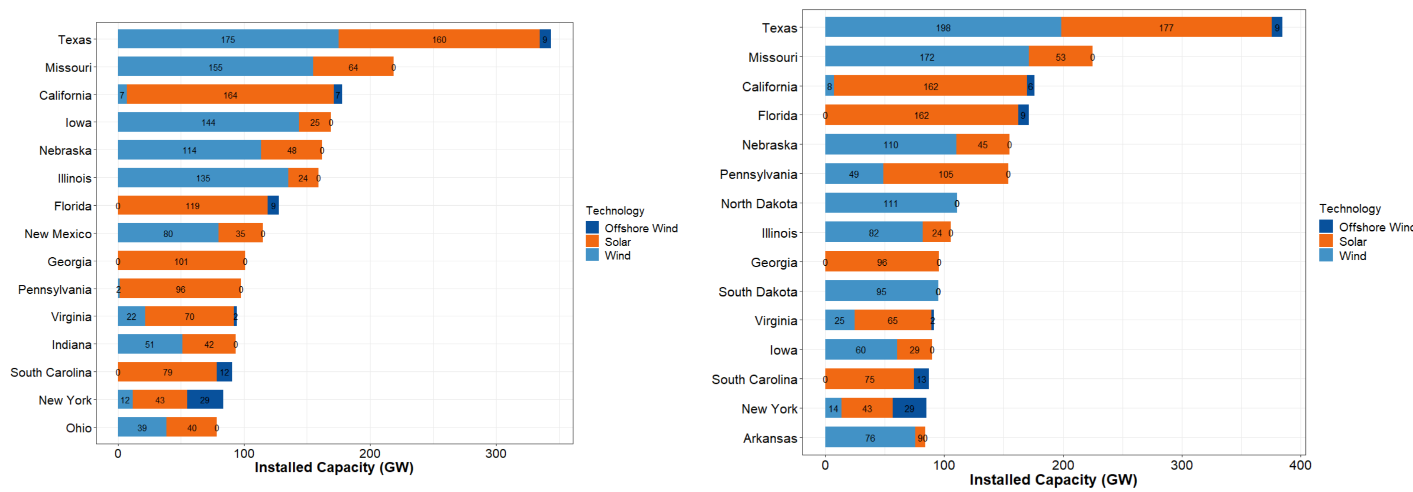


Figure 19: Land cover types affected by state (E+ scenario, base land use assumptions, directly impacted land only, as fraction of state area).

5 Discussion

The top fifteen states with most significant new infrastructure additions in the E+ scenario are summarized in Figure 20. Several states retain leadership positions across land use assumptions (Texas, Missouri, California, Nebraska). Others experience reductions when constrained land use assumptions are applied. For example, total new infrastructure in Iowa changes from $\sim$ 170 GW to $\sim$ 90 GW, and it is replaced by Florida in the top five states, under constrained land use assumptions. Of the top fifteen states, New York has the greatest offshore wind contribution (29 GW).



(a) Base land use assumptions (BLUA)

(b) Constrained land use assumptions (CLUA)

Figure 20: 2050 top fifteen states E+ BLUA and CLUA.

Energy shortfalls are summarized in Table 5. In the constrained scenarios, significant energy shortfalls occur in the following regions: Louisiana and Ozarks wind, Desert Southwest wind, Mid-Atlantic and Great Lakes wind (onshore and offshore), New England wind (offshore only), New York wind (offshore only). For onshore resources, this indicates that significant impacts to intact landscapes and prime farmland may occur for the modeled infrastructure deployment in these regions if infrastructrue expansion is not planned or guided by policy to avoid these impacts. Offshore wind shortfalls reflect a lack of available development area in current BOEM offshore lease and study areas.

There are several instances in which the selected sites exceed the portfolio targets by large percentages (PNW solar shortfalls are 255% and 222% for BLUA and CLUA respectively), but absolute value of the shortfall is small (3 TWh and 2 TWh respectively; compared to 3000 TWh national). These instances are marked 'de minimis' in Table 5. In these locations, this small difference could be corrected by assuming 100% of queued projects in a region are likely to come online vs. assuming only 50% (a risk-adjusted value).

For some regions, offshore wind shortfalls are 100% due to unavailability of areas beyond BOEM offshore wind planning or leasing areas, under CLUA. These shortfalls have been filled in Figure 8 and 9, per the methods described earlier (BLUA sites have been added for wind, and more than 20% area has been allowed to be selected for solar). Only one significant offshore shortfall remains unaddressed in Figures 9, because in the MAGL region, all base as well as constrained CPAs are exhausted. Thus additional base CPAs cannot be added within the region boundary.

Table 5: Energy shortfalls, E+ portfolio

	Solar BLUA	Solar CLUA	Wind BLUA	Wind CLUA	Offshore Wind BLUA	Offshore Wind CLUA
California	0%	0%	0%	0%	0%	0%
Desert_Southwest	1%	5%	0%	6%	n/a	n/a
Florida	0%	1%	0%	0%	0%	100%
Louisiana_and_Ozarks	0%	2%	0%	46%	0%	100%
Lower_Midwest	0%	1%	0%	0%	n/a	n/a
Mid_Atlantic_and_Great_Lakes	2%	1%	0%	4%	28%	70%
New_England	4%	0%	0%	0%	0%	70%
New_York	0%	0%	0%	0%	0%	33%
Pacific_Northwest	de minimis	de minimis	0%	0%	0%	0%
Rocky_Mountains	de minimis	de minimis	0%	0%	n/a	n/a
Southeast	0%	4%	de minimis	de minimis	de minimis	de minimis
Texas	0%	1%	0%	0%	0%	100%
Upper_Midwest	0%	0%	0%	0%	n/a	n/a
Utah_Nevada	0%	0%	0%	0%	n/a	n/a
Total	0%	1%	0%	11%	11%	57%

This indicates that BOEM-designated offshore wind leasing and planning areas may be inadequate, and there is a need for increased federal designation of leasing and planning areas for offshore wind especially in New England, New York, and the Mid-Atlantic regions.

6 Conclusion

Land use considerations are a critical component of infrastructure planning for any deep decarbonization future. This study provides a snapshot of what the requisite wind and solar infrastructure expansion might look like for a range of national 2050 deep decarbonization scenarios for the U.S. (REF, RE−, E+ and RE+ scenarios selected by the RIO model).

This study demonstrates how tools such as those in the ORB framework can help to visualize infrastructure plans, and make it easier for decision makers to contextualize the options, implications, and tradeoffs inherent to the selected portfolios.

Results showing the spatial pattern of potential infrastructure expansion in this study are not meant to be prescriptive, but they can help provide the necessary information to support least-regrets planning. For example, policies that prioritize preferred resource areas could be considered least-regrets, as resources appearing under constrained land use assumptions presumably have lower environmental impact and lower risk of siting conflicts.

This study highlights several areas of potential future investigation: 1) the sensitivity of spatial clean energy infrastructure deployment patterns to transmission assumptions, especially interregional transmission costs, 2) the need for publicly available national spatial representation of transmission network upgrade opportunities and costs, 3) the sensitivity of interregional transmission and network upgrade costs to wildfire risk, and 4) the relative importance of changes in site suitability criteria over time.

In practice, the planning, zoning, and siting decisions associated with the national portfolio ultimately take place at the local level, and at a higher spatial resolution that would be more computationally intensive and thus challenging to perform nationally. Communities will need to develop their own plans to identify least-regrets policies that incorporate their community values. Spatial analysis can make it easier for communities to develop such plans, and to identify preferred least-regrets spatial patterns of clean energy infrastructure deployment. This in turn can help position the country well to achieve the national deep decarbonization targets necessary for a climate-safe future.

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Appendix A: Methods

Figure 21: Detailed methodological flow chart

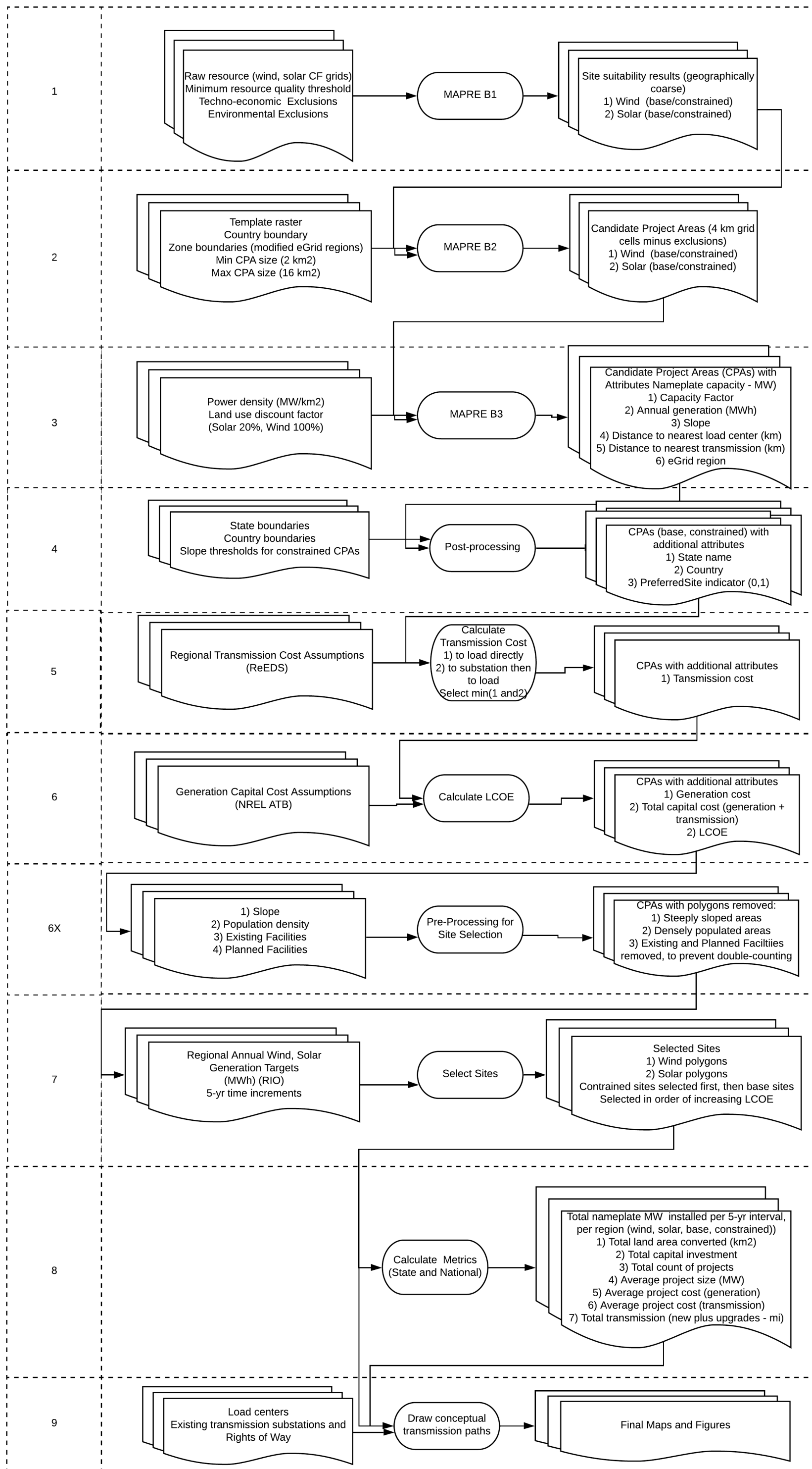

Table 6: Raw resource potential inputs

Data	Source	URL	Type	Spatial Resolution
Raw onshore wind resource potential	NREL Wind Toolkit	https://data.nrel.gov/submissions/54	Shapefile, points	2 km centers
Raw onshore solar resource potential	Black & Veatch unpublished dataset, NREL SAM, NREL NSRDB	https://sam.nrel.gov/photovoltaic.html	Shapefile, points	10 km centers
Raw offshore wind resource potential	Vibrant Clean Energy	https://onlinelibrary.wiley.com/doi/pdf/10.1002/we.1944	Shapefile, points	13 km centers

Table 7: Site suitability datasets (percent excluded)

Dataset	Type	Source	BLUA Solar	BLUA Wind	CLUA Solar	CLUA Wind	Offshore wind
Slope (lower 48)	techo-econ	USGS	exclude $> 10°$	exclude $> 19°$	exclude $> 10°$	exclude $> 19°$	na
Water bodies and rivers	techo-econ	EZMT	exclude all < 250m outside bodies		exclude all < 250m outside bodies		na
Urban Areas	techo-econ	US Census Bureau	exclude < 500m	exclude< 1000m	exclude < 500m	exclude< 1000m	na
Population Density	techo-econ	Landscan	exclude areas > 100 person/km^2		exclude areas > 100 person/km^2		
Military Installation Areas	techo-econ	EZMT	exclude < 1000m	exclude < 3000m	exclude < 1000m	exclude < 3000m	na
Active mines	techo-econ	USGS	exclude < 1000m from sites		exclude < 1000m		na
Airports	techo-econ	EZMT	exclude < 1000m	exclude < 3000m	exclude < 1000m	exclude < 3000m	na
Airport runways	techo-econ	EZMT	exclude < 1000m	exclude < 3000m	exclude < 1000m	exclude < 3000m	na
Railways	techo-econ	EZMT	exclude all < 250m outside bodies		exclude all < 250m outside bodies		
Capacity factor	techo-econ	Lopez et al. 2012	< 0%	< 20%	< 0%	< 20%	na
Flood Zones - FEMA 1% annual	techo-econ	FEMA	100%	100%	100%	100%	na
Marine Protected Area - except BOEM lease areas	enviro	PADv2	100%	100%	100%	100%	100%
BOEM offshore lease areas for renewable energy	techno-econ	BOEM	100%	100%	100%	100%	0%
Area of Critical Environmental Concern	enviro	PADv2	100%	100%	100%	100%	na
Conservation easements	enviro	PADv2	100%	100%	100%	100%	na
Fish and Wildlife Service Areas	enviro	EZMT	100%	100%	100%	100%	na
Historic or Cultural Area	enviro	PADv2	100%	100%	100%	100%	na
Inventoried Roadless Areas	enviro	PADv2	100%	100%	100%	100%	na
Landscape intactness (Theobald human modification index (HMI))	techno-econ	paper/data	0%	0%	HMI < 0.082		na
Local Conservation Area	enviro	PADv2	100%	100%	100%	100%	na
Local Historic or Cultural Area	enviro	PADv2	100%	100%	100%	100%	na
Military Land	techo-econ	PADv2	100%	except for ridgecrests	100%	except for ridgecrests	na
Mitigation Land or Bank	enviro	PADv2	100%	100%	100%	100%	na
National Conservation area	enviro	PADv2	100%	100%	100%	100%	na
National Forest	enviro	PADv2	100%	except for ridgecrests	100%	except for ridgecrests	na
National Historic or Scenic Trail	enviro	PADv2	100%	100%	100%	100%	na
National Lakeshore or Seashore	enviro	PADv2	100%	100%	100%	100%	na
National Park	enviro	PADv2	100%	100%	100%	100%	na
National Recreation area	enviro	PADv2	100%	100%	100%	100%	na
National Scenic, Botanical or Volcanic Area	enviro	PADv2	100%	100%	100%	100%	na
National Wildlife Refuge	enviro	PADv2	100%	100%	100%	100%	na
Native American Land Area	enviro	PADv2	100%	100%	100%	100%	na
Prime Farmland (USA Soils Farmland Class, ESRI Living Atlas)	techno-econ	ESRI	100%	0%	100%	100%	na
Private Conservation (includes National Natural Landmarks)	enviro	PADv2	100%	100%	100%	100%	na
Private Forest Stewardship	enviro	PADv2	100%	except for ridgecrests	100%	except for ridgecrests	na
Private Forest Stewardship Easement	enviro	PADv2	100%	100%	100%	100%	na
Research Natural Area	enviro	PADv2	100%	100%	100%	100%	na
Special Designation Area	enviro	PADv2	100%	100%	100%	100%	na
State Conservation area (includes National Natural Landmarks)	enviro	PADv2	100%	100%	100%	100%	na
State Historic or Cultural Area	enviro	PADv2	100%	100%	100%	100%	na
State Forests (in multiple PAD designations)	enviro	PADv2	100%	100%	100%	100%	na
State Park	enviro	PADv2	100%	100%	100%	100%	na
State Wilderness	enviro	PADv2	100%	100%	100%	100%	na
Watershed Protection Area	enviro	PADv2	100%	100%	100%	100%	na
Wild and Scenic Rivers	enviro	PADv2	100%	100%	100%	100%	na
Wilderness area	enviro	PADv2	100%	100%	100%	100%	na
Wilderness study area	enviro	PADv2	100%	100%	100%	100%	na
National Wetlands Inventory	enviro	FWS	100%	100%	100%	100%	na
BLM-WIND: "High" and "Moderate" Siting Considerations	enviro	BLM - WWWMP	0%	100%	0%	100%	na
BLM-Solar Exclusions	enviro	BLM - SEP, WSP	100%	0%	100%	0%	na
Marine Protected Areas	enviro	EZMT	na	na	na	na	100%
Shipping Lanes	techno-econ	EZMT	na	na	na	na	100%
Military Installation Areas	techno-econ	EZMT	na	na	na	na	100%
Offshore Military Danger Zones	techno-econ	EZMT	na	na	na	na	100%
Marine Restriction - Sanctuary	enviro	EZMT	na	na	na	na	100%
Areas Outside Leasing, Planning Areas	techno-econ	BOEM	na	na	na	na	100%

Table 8: Input datasets for CPA attribute calculations

Data	Source	URL
Population density	ORNL Landscan	https://landscan.ornl.gov/
Electric transmission lines and substations	US DHS Homeland Infrastructure Foundation-Level Data (HIFLD)	https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-power-transmission-lines/data
Generation capital cost	NREL ATB	https://atb.nrel.gov/
Transmission capital cost	NREL "Regional Energy Deployment System (ReEDS) Model Documentation 2018	https://doi.org/10.2172/1505935
Existing Solar Facilities	USGS National Solar Arrays	https://www.sciencebase.gov/catalog/item/57a25271e4b006cb45553efa
Existing Wind Facilities	USWTDB	https://eerscmap.usgs.gov/uswtdb/
Planned Wind and Solar Facilities	US EIA 860	https://www.eia.gov/tools/ height

Table 9: Existing and Planned Wind and Solar Infrastructure ([16], [17], [11]

Region	Existing Solar GW	Planned Solar GW	Existing Wind GW	Planned Wind GW
California	12.8	3.1	5.2	0.4
Desert Southwest	16.9	5.6	1.4	0.7
Florida	0.2	2.9	0.0	0.0
Louisiana and Ozarks	0.0	0.7	4.0	2.0
Lower Midwest	0.2	3.0	20.3	6.5
Mid Atlantic and Great Lakes	1.3	1.2	8.4	2.2
New England	0.6	0.5	1.4	0.1
New York	0.1	0.7	2.0	1.5
Pacific Northwest	0.6	1.2	8.1	2.1
Rocky Mountains	0.2	0.3	4.9	5.4
Southeast	0.6	6.3	0.2	0.0
Texas	0.2	5.9	21.5	10.9
Upper Midwest	0.0	0.9	19.3	8.2
Utah Nevada	0.2	1.7	0.5	0.0
Total	33.9	33.9	97.2	39.9

Figure 22: Solar power density calculation methods

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Basic analysis of solar PV density results

Data:

[1] Carr, Natasha B, Tammy Fancher, Araron T Freeman, and Heather M Battles Manley. "Surface Area of Solar Arrays in the Conterminous United States." US Geological Survey data release, June 9, 2016. http://dx.doi.org/10.5066/F79S1P57.
[2] EIA. "Form EIA-860 Detailed Data with Previous Form Data (EIA-860A/860B)." U.S. Energy Information Administration, 2015. https://www.eia.gov/electricity/data/eia860/.

Analysis method and notes:

1. Download USGS (2016) shapefile

2. Import into ArcGis Pro and export USGS shapefile attribute table to excel (Table to Excel - Conversion: https://pro.arcgis.com/en/pro-app/tool-reference/conversion/table-to-excel.htm)

3. Download EIA860 (Y2015) databall and access solar data (3_3_Solar_Y2015.xlsx). Note that the description of the USGS data states, 'We identified potential solar facility locations for the conterminous U.S. using the U.S. Energy Information Administration (EIA) utility-scale facilities data from 2015', but does not provide a reference to which EIA data was used.

4. Process USGS (2016) data using R
   a. Get a unique list of solar PV plants in data set, sum reported areas covered by individual arrays at each plant, record total capacity of each plant, clean data for merge

5. Process EIA860 (Y2015) data using R
   a. Get a unique list of solar PV plants in data set, sum reported nameplate and net DC capacities for the individually listed arrays at each plant,
   b. note if the nameplate and DC ratings are different, if they are and the nameplate is smaller than the DC rating, mark the nameplate as 'AC' and estimate dc:ac de-rating factors employed by each site owner,
   c. clean data for merge.

6. Merge processed USGS (2016) and EIA860 (Y2015) data by plant code
   a. Remove all PV plants that do not have an AC nameplate rating; or that have an AC nameplate rating, but an ac/dc de-rating factor of less than 1.1 (177 of 712); no ref - arbitrarily chosen threshold.
   b. Remove all PV plants for which the EIA and USGS power densities differ by more than 5 MW/km2 (171 of 520); no ref - arbitrarily chosen threshold).

   We chose to compare power density rather than reported total capacities as it allowed a little more wiggle room in capacity

Figure 23: Solar power density calculation methods (2)

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discrepancies in larger systems - which we have many fewer of in the data set, while not allowing relatively large reported discrepancies between small systems.

For example, if we used <5 MW as a filter capacity difference for the entire dataset, we would only exclude 2 of the 10 largest systems, but we would allow up to a 25% difference on systems of 20 MW or below. Use of power density as a filter rather than rated capacities allows for use of a normalized filter than works on both small and large systems, and allows some discrepancy between larger systems reported AC capacities, while also capturing relatively large discrepancies between smaller systems.

Some discrepancy between the USGS and EIA estimated power densities of larger system is allowed as the nameplate AC rating relies completely on the de-rating factor used by the company/person reporting the system. Allowed ac/dc de-rating factor range from between 1.1 to 2.4.

c. Remove all PV plants that have an estimated power density of below 10 MW/km2 (4 of 380) or above 100MW/km2 (27 of 380); no ref - arbitrarily chosen threshold).

Comparative potential cut-off thresholds based on quantiles:

0.51% - 10.1 MW/km2	:	96.65% - 100.1 MW/km2 (using)
5.00% - 27.8 MW/km2	:	95.00% - 82.2 MW/km2
10.00% - 33.1 MW/km2	:	90.00% - 66.6 MW/km2

7. Analyze data in the following arbitrarily chosen tranches
   a. >=100MW , >=20MW , >=10MW , >=5MW , >=1MW
   b. estimate capacity weighted average for each tranche using the equation: sum (power density * nameplate capacity) / sum (nameplate capacity)

Figure 24: Solar power density calculation methods (3)

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Data subset (>=5MW)

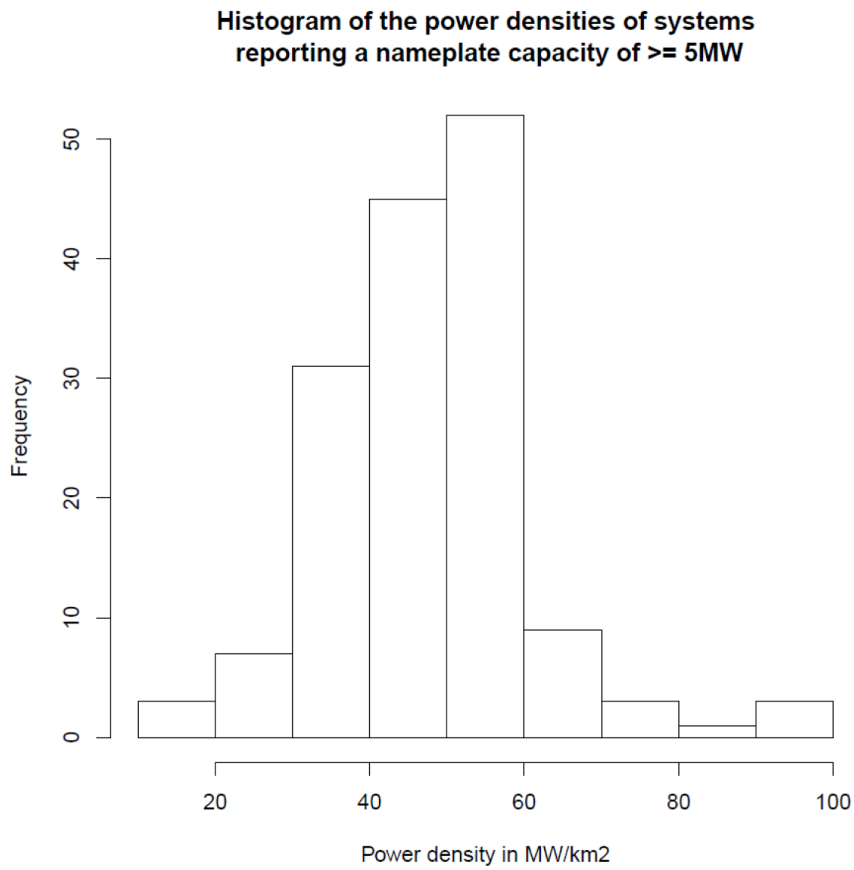
Power density: EIA860 (Y2015) reported AC nameplate capacity in MW / USGS (2016) land area in km2 for systems with an AC nameplate capacity of >= 5MW (154systems).

Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
18.23	39.62	48.17	47.83	55.50	97.12

DC/AC de-rating factors: Relationship between EIA860 (Y2015) reported nameplate capacity in MW and reported DC net capacity in MW for systems with an AC nameplate capacity of >= 5MW (154systems).

Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
1.100	1.200	1.258	1.252	1.300	1.486

Capacity weighted average: 45.49 MW/km2



Appendix B: Maps and Results

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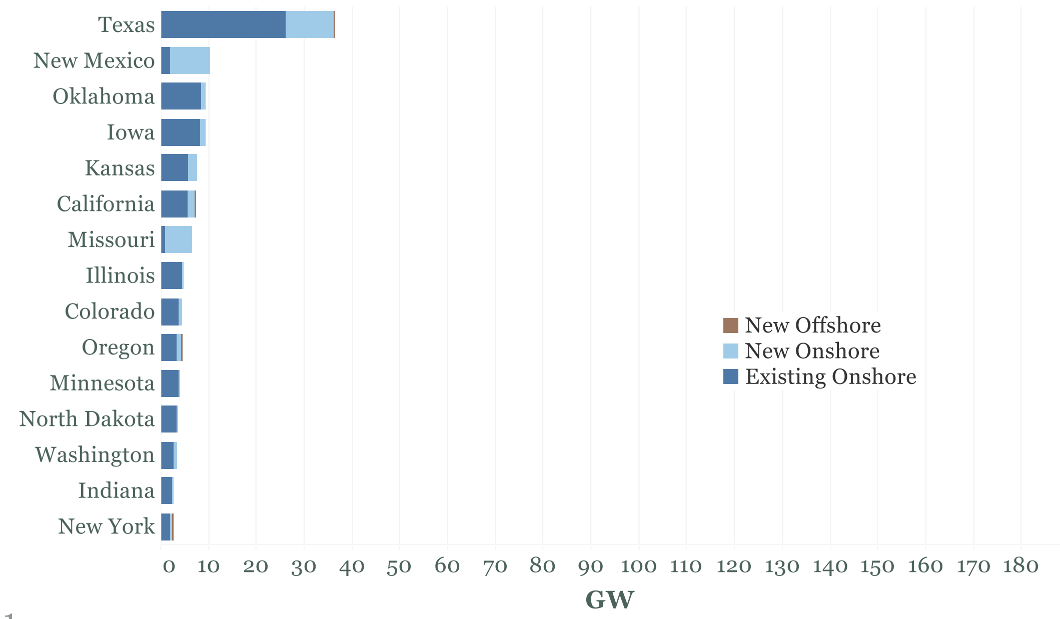
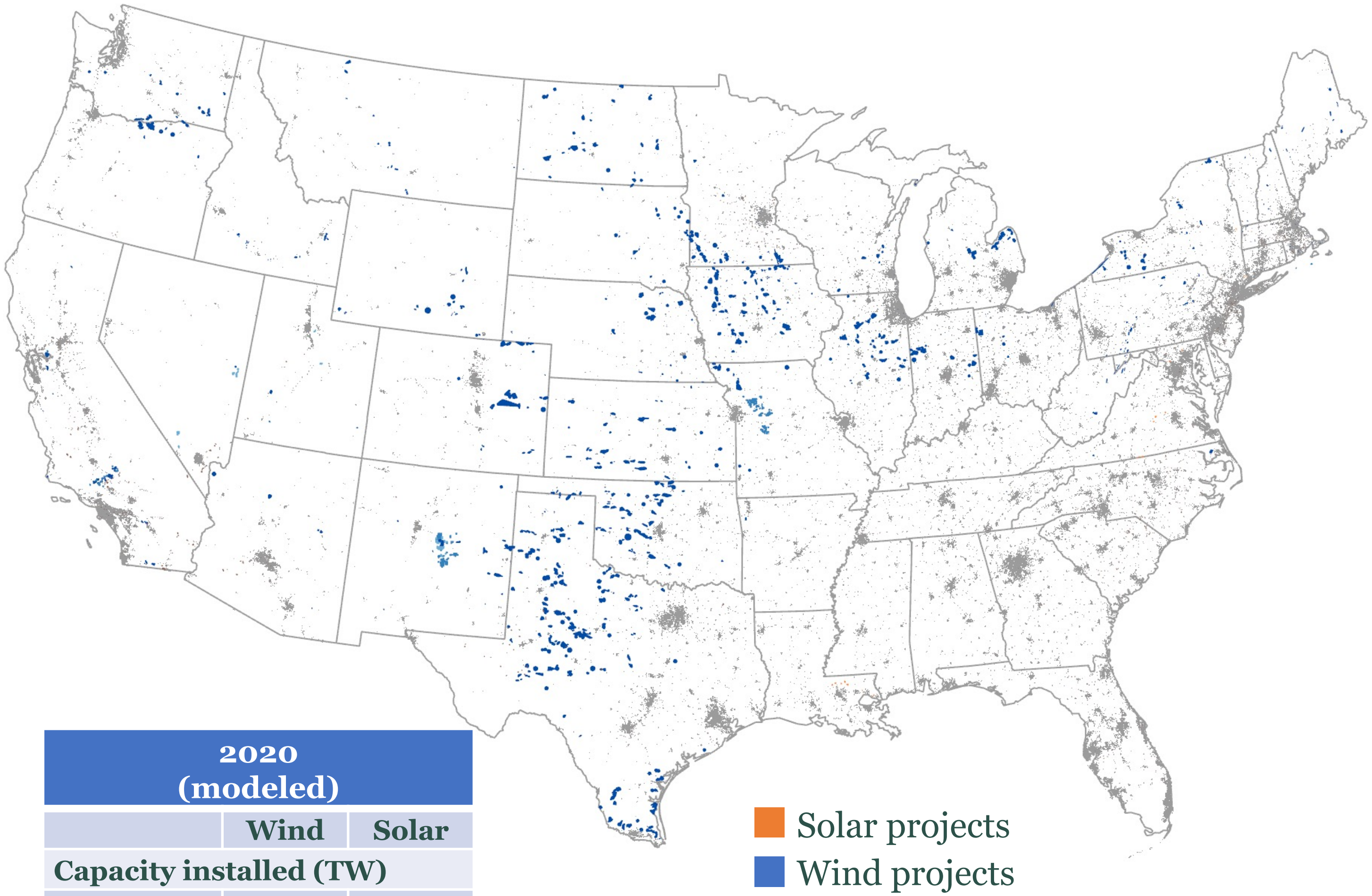
Appendix B Contents

E+ Base 2020

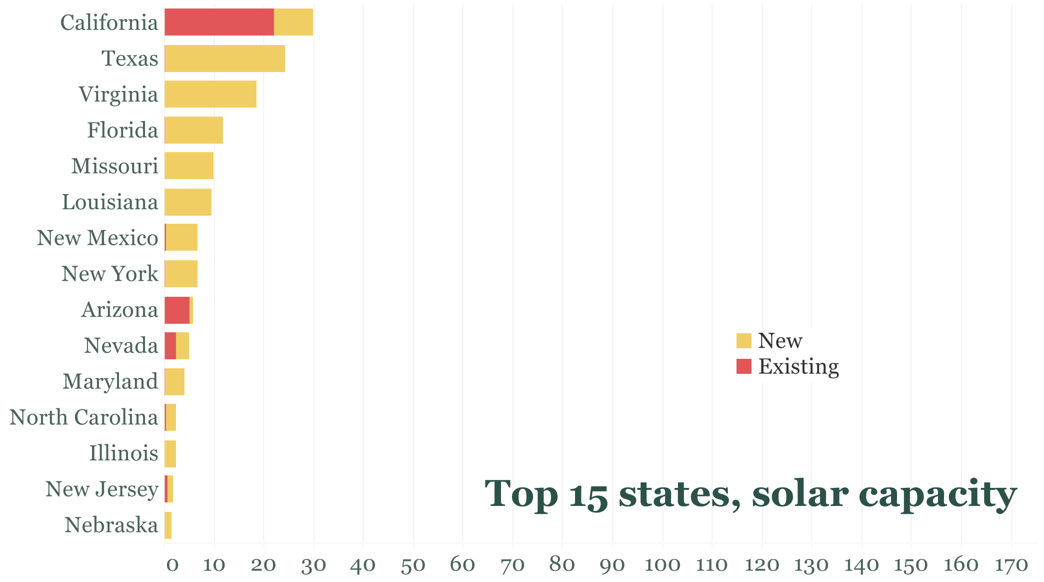


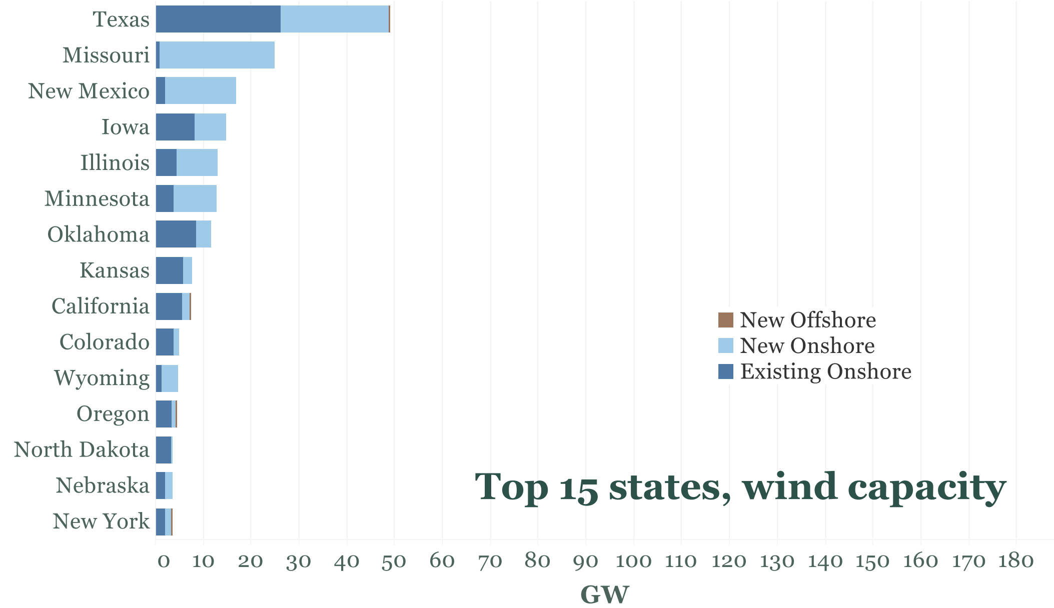


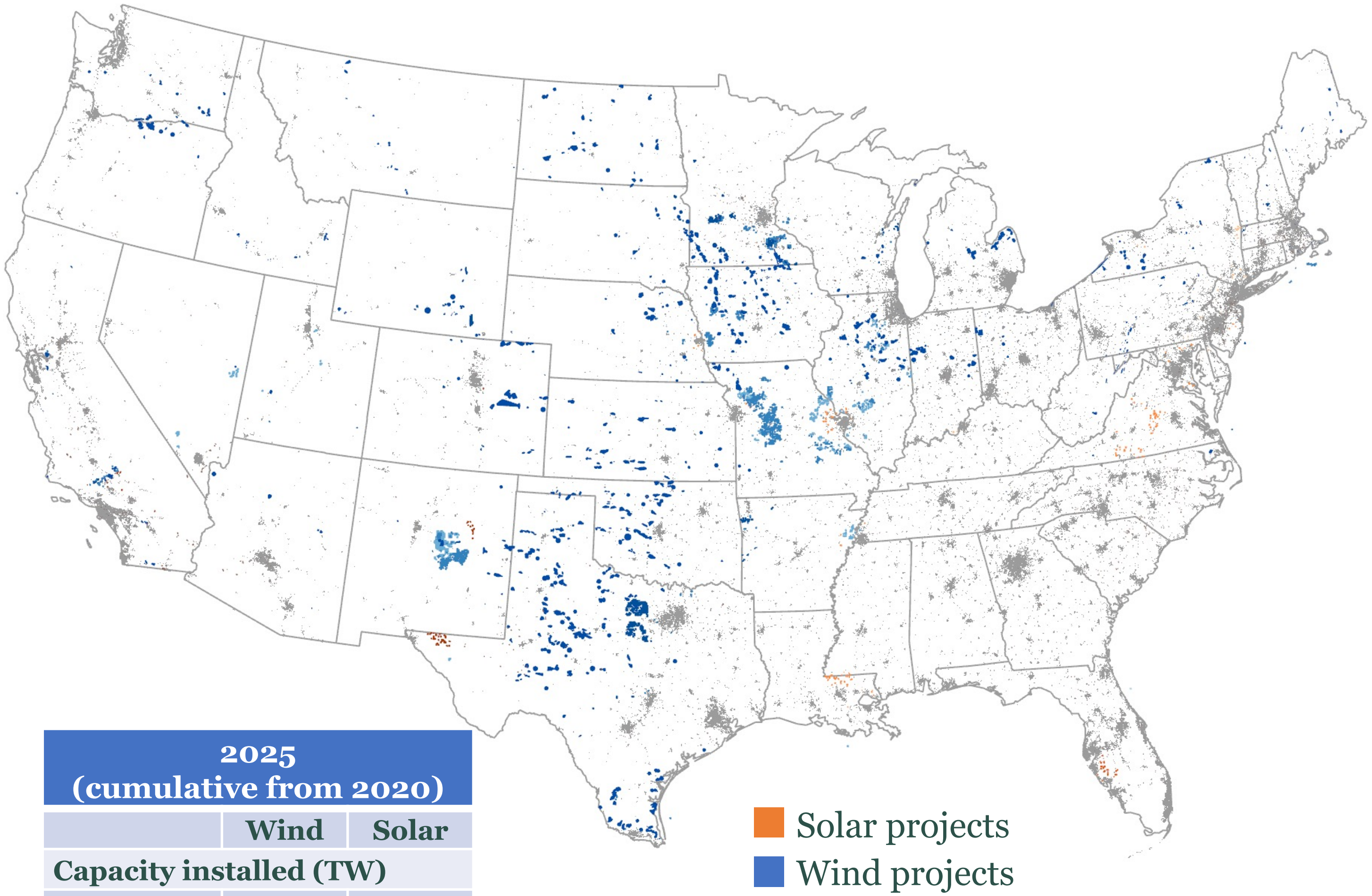
2020 (modeled)		
	Wind	**Solar**
Capacity installed (TW)		
	0.13	0.07
Land area (1000 km²)		
Total	58	1.08
Direct	0.6	0.98
Capital invested (2018$)		
Trillion $	0.06	0.05

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ Base 2025



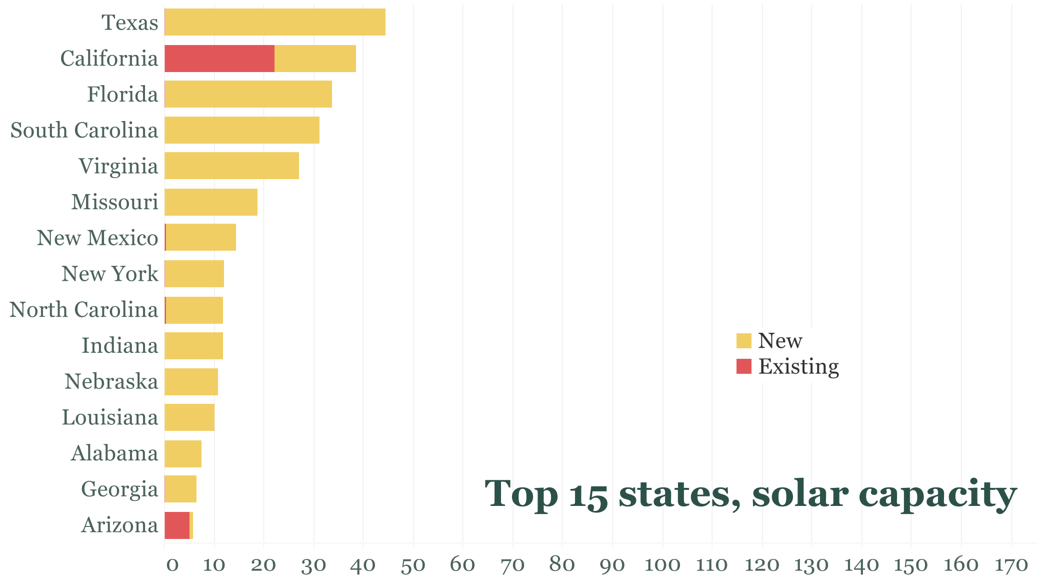


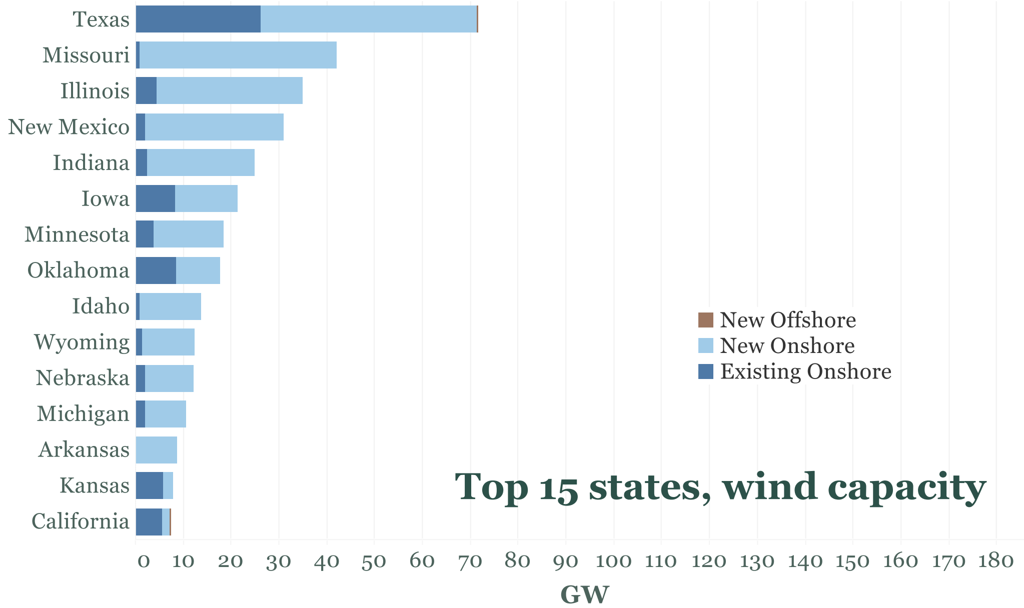


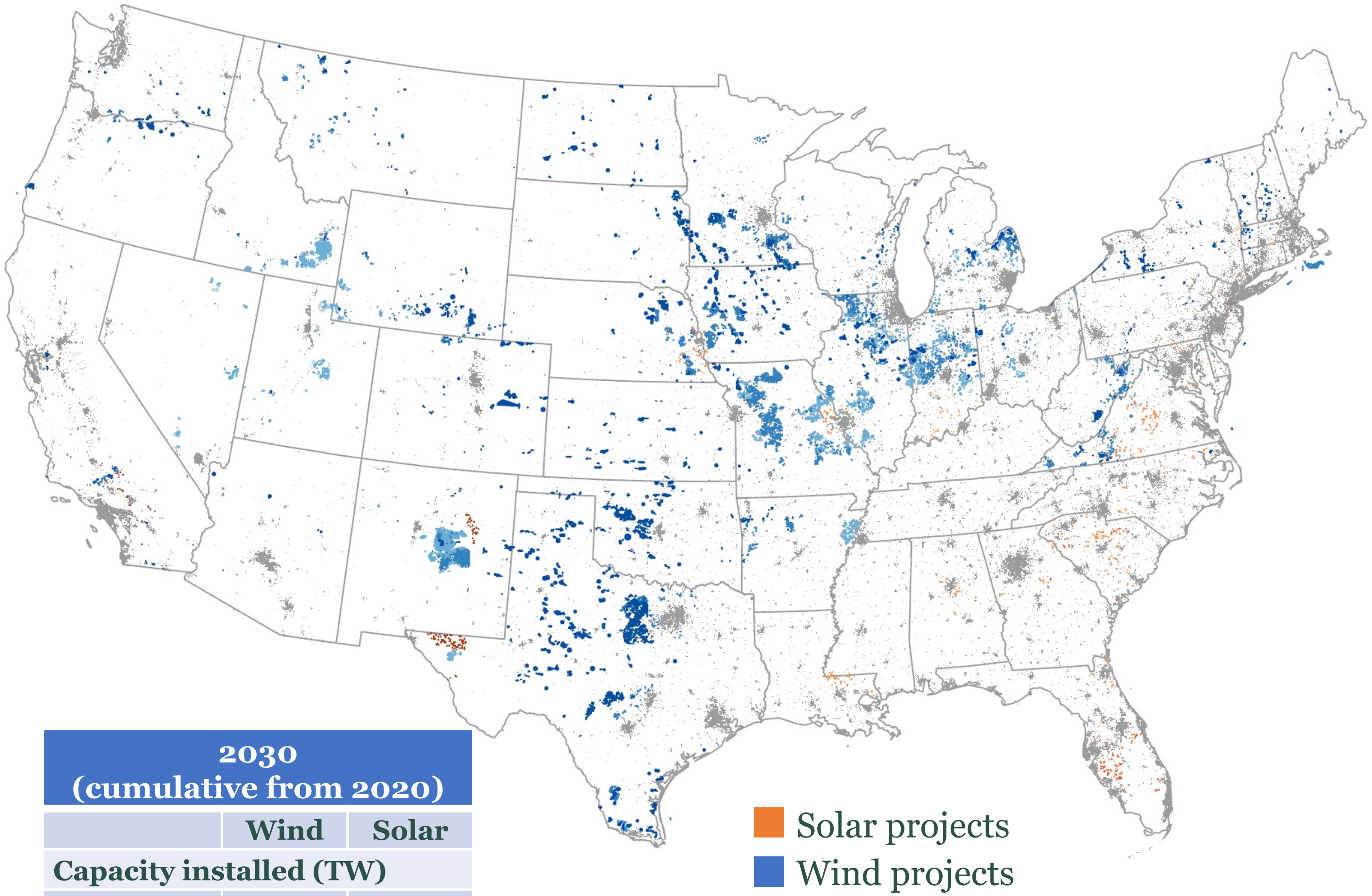
2025 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.21	0.15
Land area (1000 km²)		
Total	82	3.31
Direct	0.82	3.01
Capital invested (2018$)		
Trillion $	0.17	0.16

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ Base, 2030



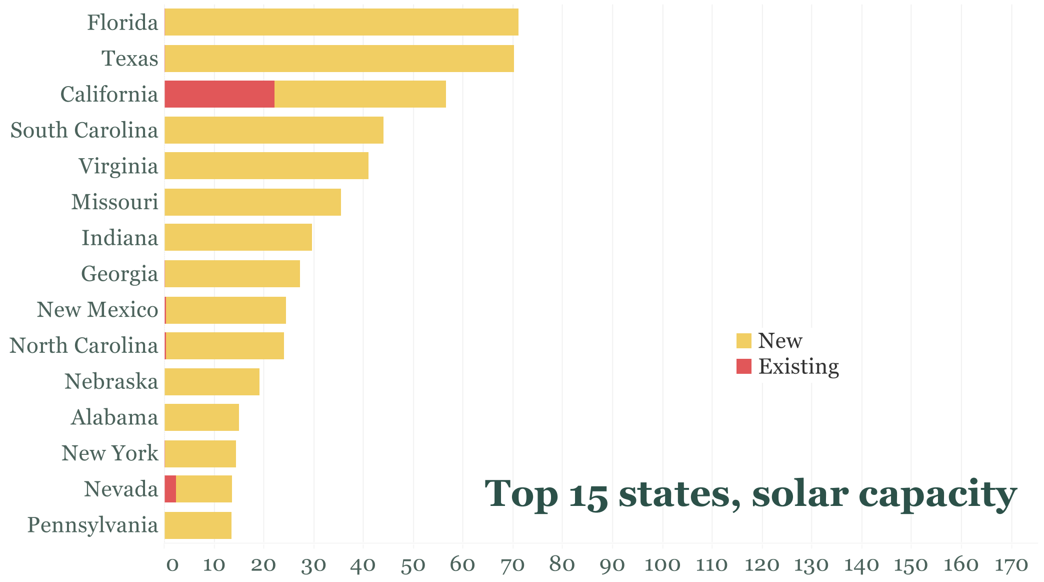


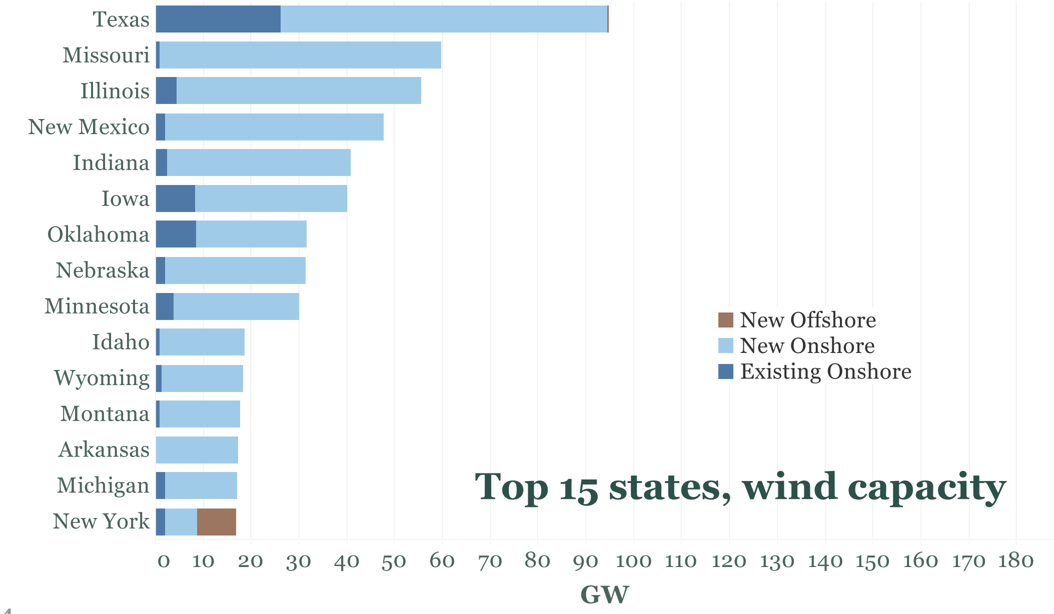


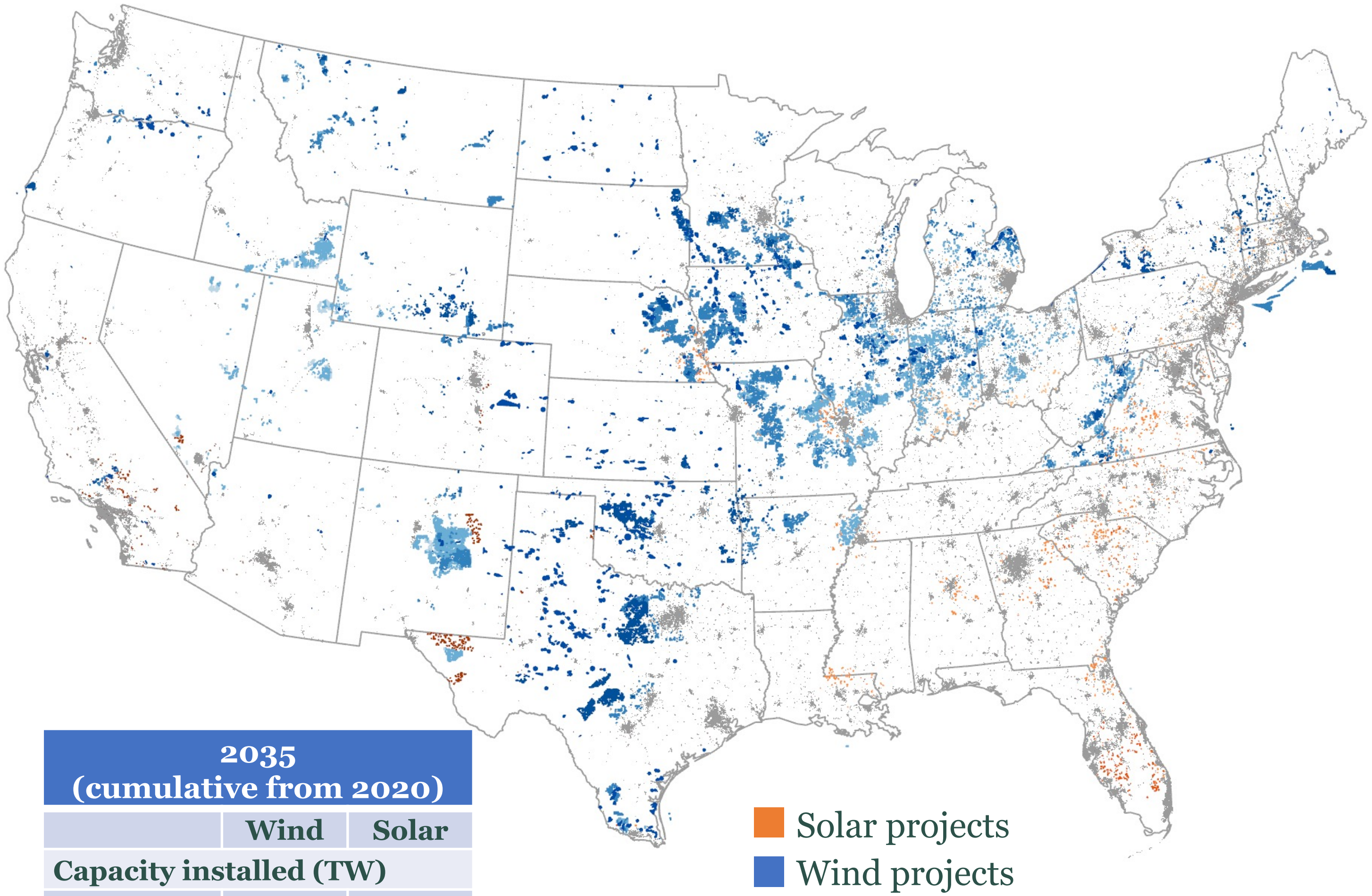
2030 (cumulative from 2020)		
	Wind	Solar
Capacity installed (TW)		
	0.42	0.32
Land area (1000 km²)		
Total	157	7.75
Direct	1.57	7.06
Capital invested (2018$)		
Trillion $	0.44	0.35

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ Base, 2035



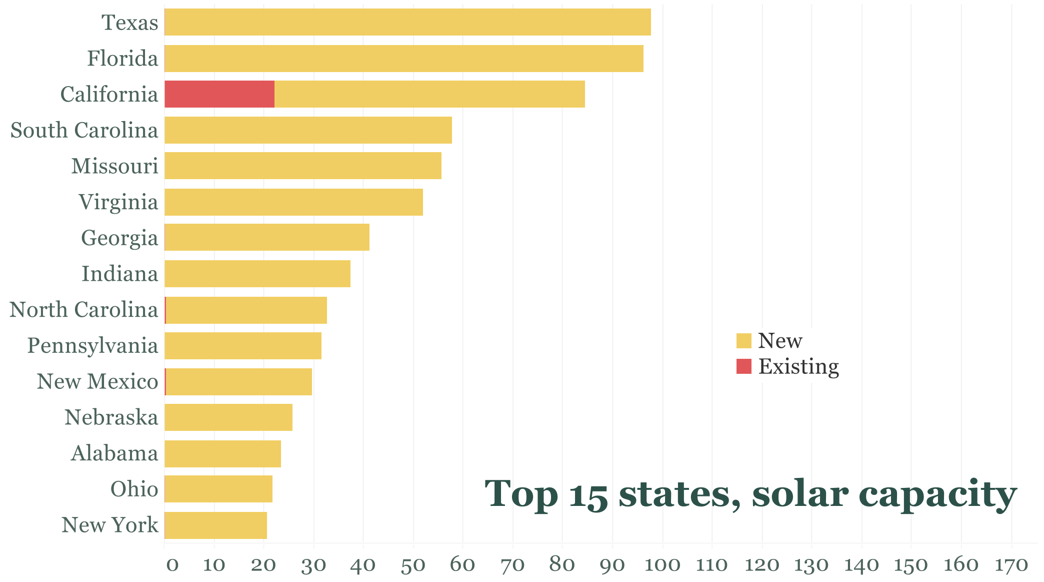


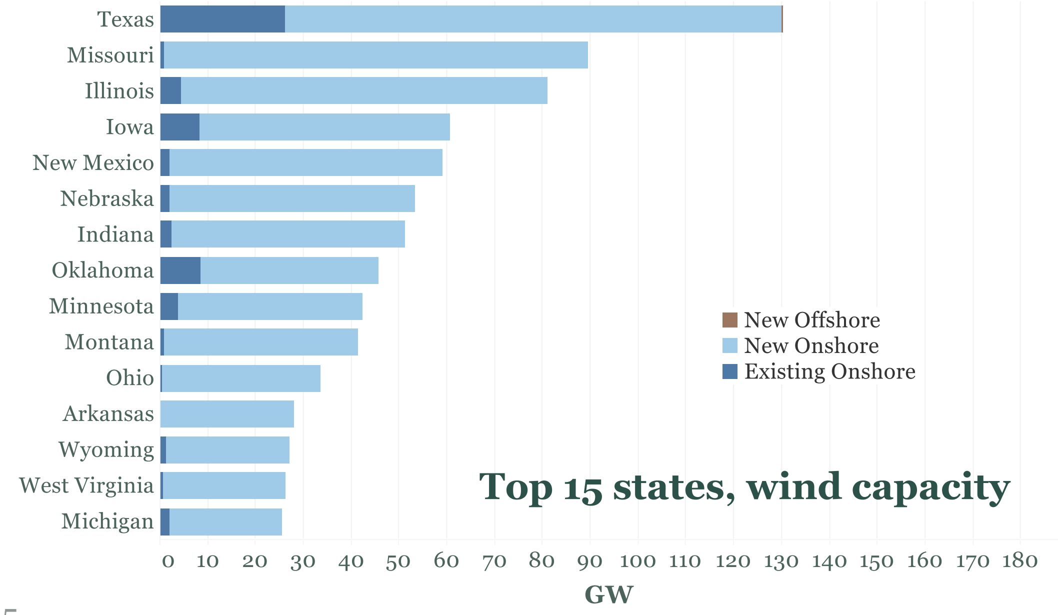


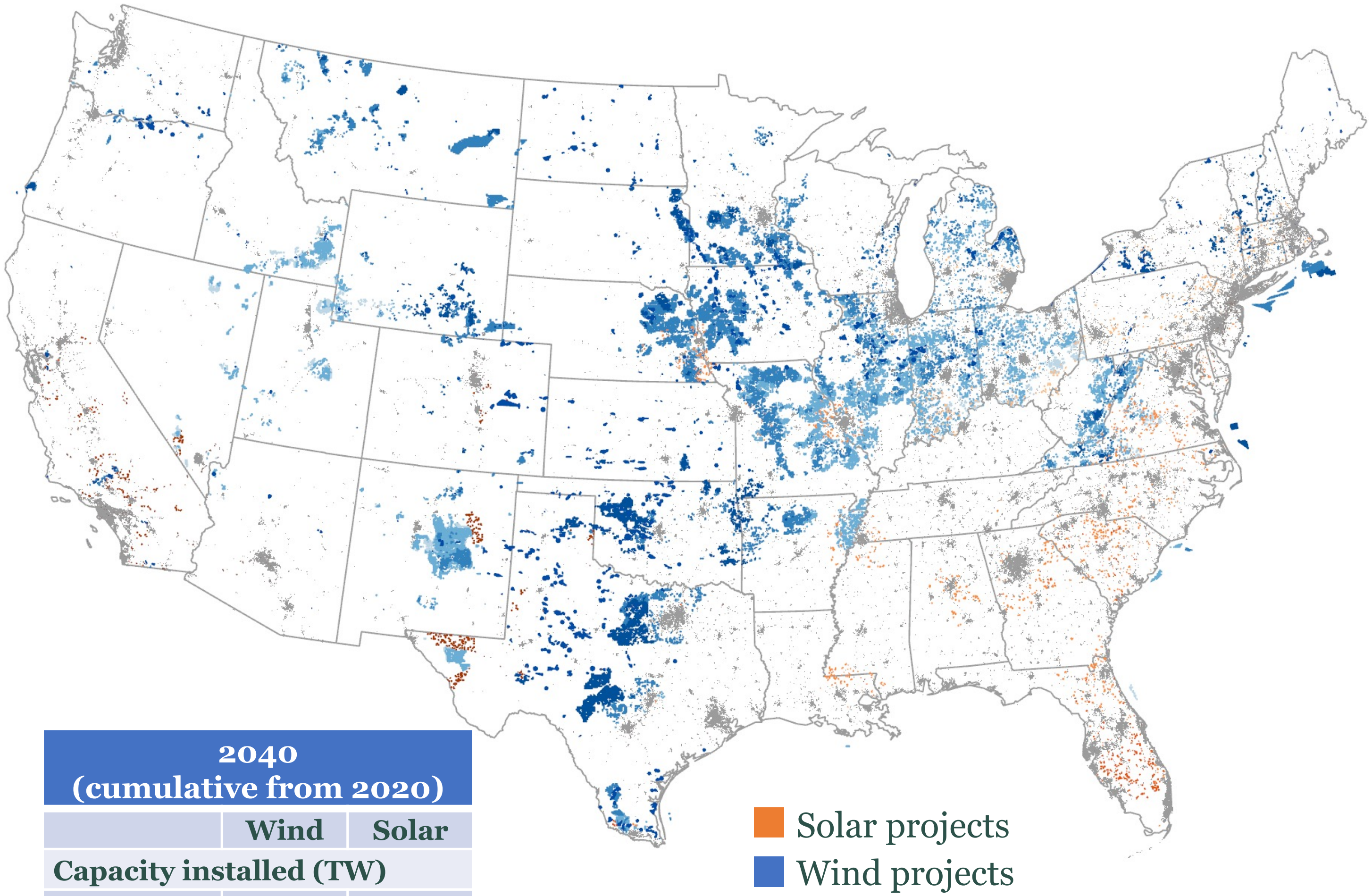
2035 (cumulative from 2020)		
	Wind	Solar
Capacity installed (TW)		
	0.67	0.59
Land area (1000 km²)		
Total	245	14.7
Direct	2.45	13.4
Capital invested (2018$)		
Trillion $	0.77	0.64

Note: *Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).*

E+ Base, 2040



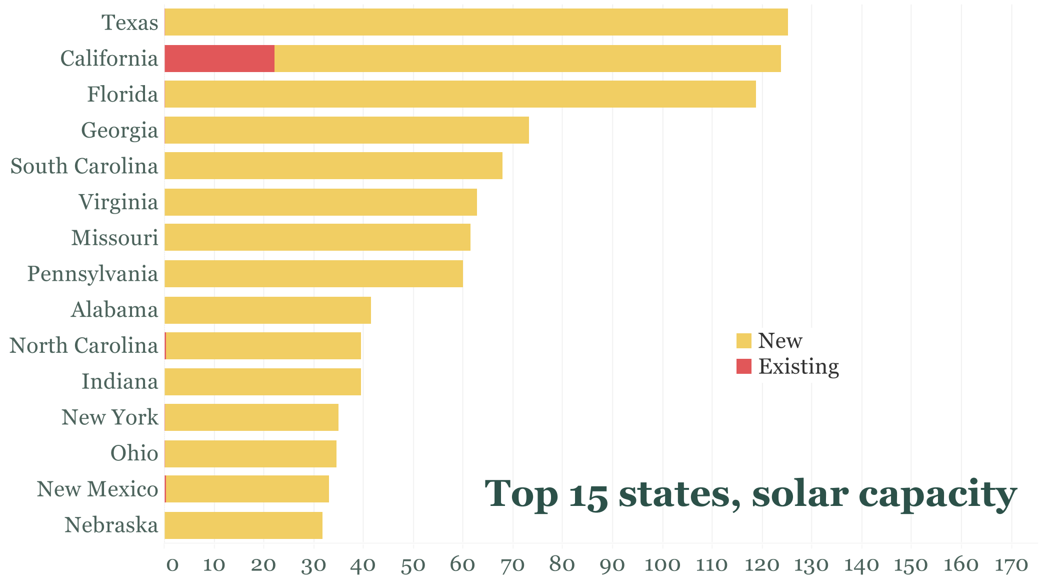


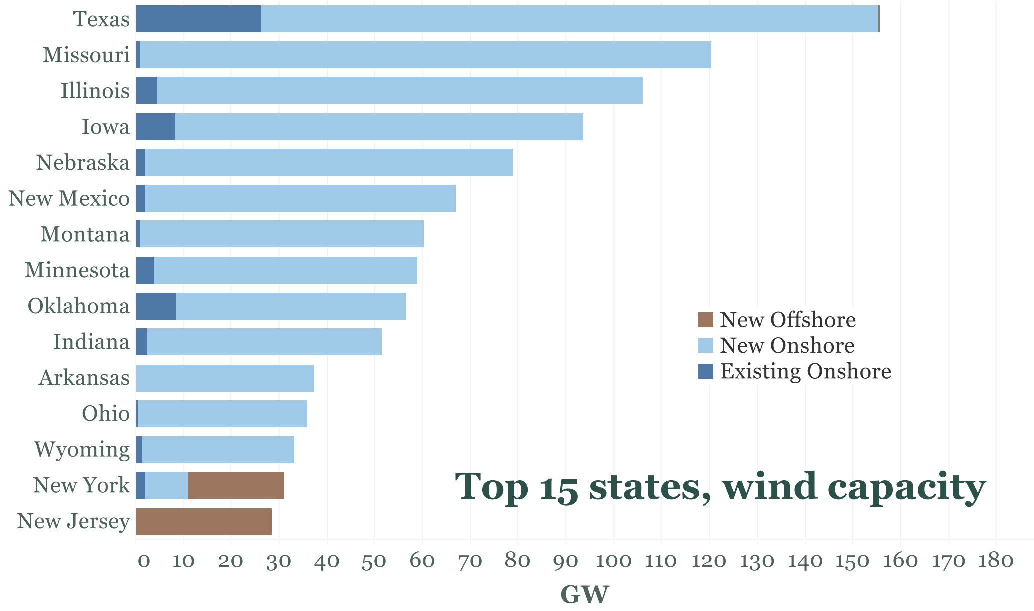


2040 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.99	0.85
Land area (1000 km²)		
Total	355	21.5
Direct	3.55	19.6
Capital invested (2018$)		
Trillion $	1.15	0.90

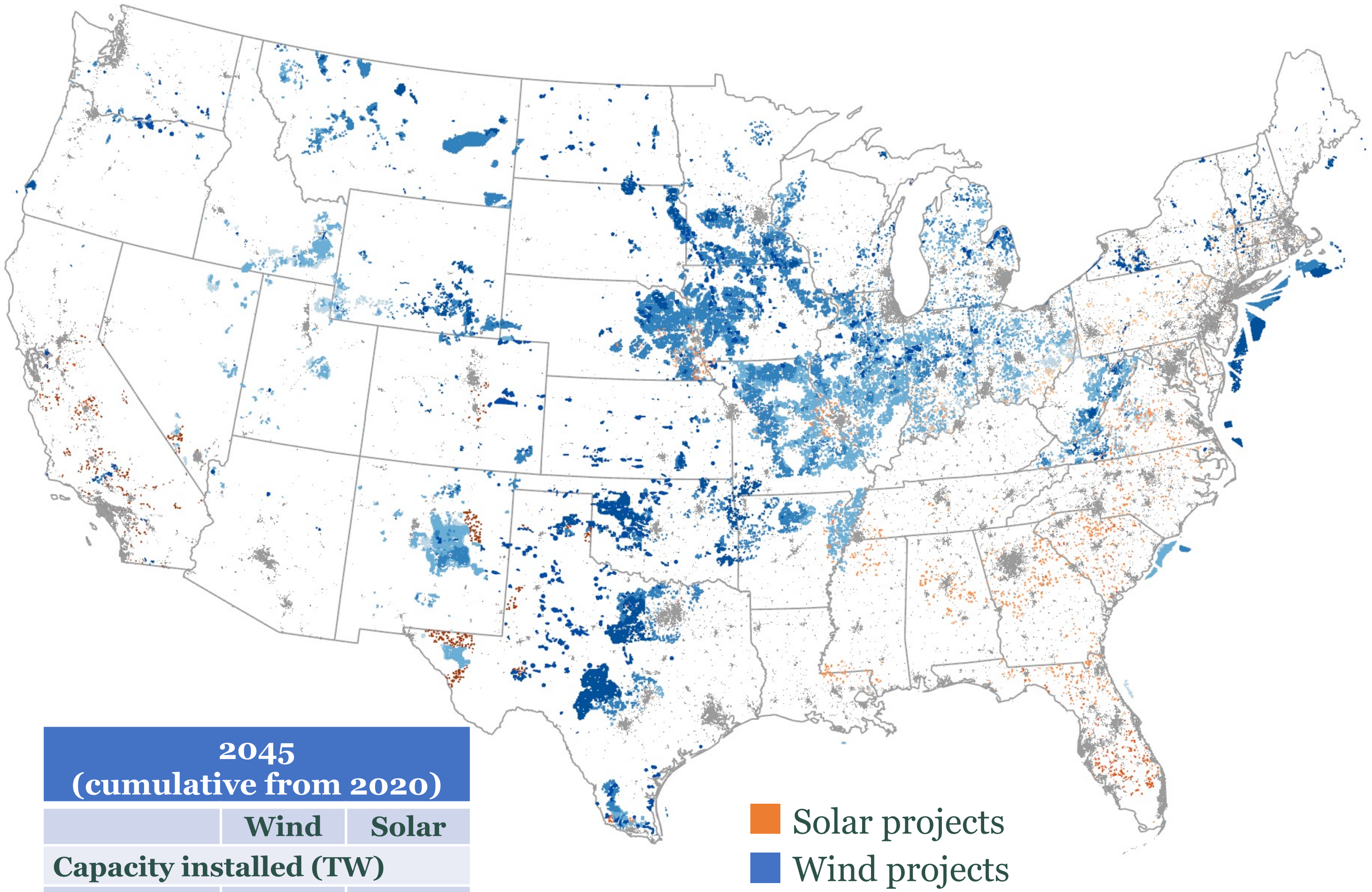
Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ Base, 2045



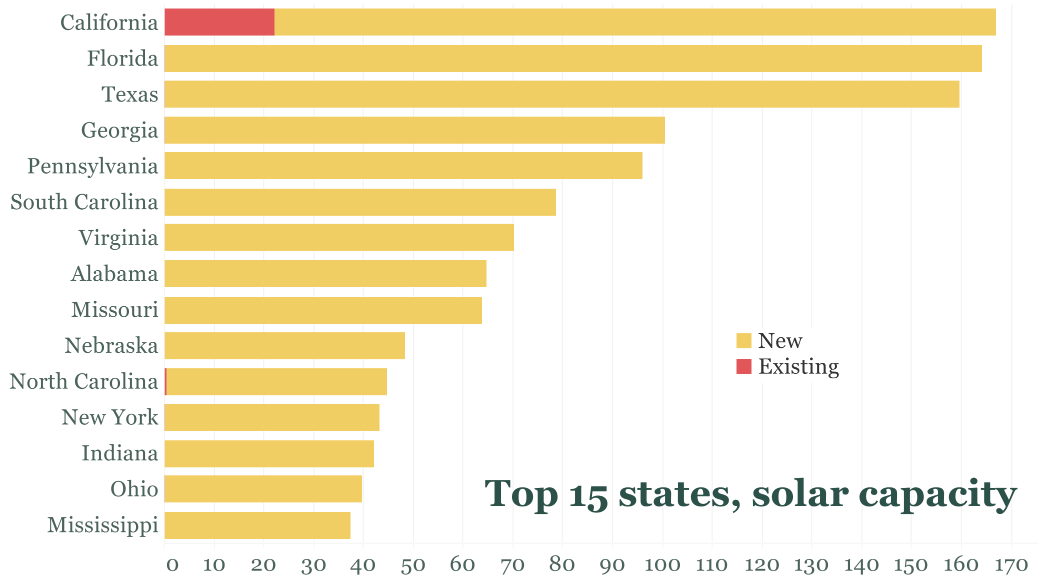


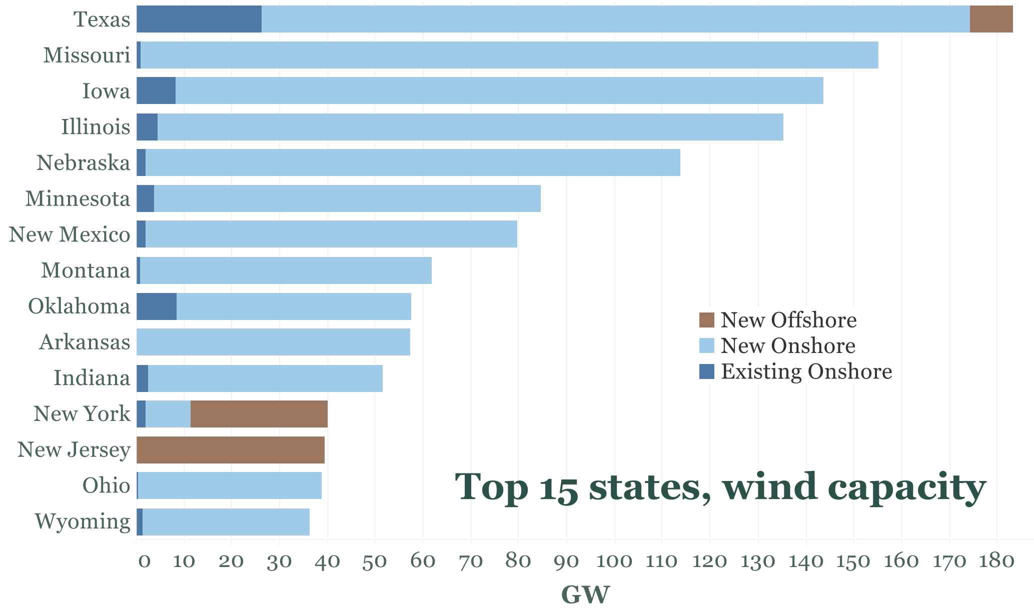
2045 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	1.30	1.15
Land area (1000 km²)		
Total	446	29.4
Direct	4.46	26.7
Capital invested (2018$)		
Trillion $	1.51	1.18

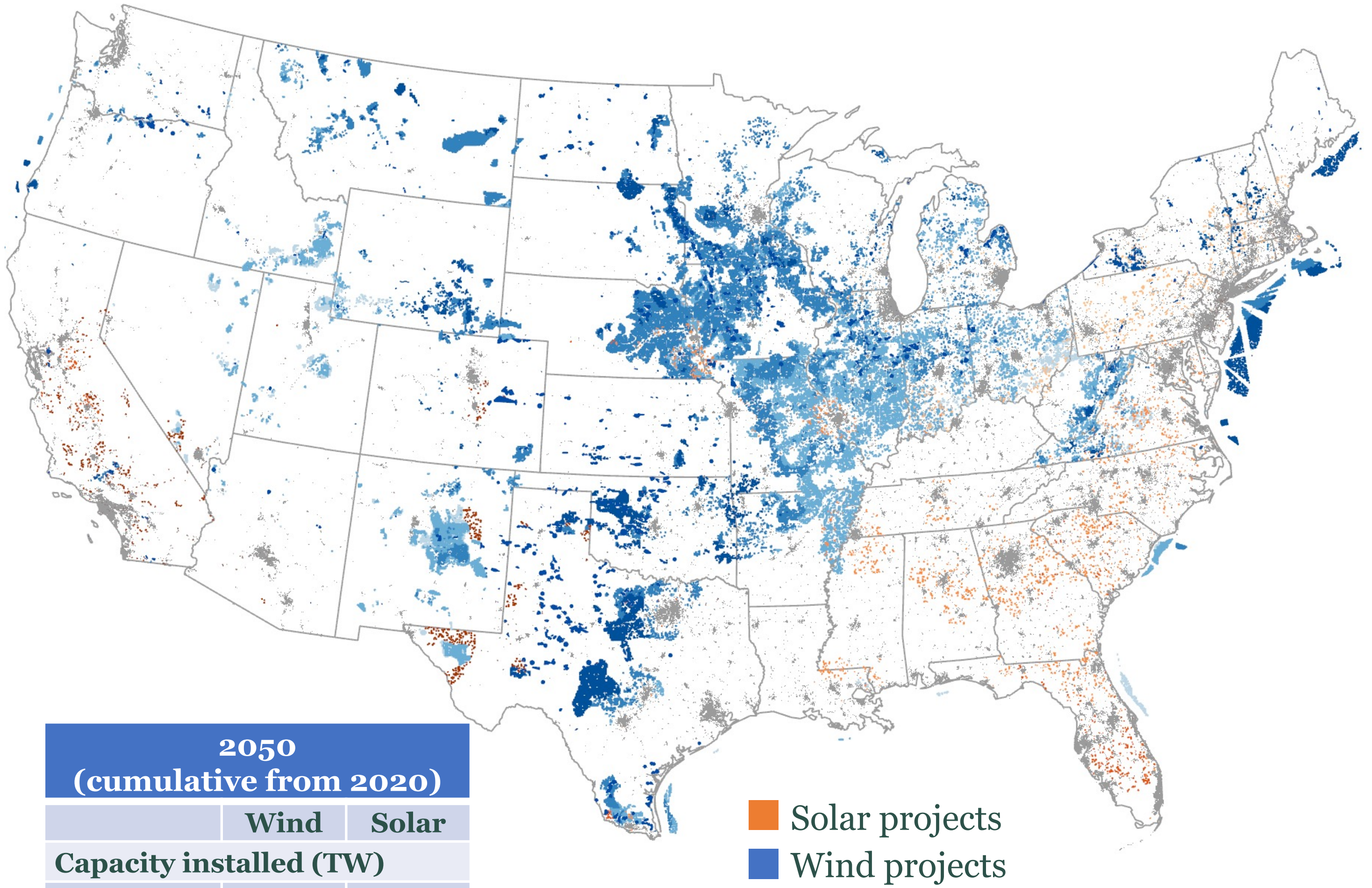


Note: *Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).*

E+ Base, 2050



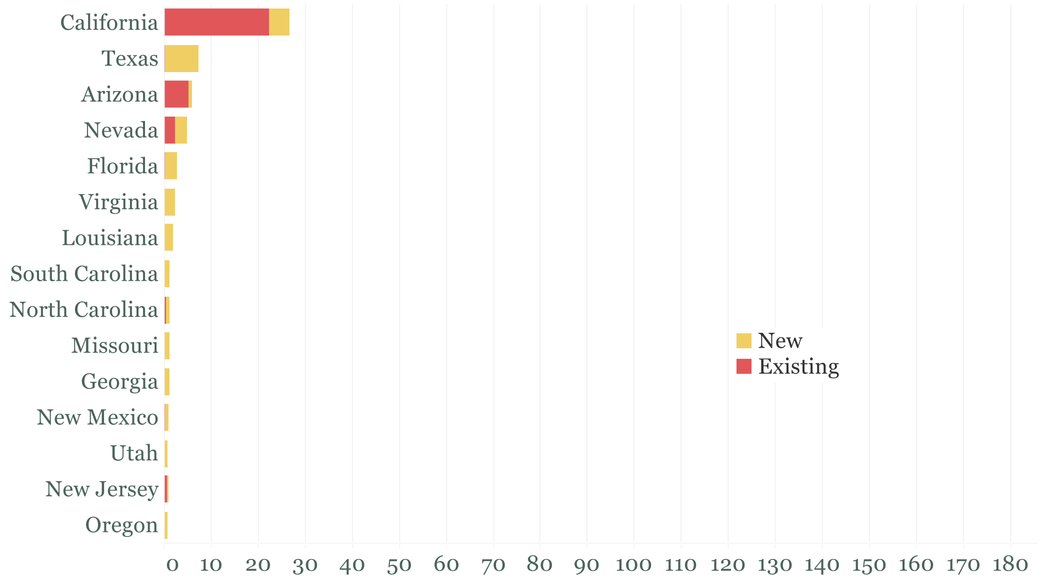


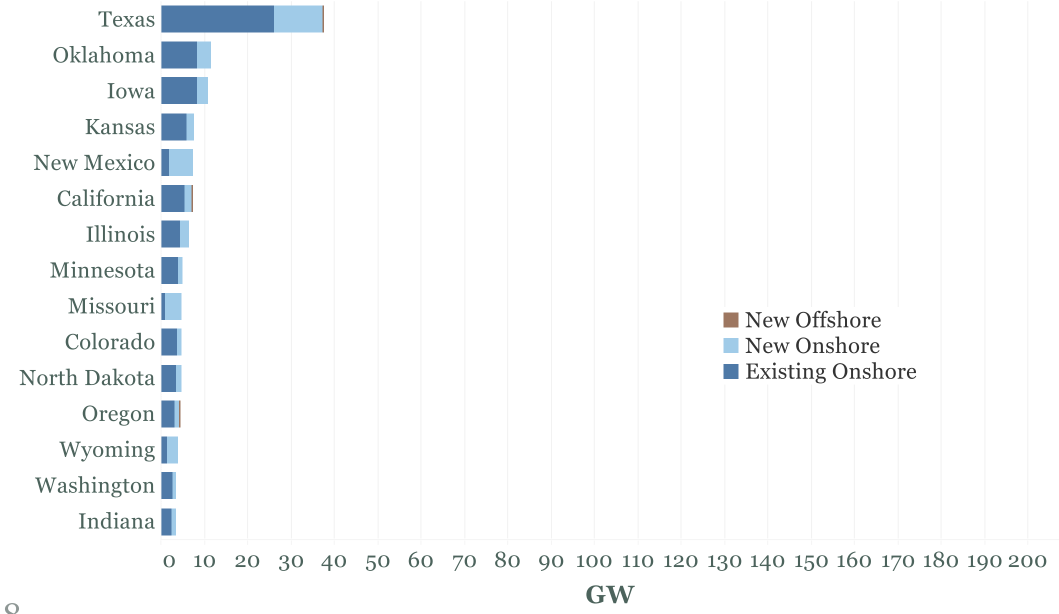


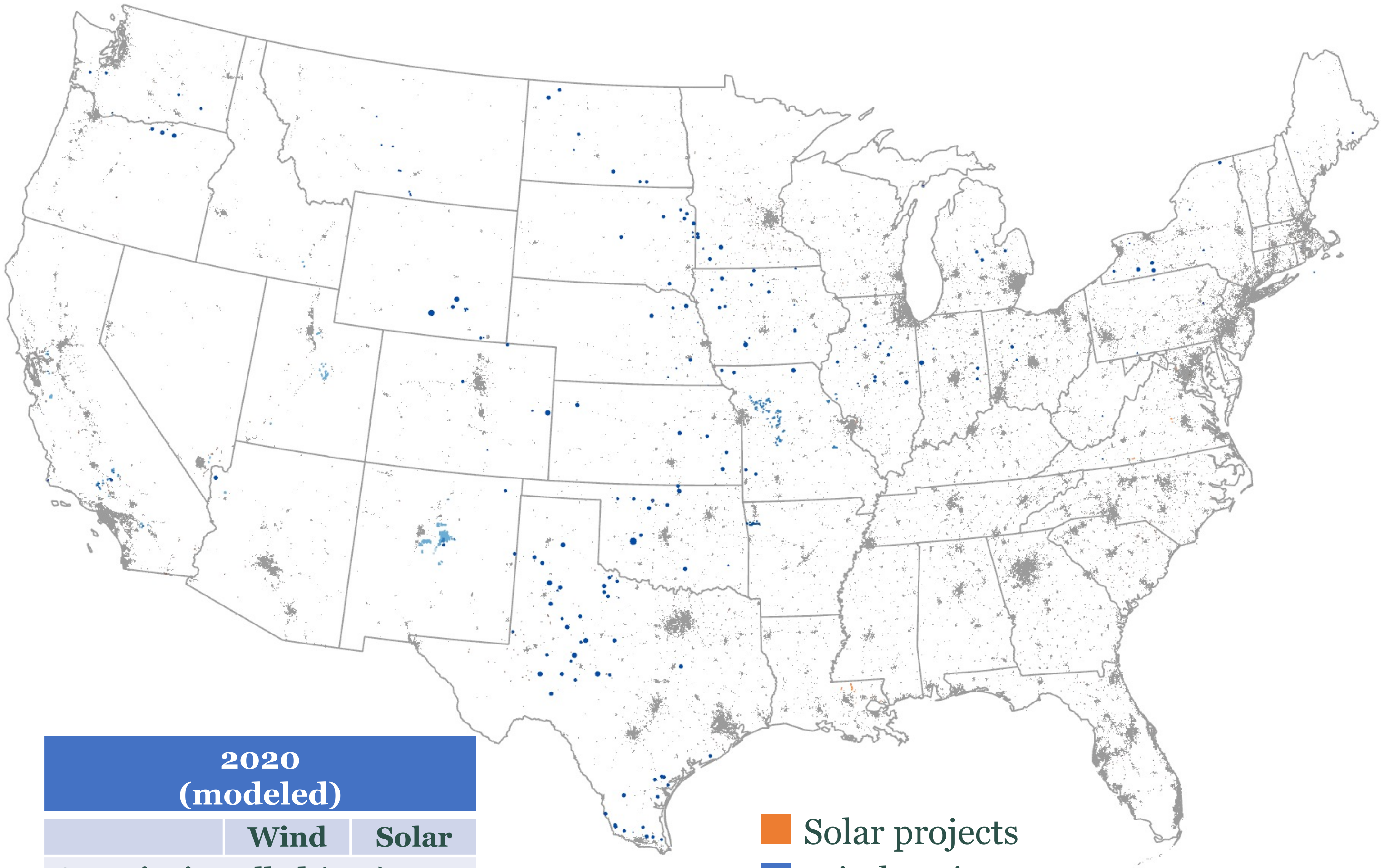
2050 (cumulative from 2020)		
	Wind	Solar
Capacity installed (TW)		
	1.67	1.50
Land area (1000 km²)		
Total	551	38.3
Direct	5.51	34.9
Capital invested (2018$)		
Trillion $	1.91	1.49

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ Constrained, 2020



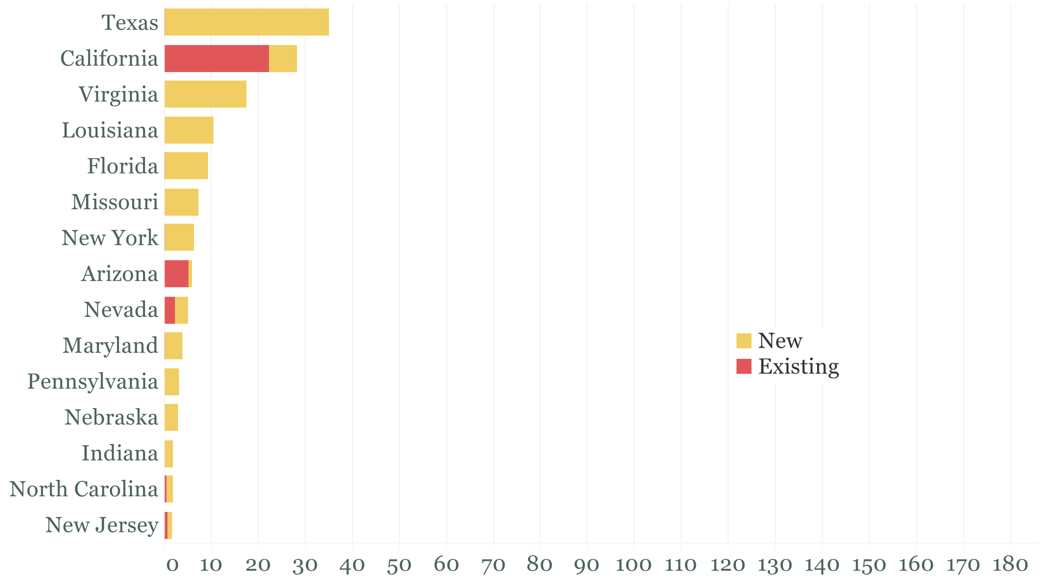


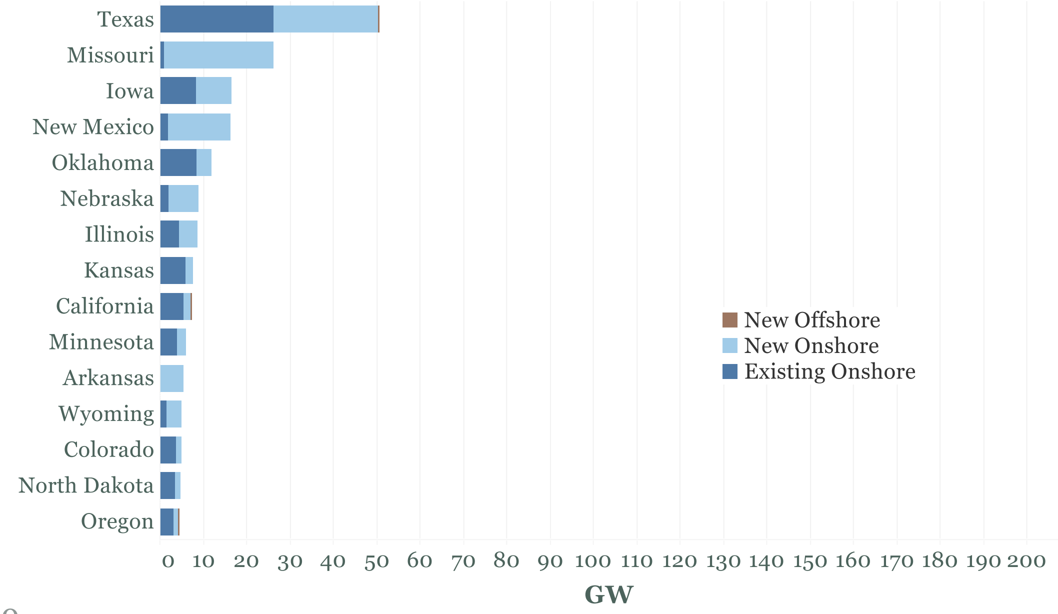


2020 (modeled)		
	Wind	**Solar**
Capacity installed (TW)		
	0.15	0.07
Land area (1000 km²)		
Total	55	0.94
Direct	0.55	0.85
Capital invested (2018$)		
Trillion $	0.08	0.04

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ Constrained, 2025





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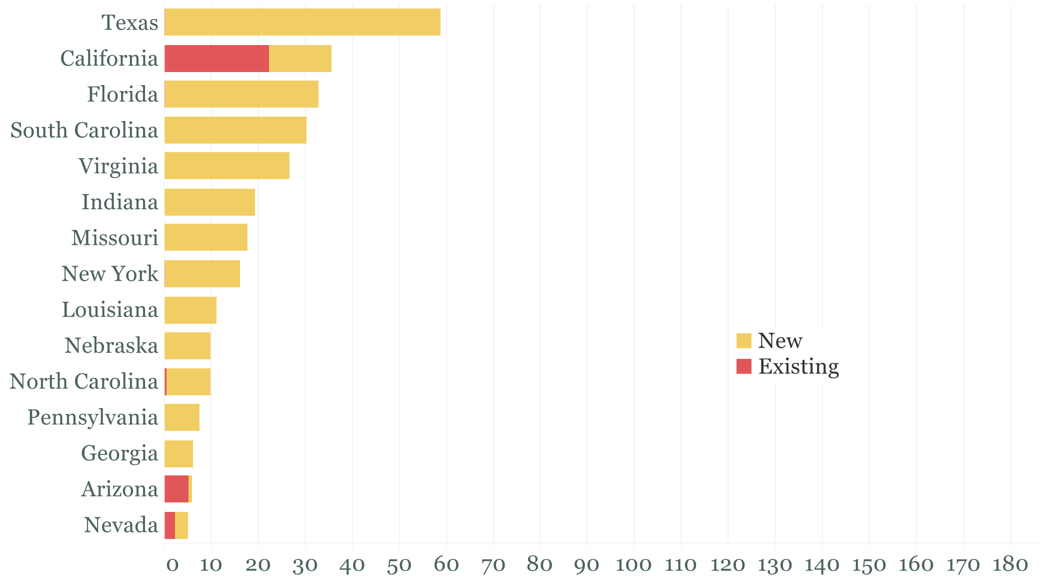
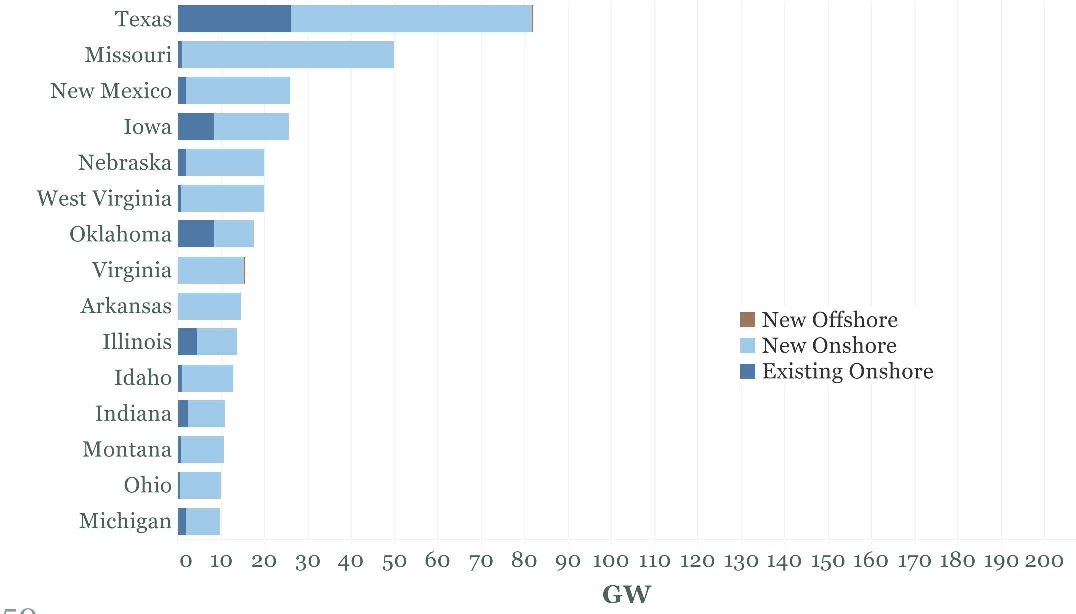
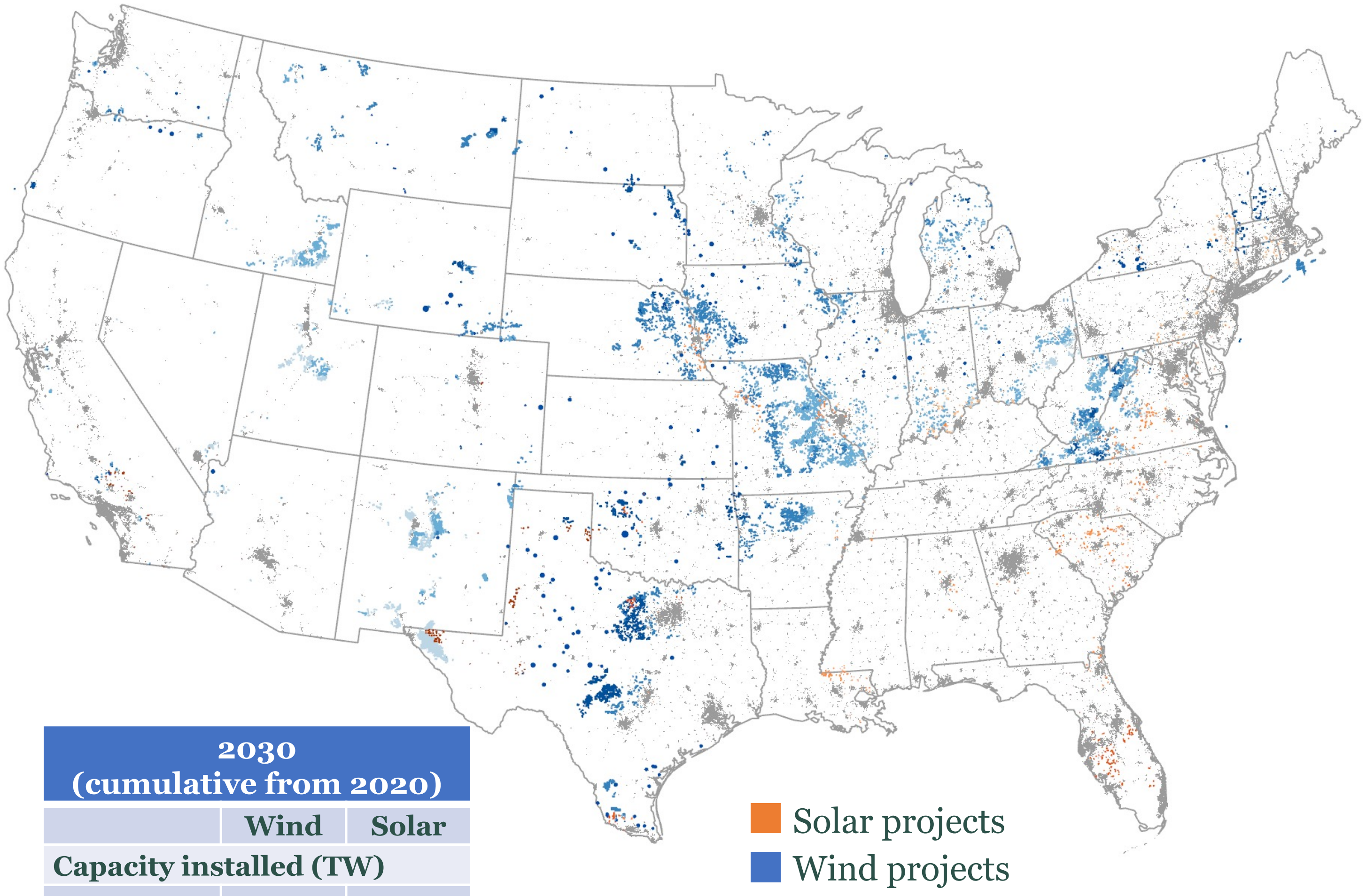
2025 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.21	0.15
Land area (1000 km²)		
Total	80	3.23
Direct	0.80	2.94
Capital invested (2018$)		
Trillion $	0.17	0.16

Solar projects
Wind projects

E+ Constrained, 2030



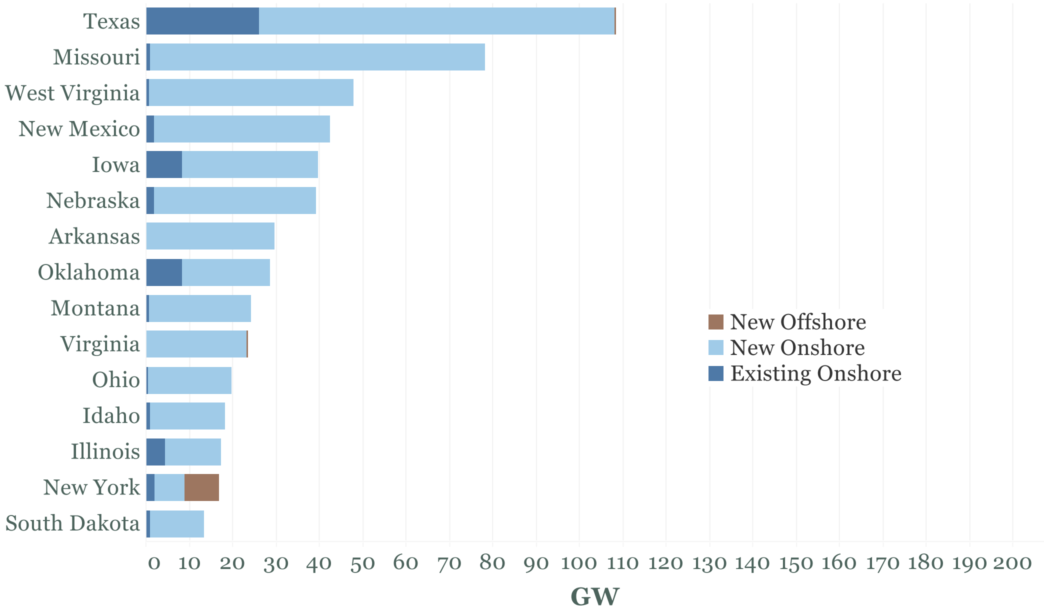




2030 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.43	0.34
Land area (1000 km²)		
Total	158	8.02
Direct	1.58	7.30
Capital invested (2018$)		
Trillion $	0.46	0.37

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ Constrained, 2035



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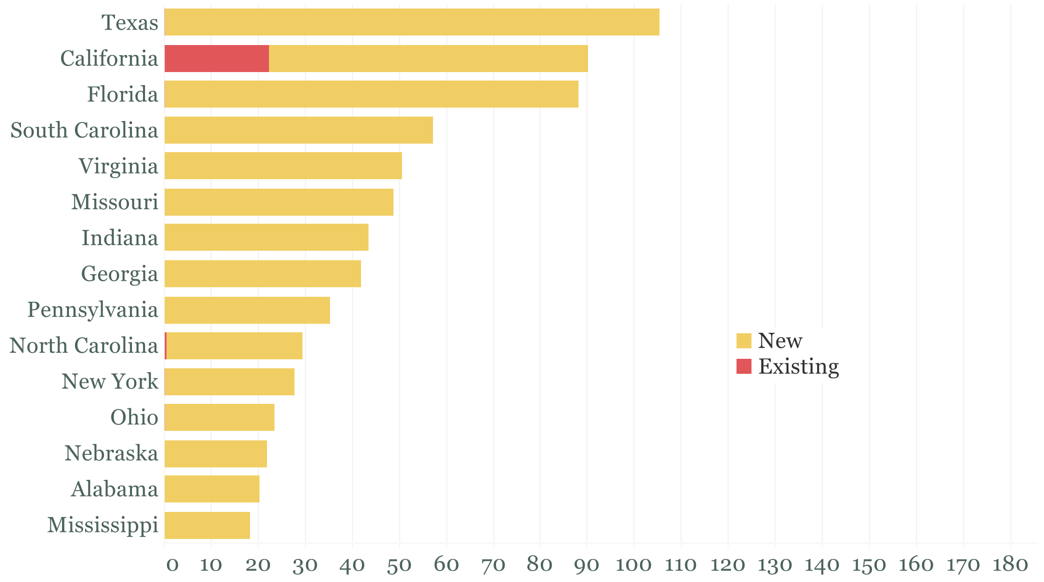
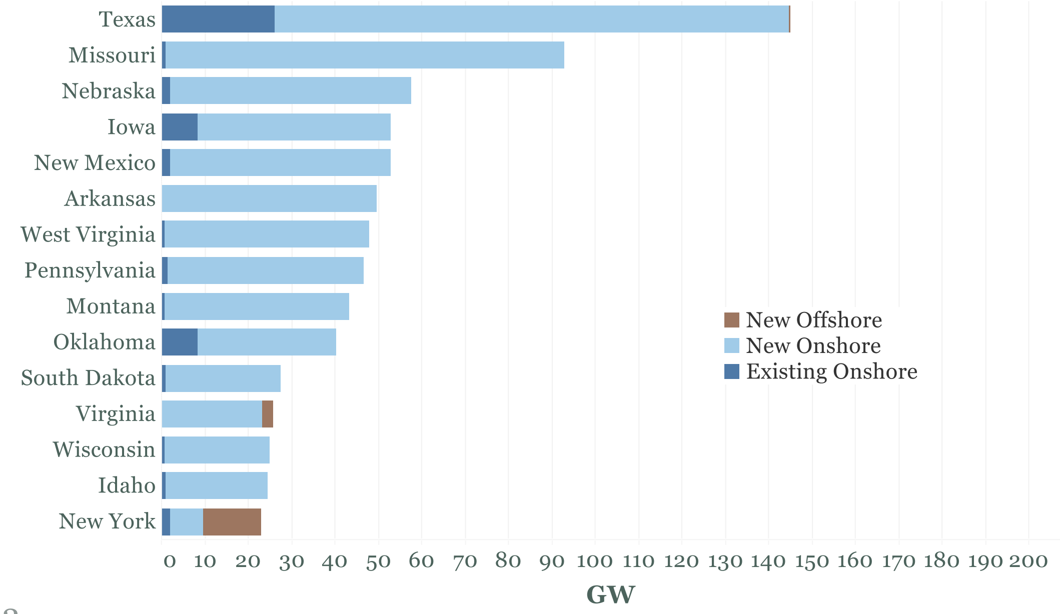
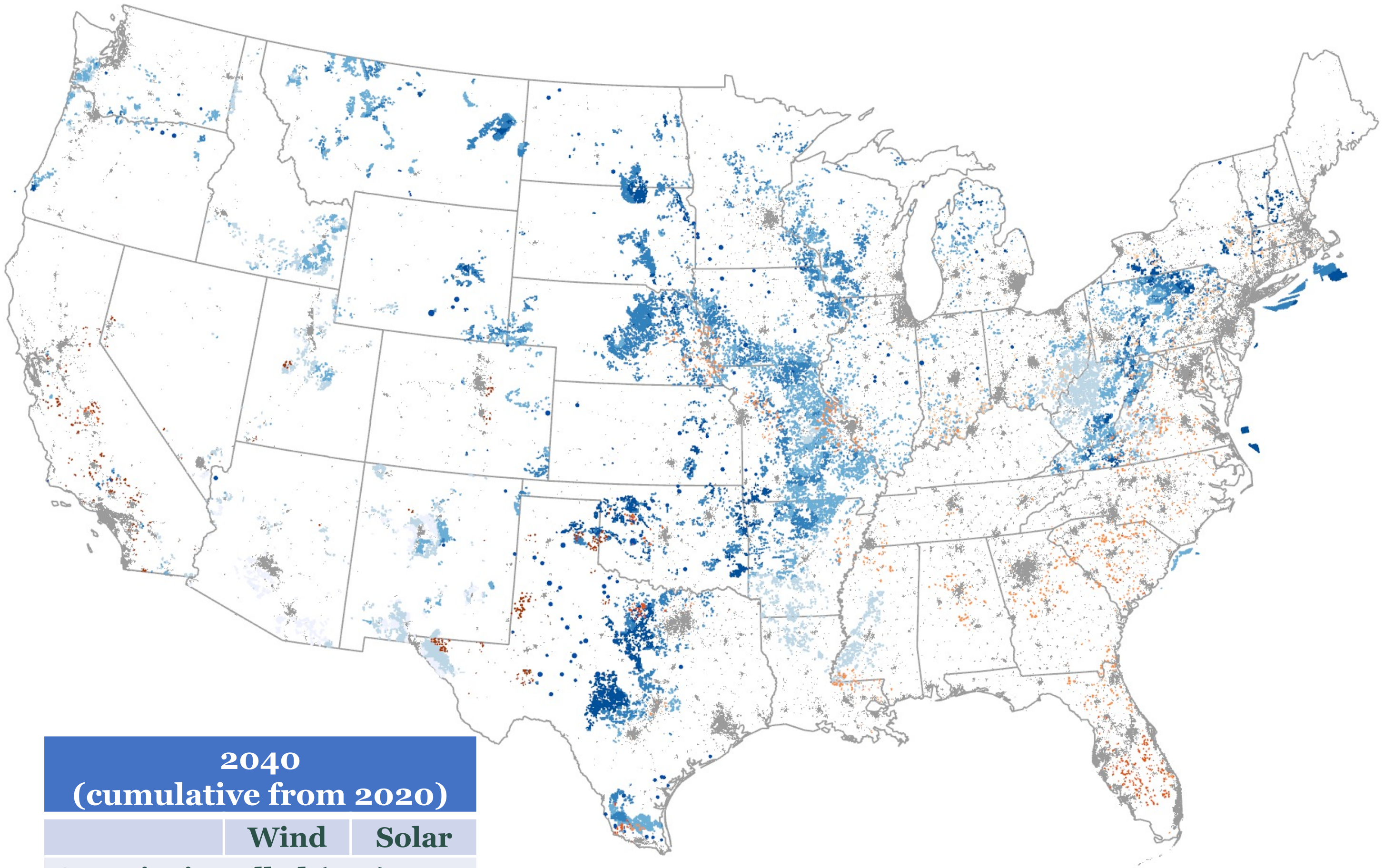
2035 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.70	0.59
Land area (1000 km²)		
Total	254	14.5
Direct	2.54	13.2
Capital invested (2018$)		
Trillion $	0.81	0.63

Solar projects
Wind projects

E+ Constrained, 2040



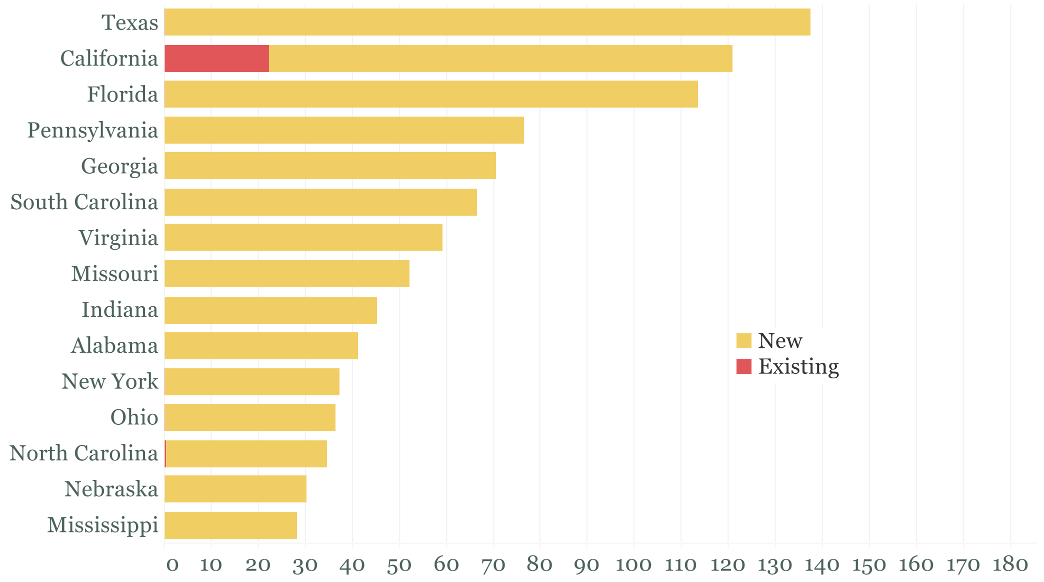


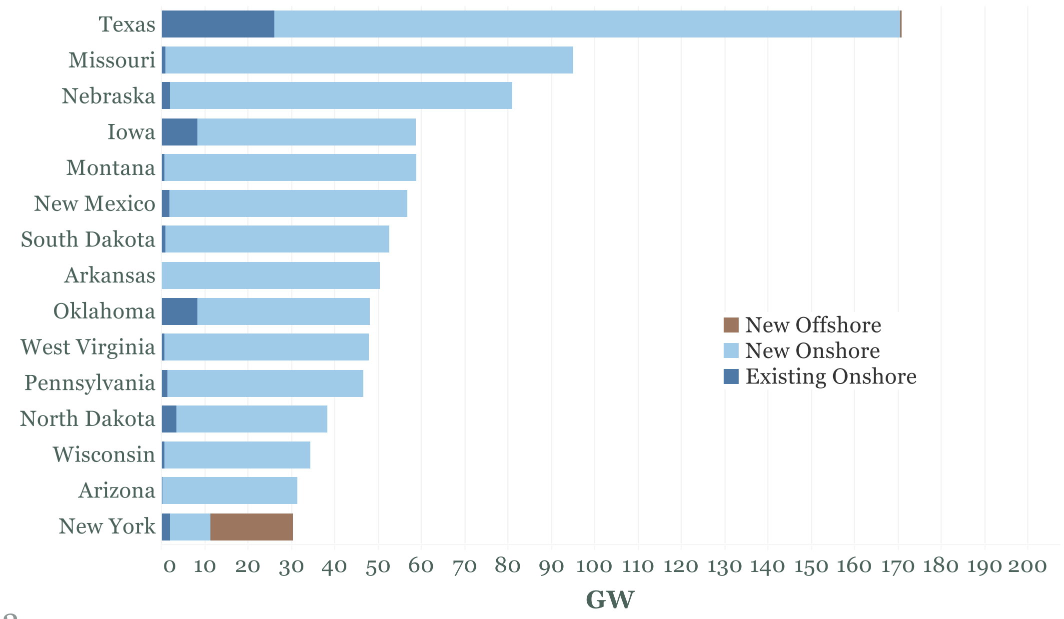


2040 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	1.01	0.85
Land area (1000 km²)		
Total	362	21.3
Direct	3.62	19.4
Capital invested (2018$)		
Trillion $	1.23	0.89

Note: *Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).*

E+ Constrained, 2045





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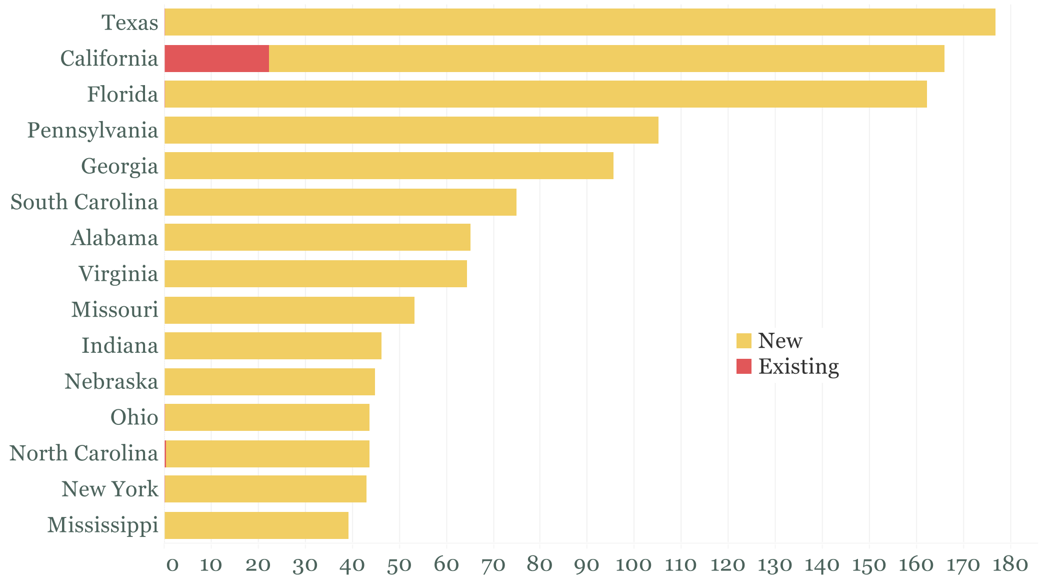
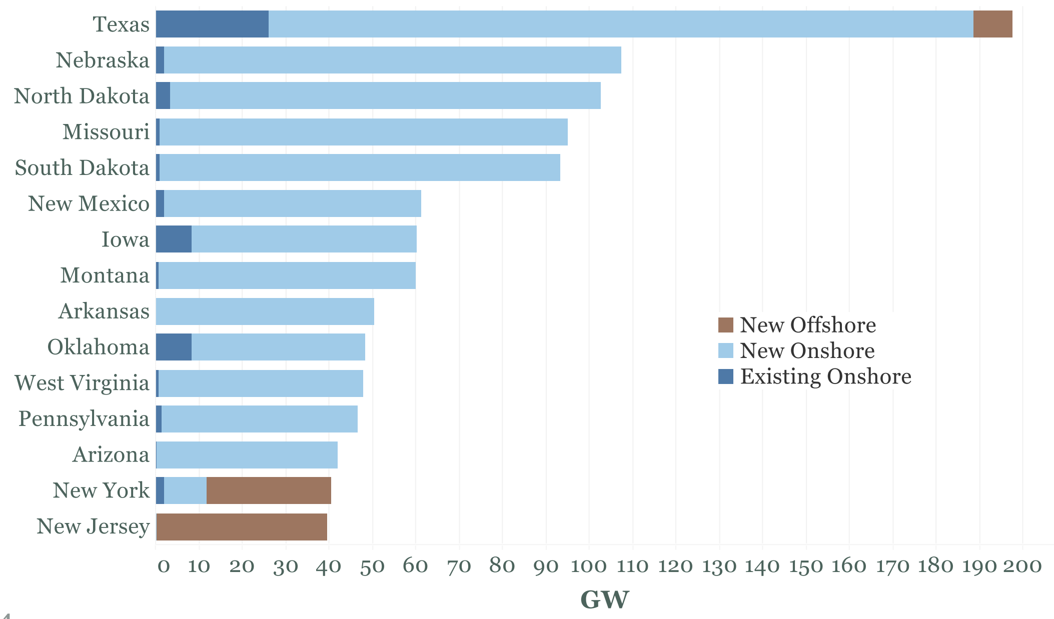
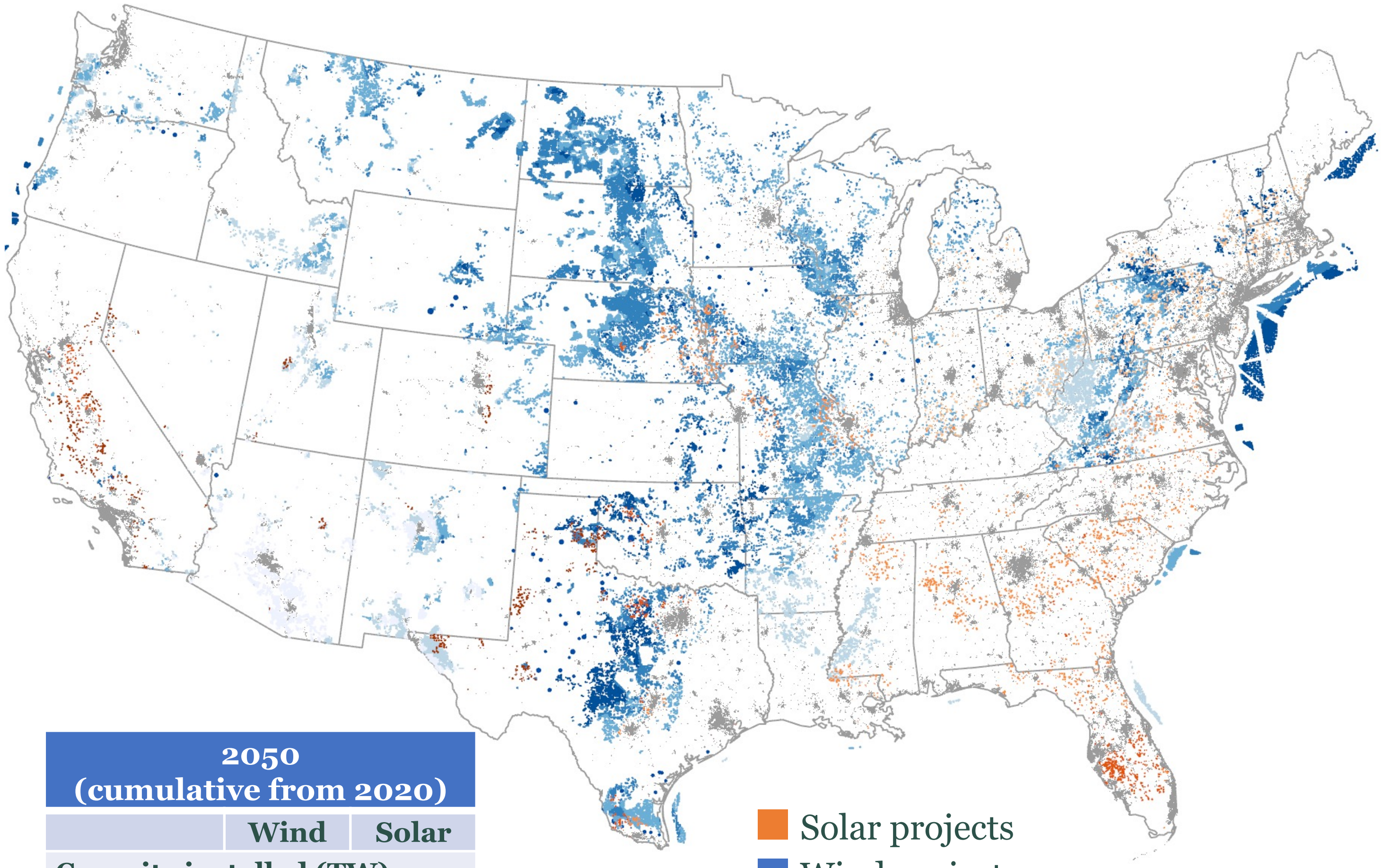
2045 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	1.25	1.15
Land area (1000 km²)		
Total	434	29.2
Direct	4.34	26.5
Capital invested (2018$)		
Trillion $	1.51	1.18

Solar projects
Wind projects

E+ Constrained, 2050



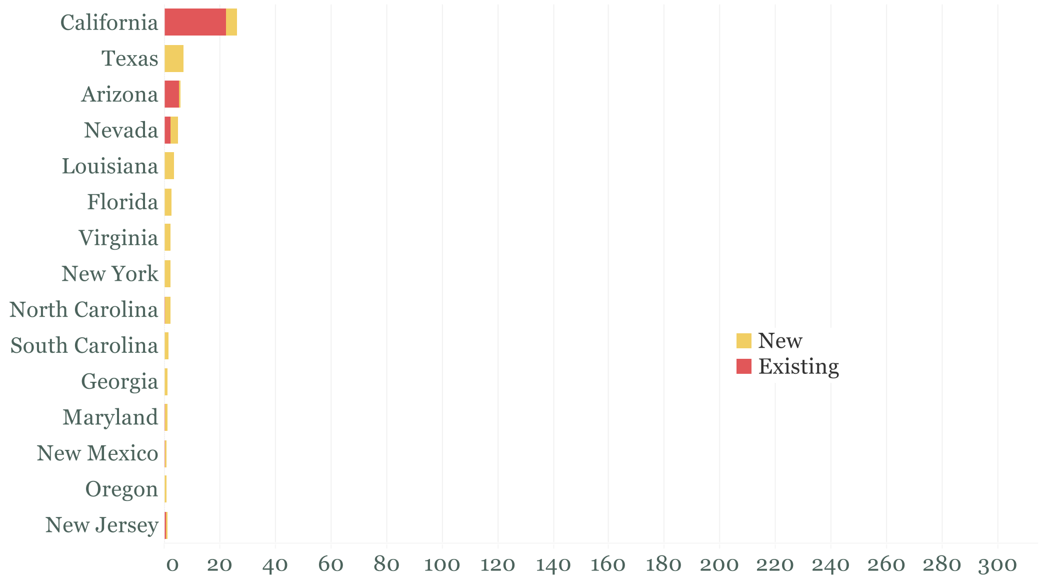


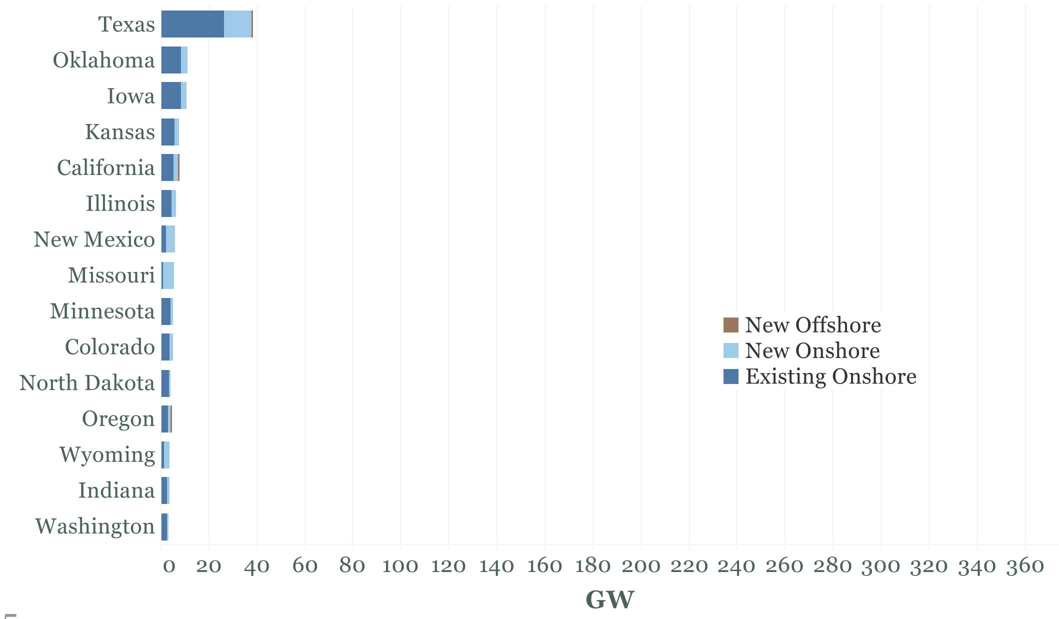


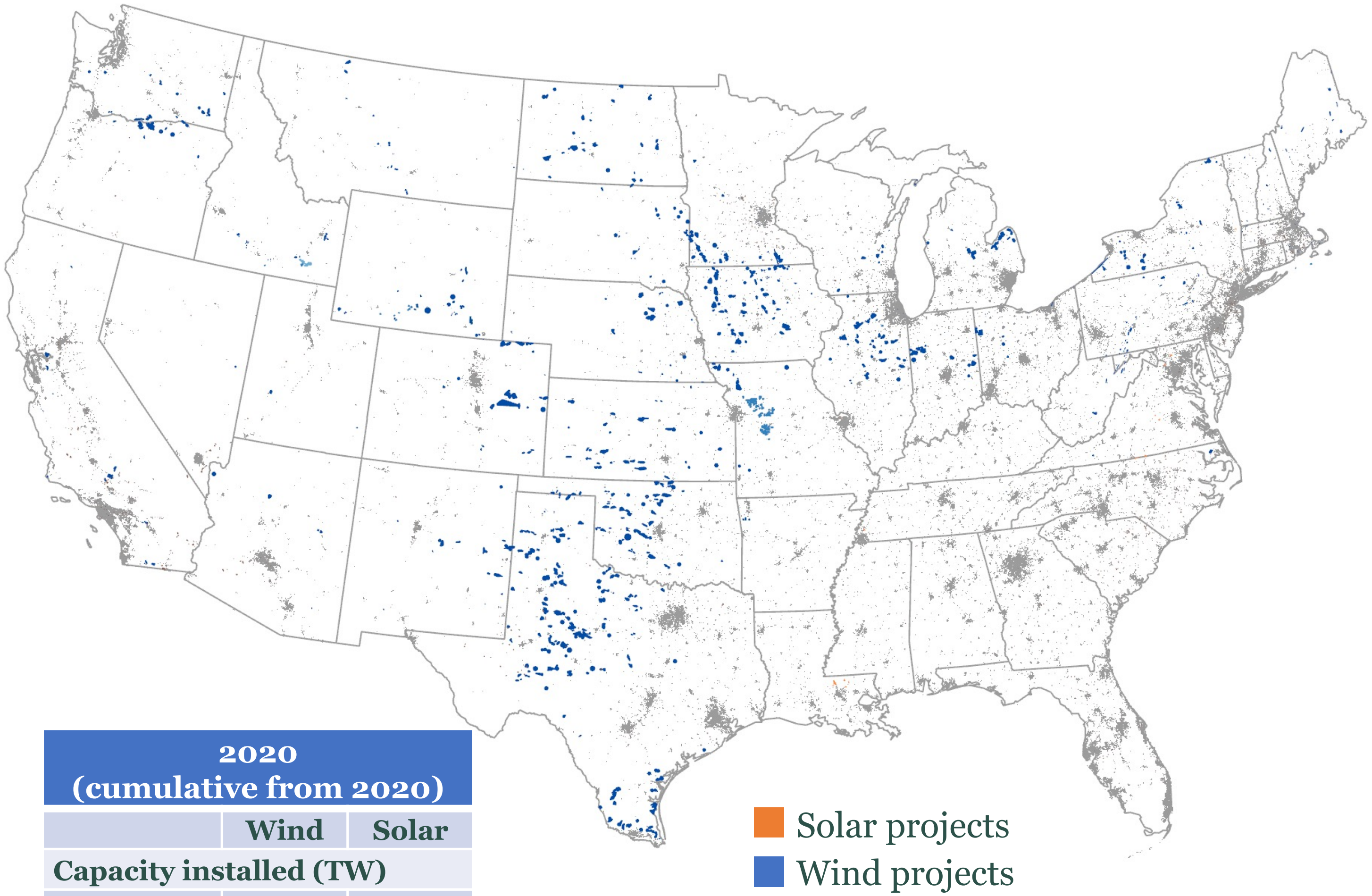
2050 (cumulative from 2020)		
	Wind	Solar
Capacity installed (TW)		
	1.55	1.48
Land area (1000 km²)		
Total	505	37.8
Direct	5.05	34.4
Capital invested (2018$)		
Trillion $	1.85	1.47

Note: *Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).*

E+ RE+ Base 2020



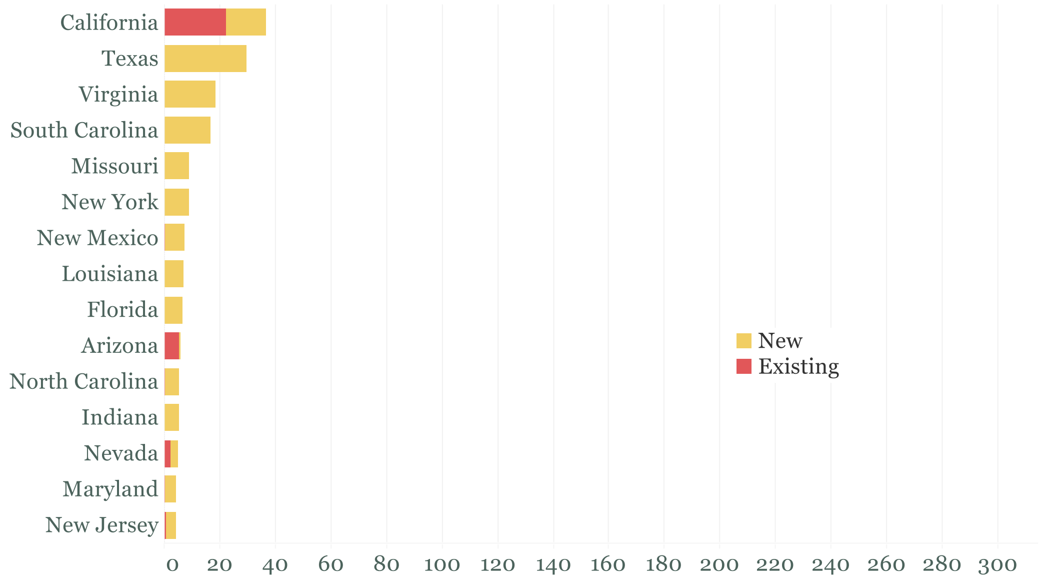


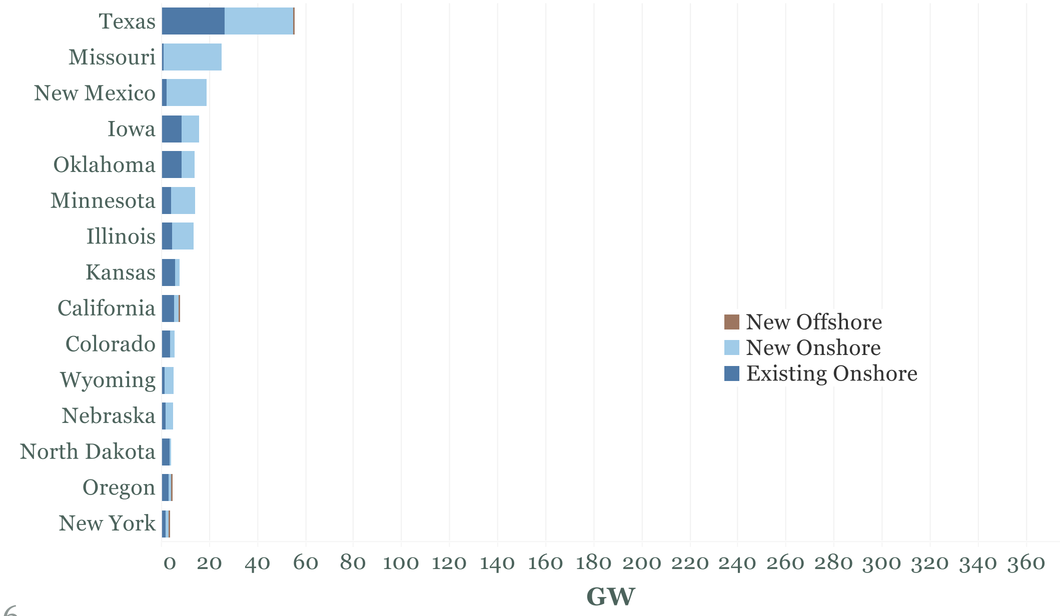


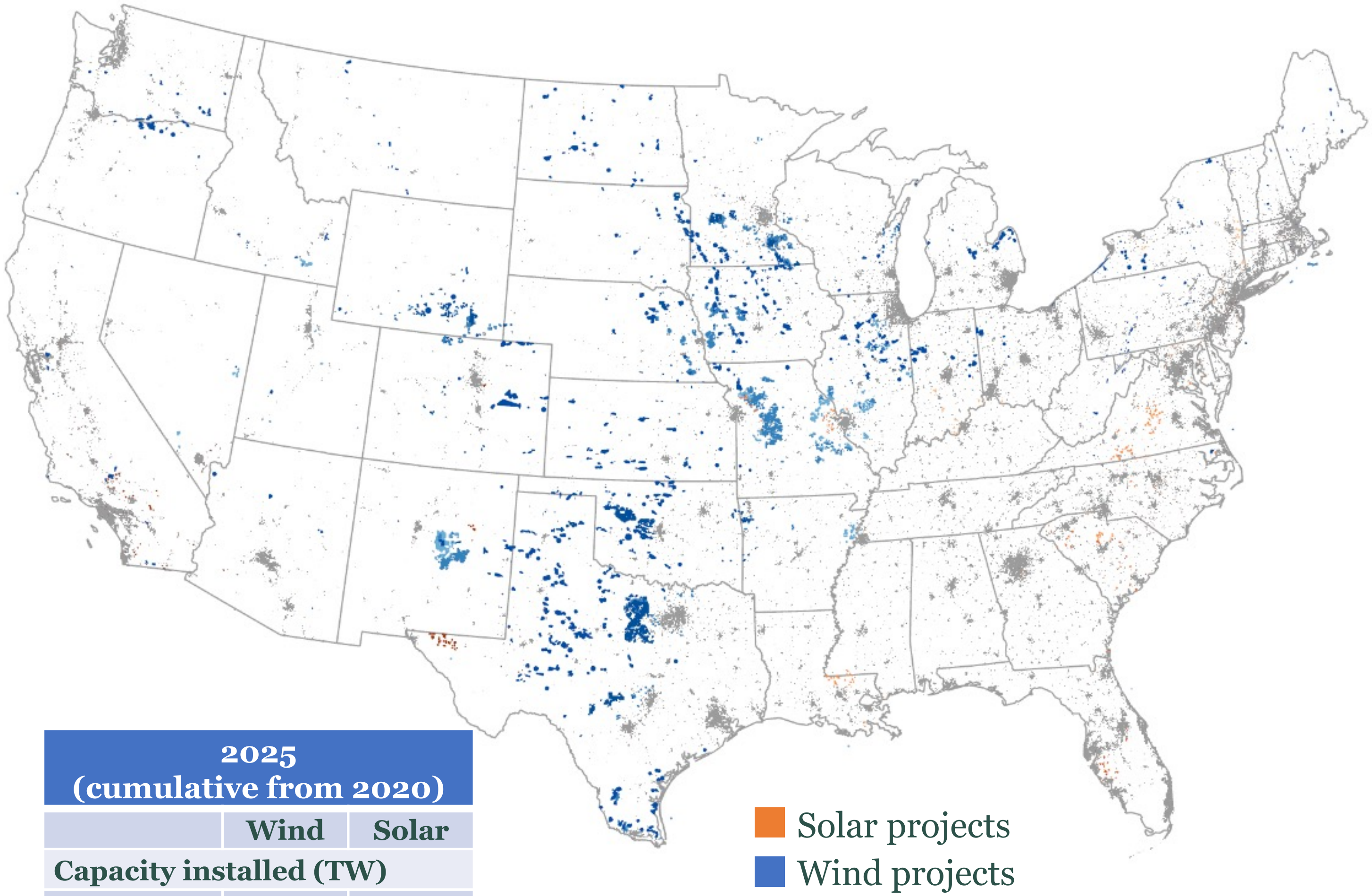
2020 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.14	0.07
Land area (1000 km²)		
Total	58	1.14
Direct	0.58	1.02
Capital invested (2018$)		
Trillion $	0.07	0.05

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ RE+ Base 2025



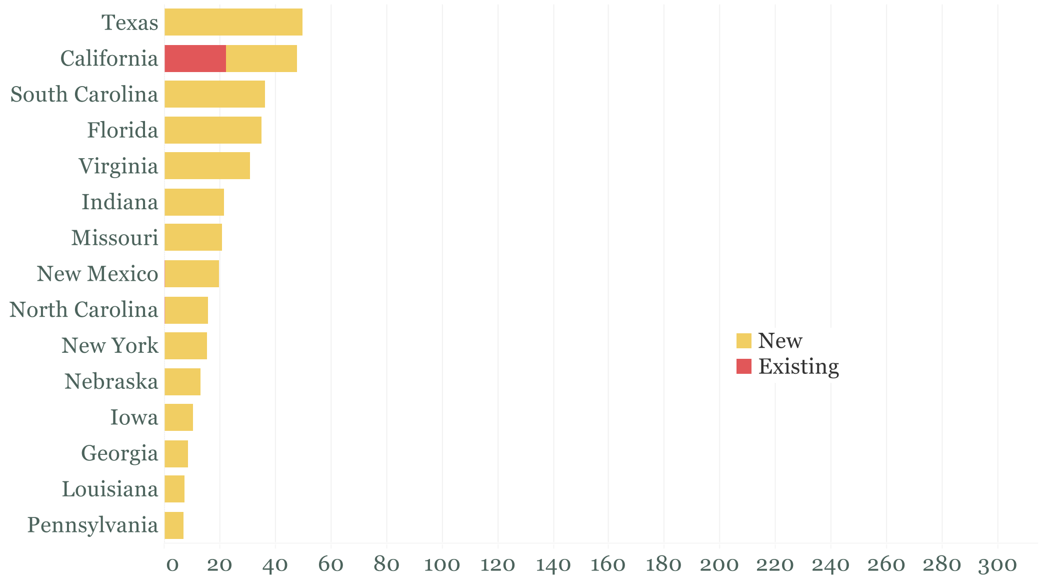


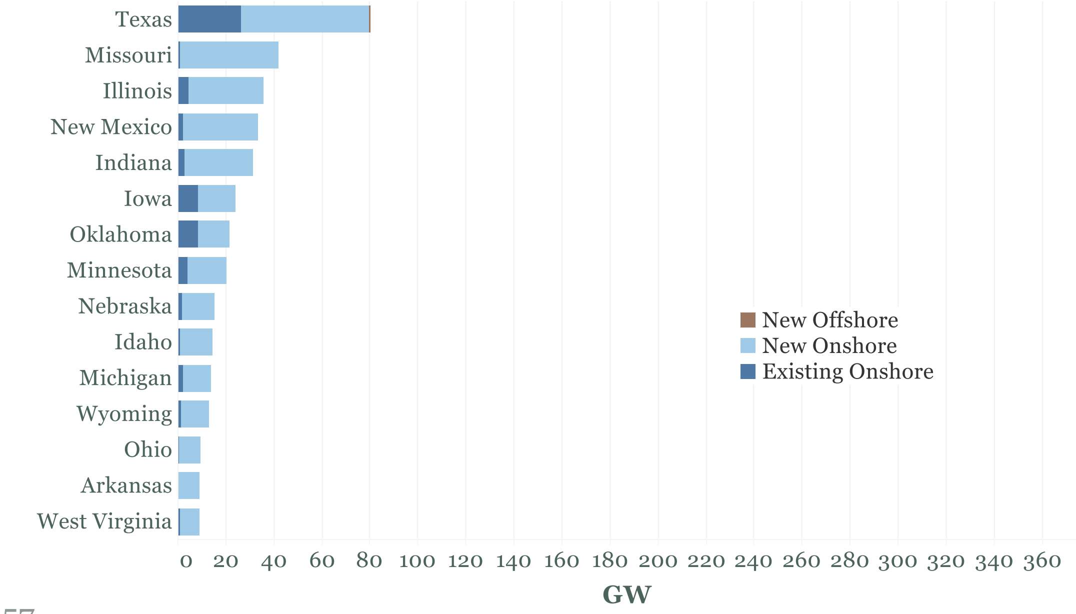


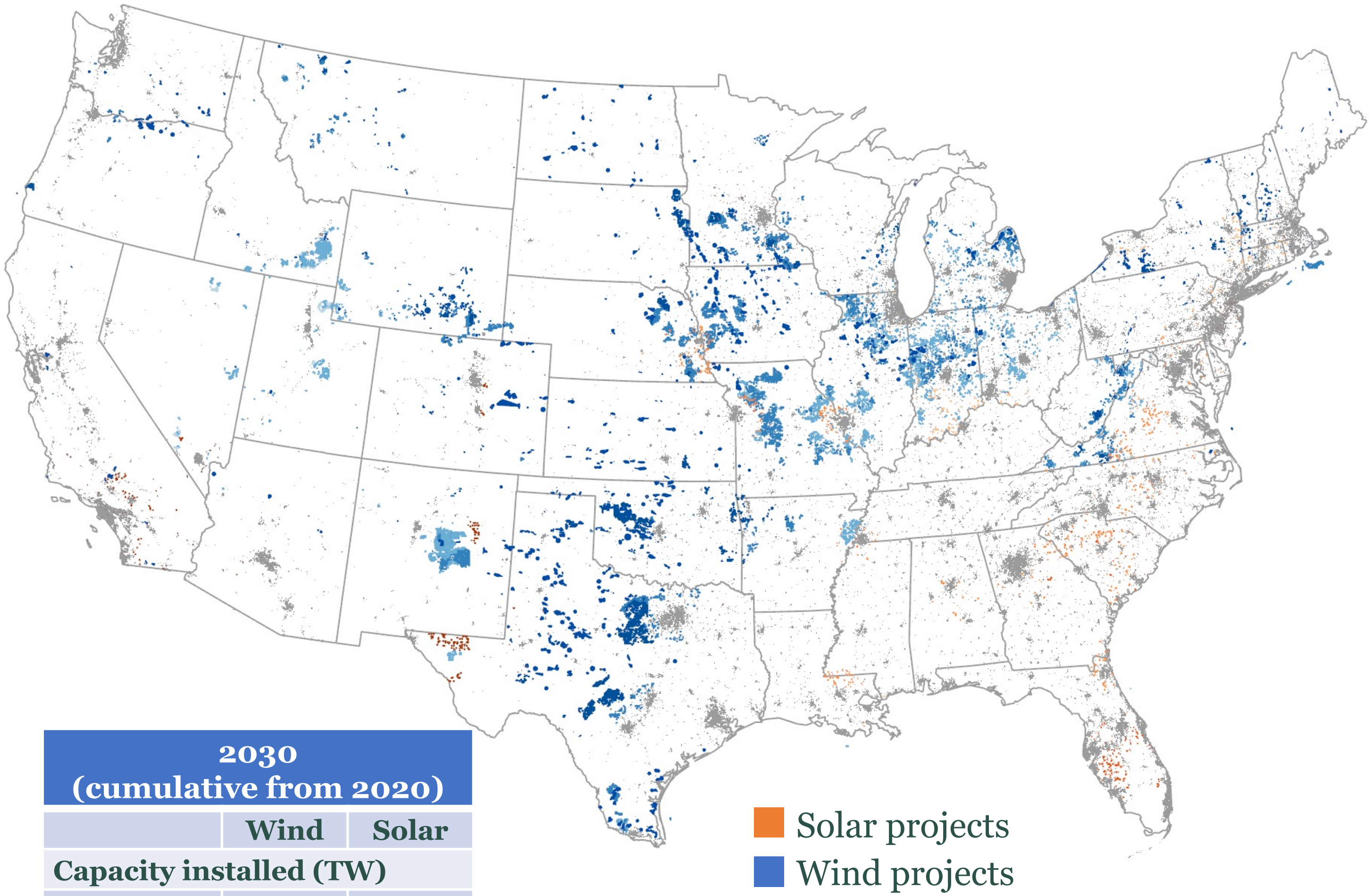
2025 (cumulative from 2020)		
	Wind	Solar
Capacity installed (TW)		
	0.23	0.19
Land area (1000 km²)		
Total	88	3.85
Direct	0.88	3.50
Capital invested (2018$)		
Trillion $	0.19	0.20

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ RE+ Base 2030



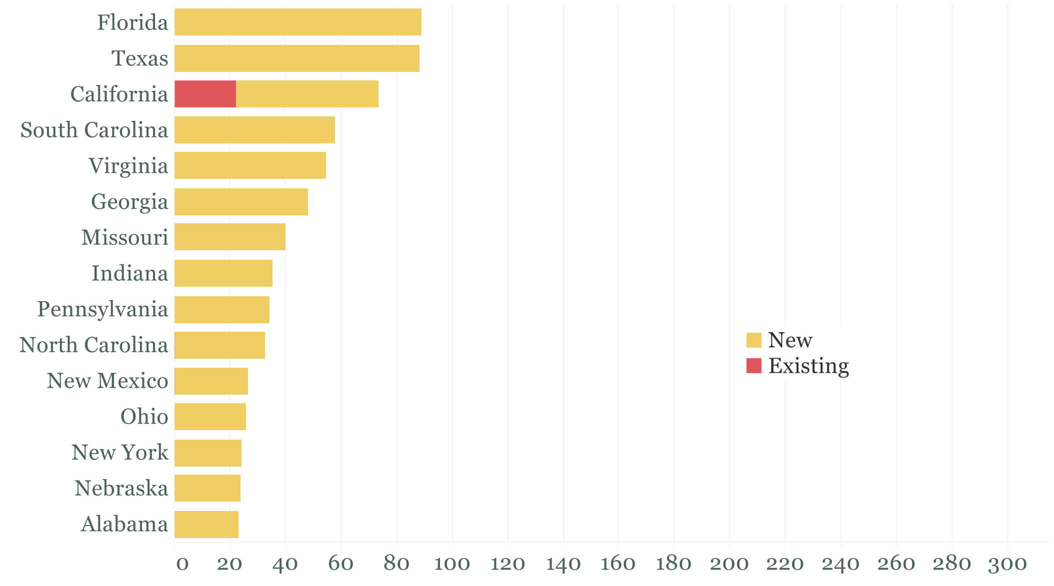


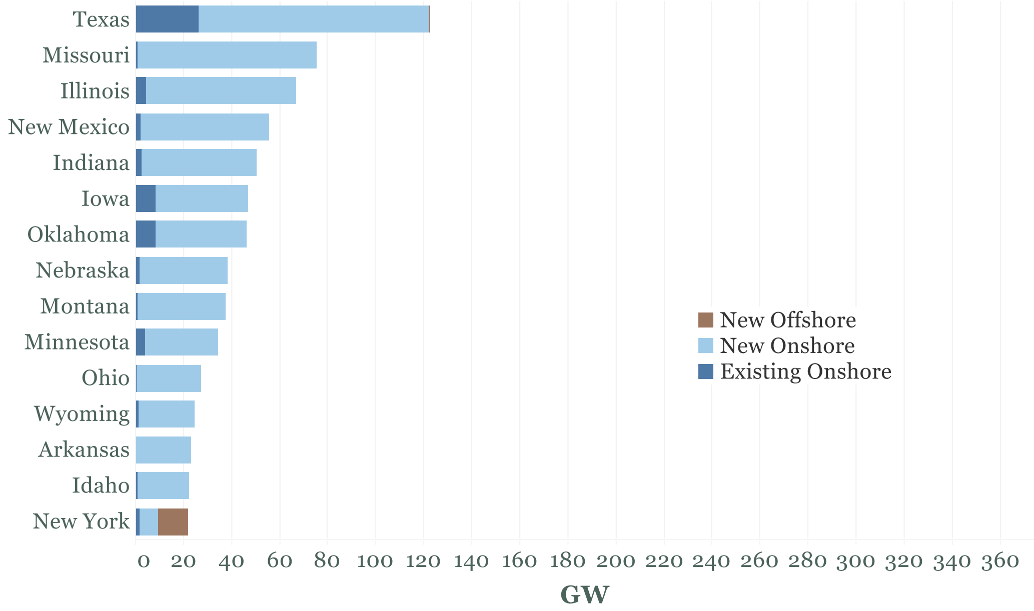


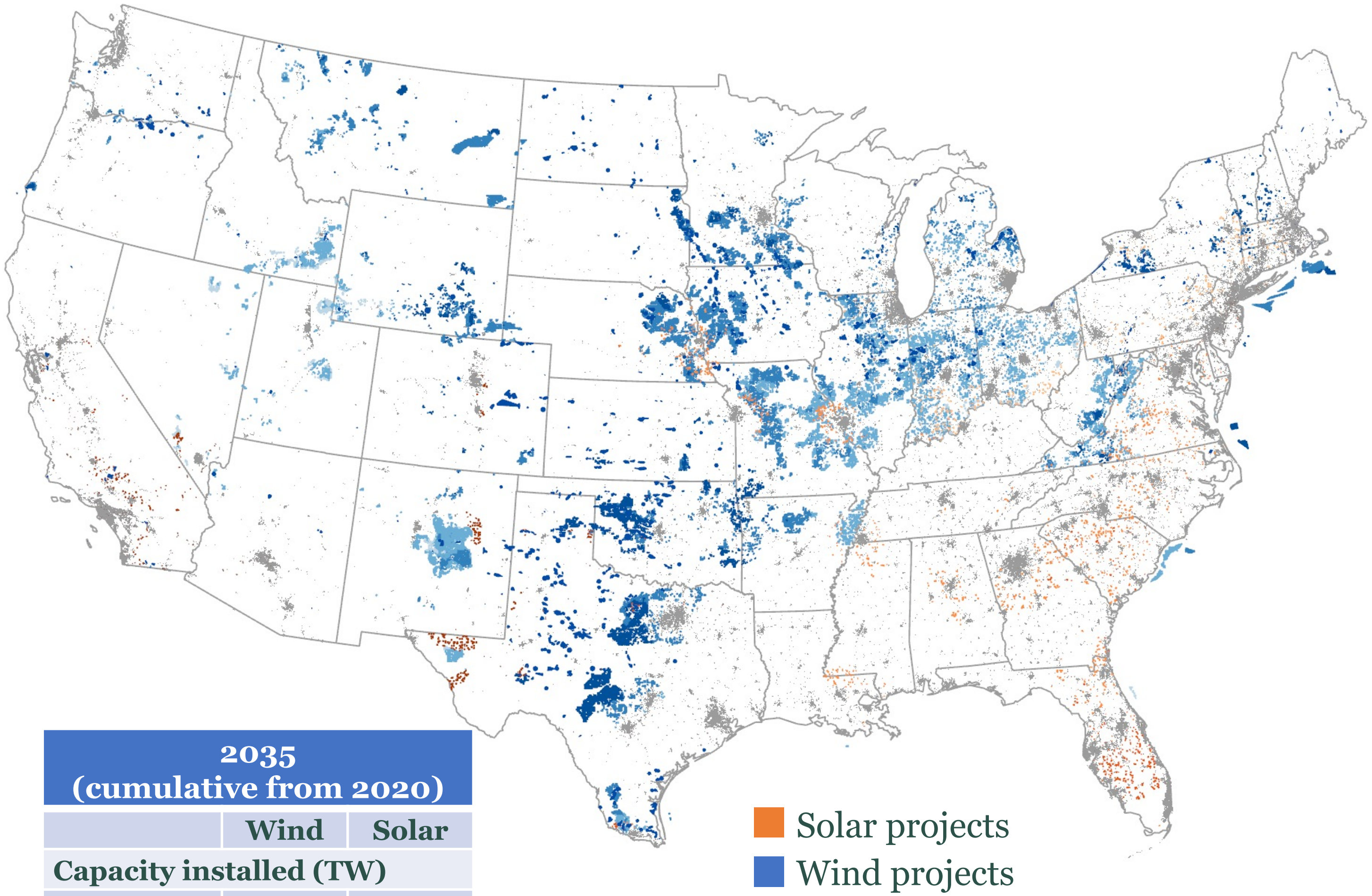
2030 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.46	0.40
Land area (1000 km²)		
Total	174	8.67
Direct	1.74	7.89
Capital invested (2018$)		
Trillion $	0.51	0.45

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ RE+ Base 2035



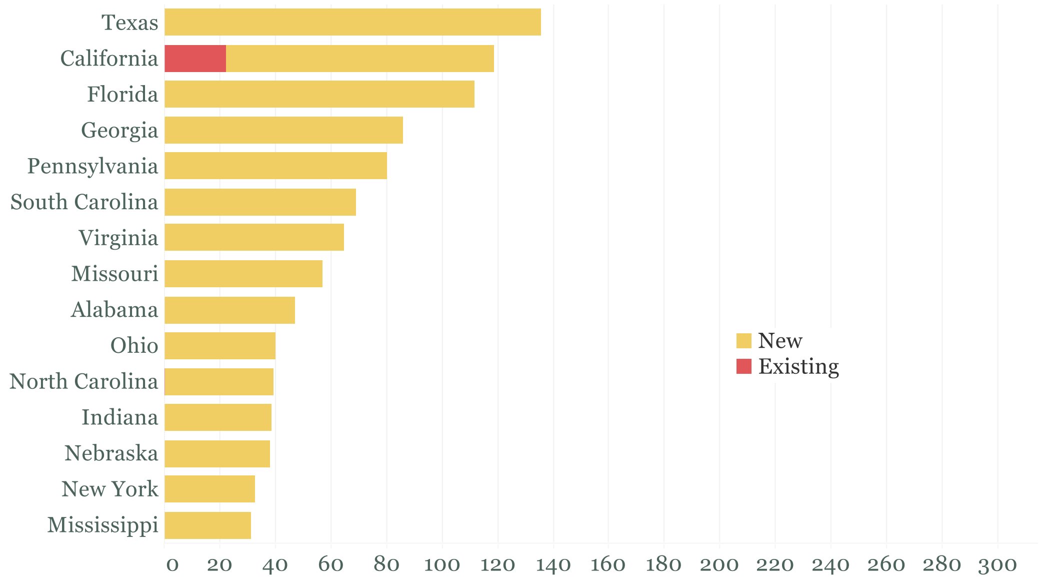


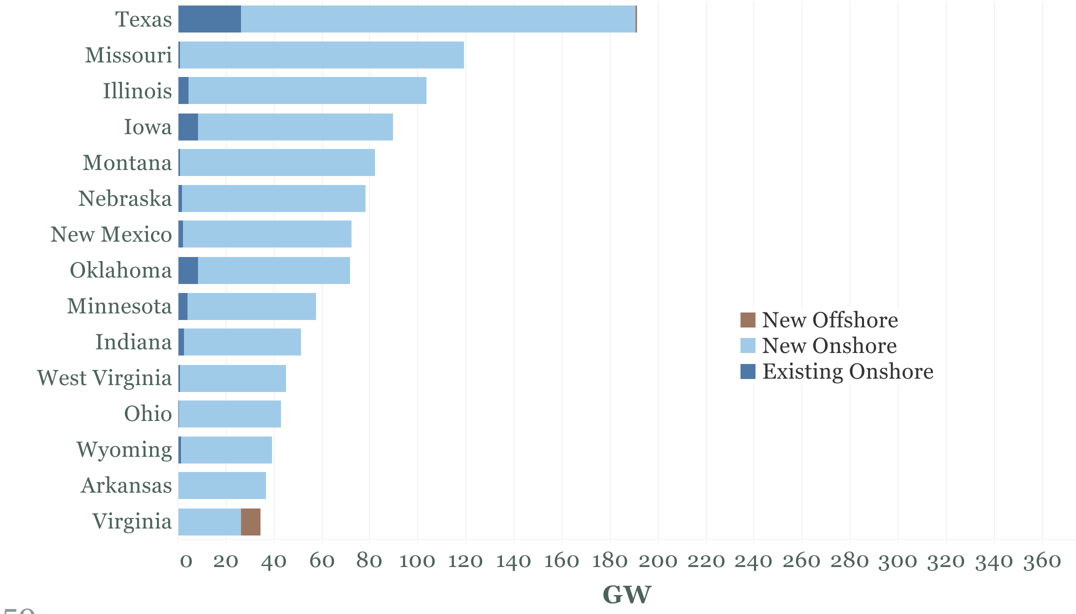


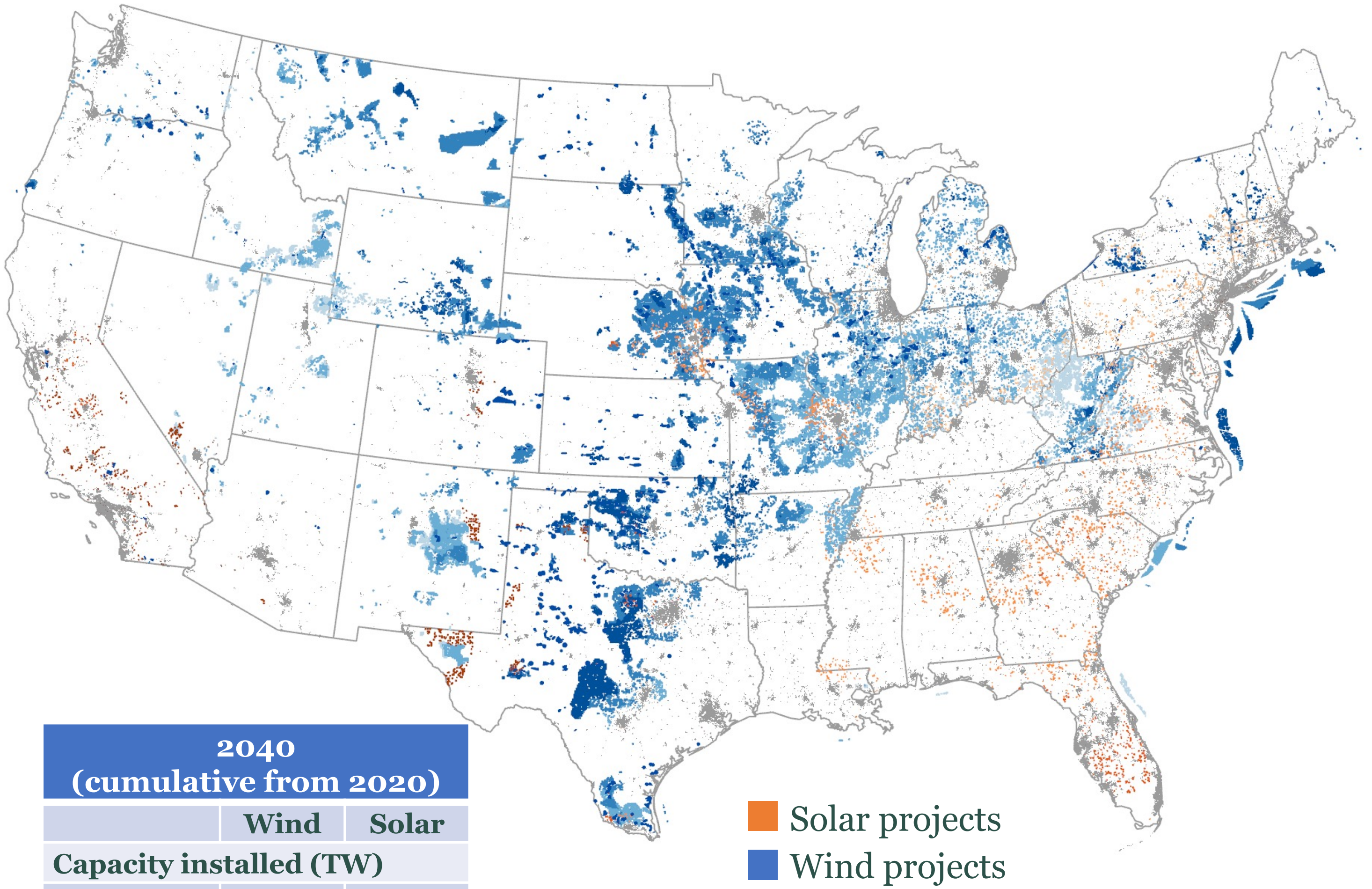
2035 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.87	0.82
Land area (1000 km²)		
Total	312	18.0
Direct	3.12	16.4
Capital invested (2018$)		
Trillion $	1.05	0.89

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ RE+ Base 2040



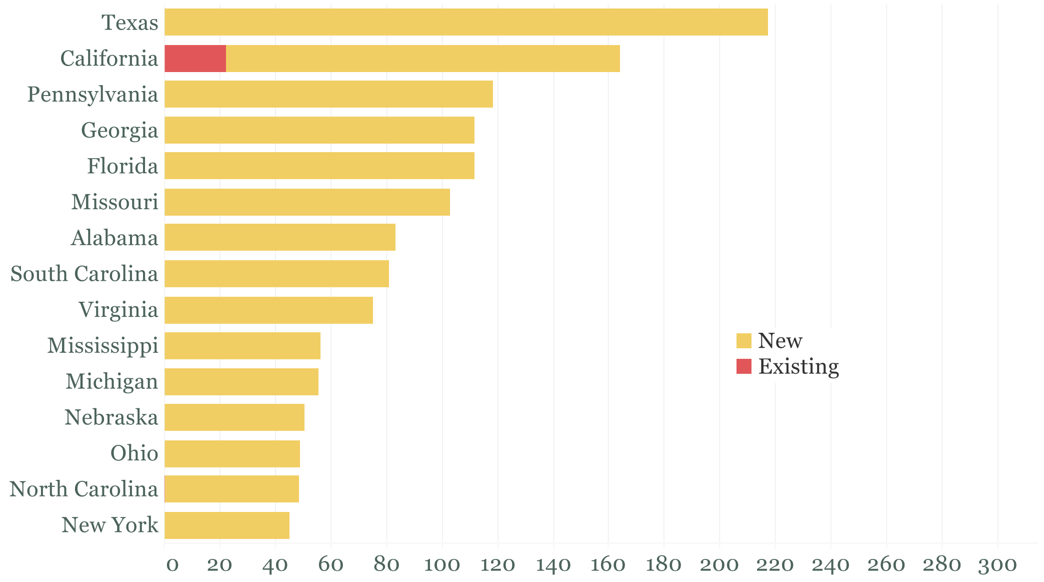


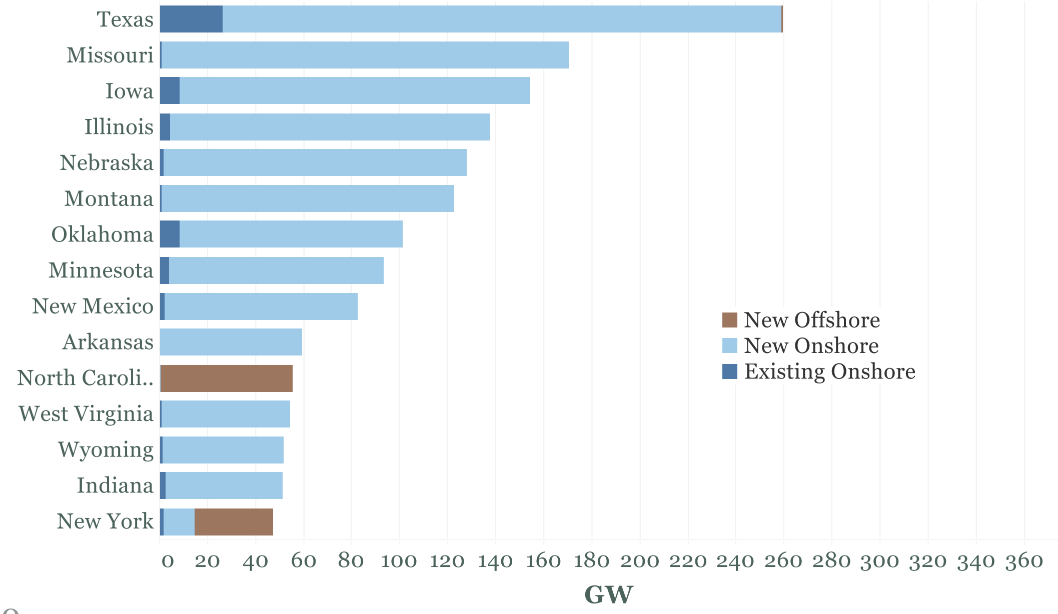


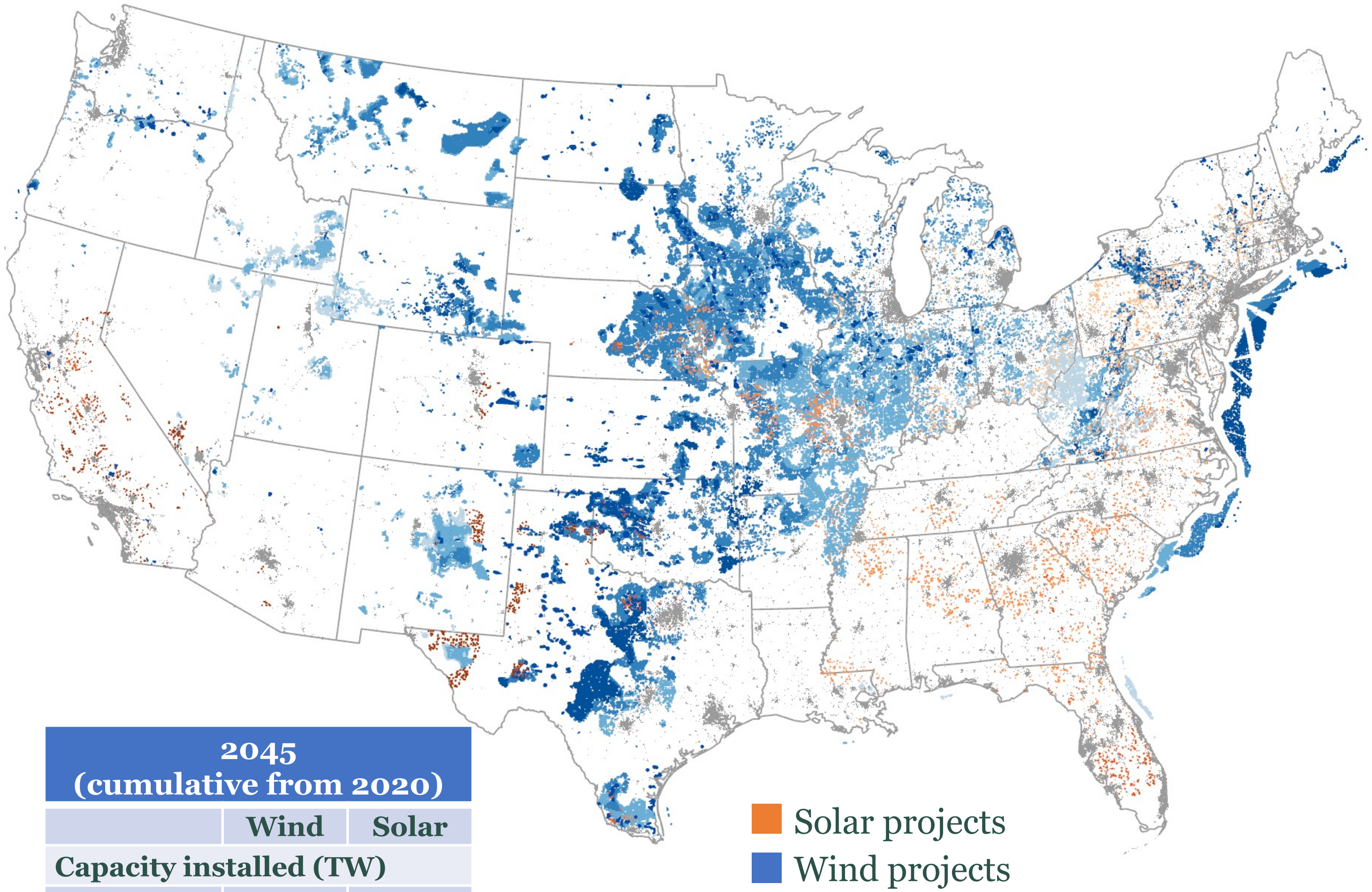
2040 (cumulative from 2020)		
	Wind	Solar
Capacity installed (TW)		
	1.42	1.23
Land area (1000 km²)		
Total	493	26.9
Direct	4.93	24.5
Capital invested (2018$)		
Trillion $	1.72	1.31

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ RE+ Base 2045



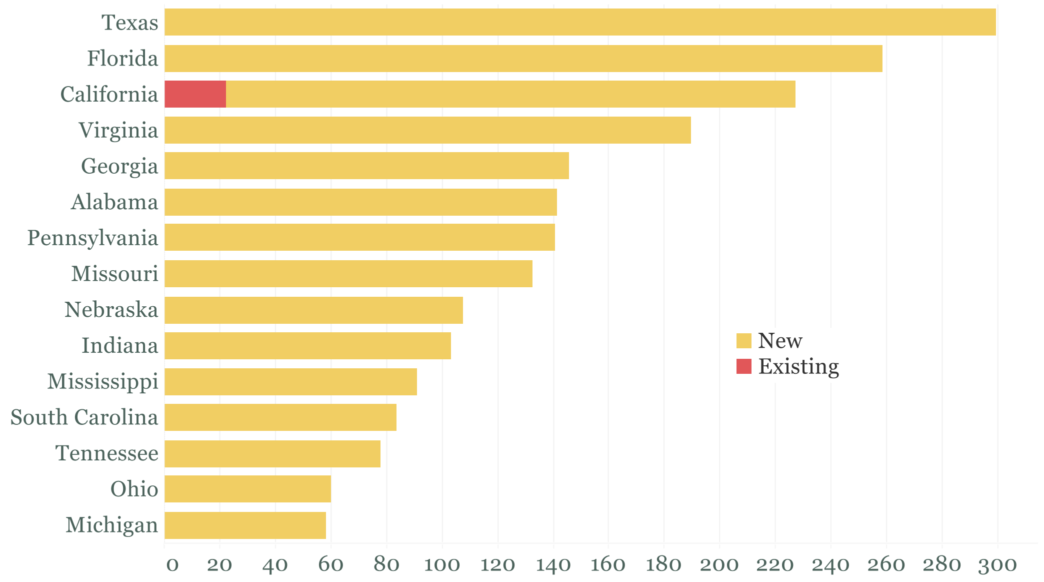


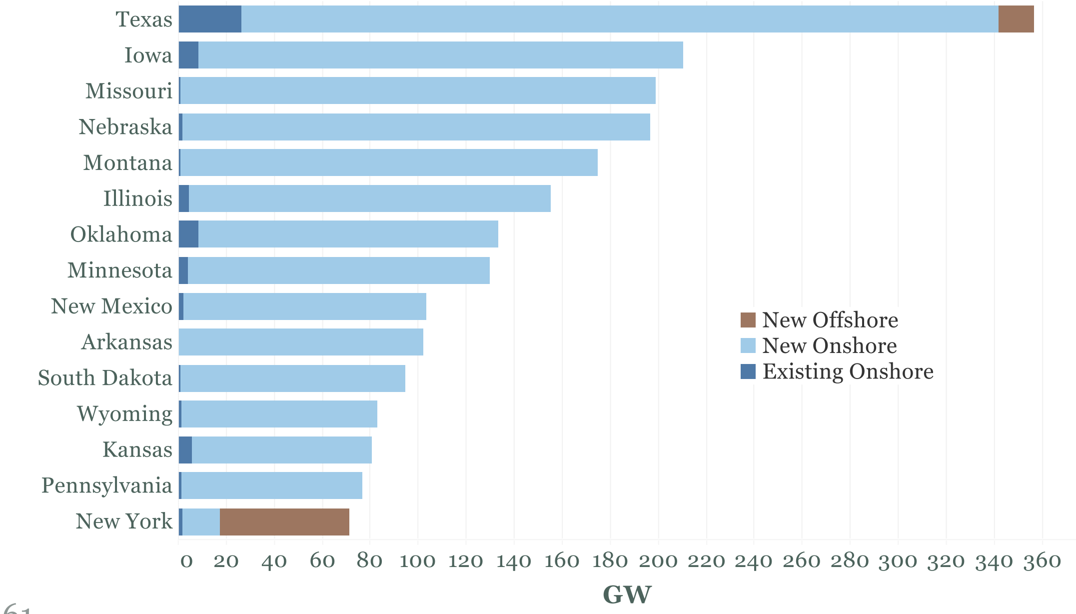


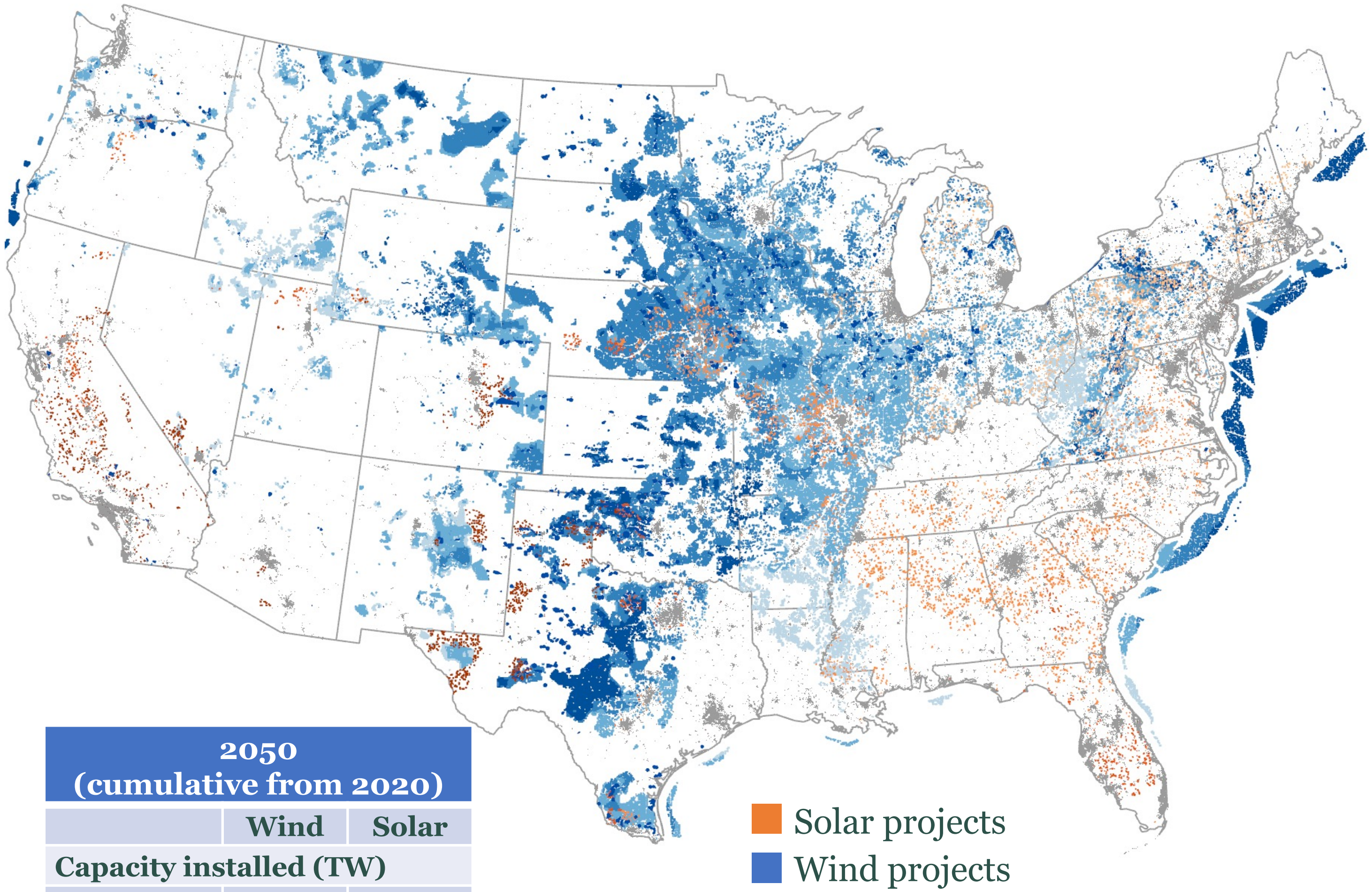
2045 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	2.12	1.77
Land area (1000 km²)		
Total	705	38.6
Direct	7.05	35.1
Capital invested (2018$)		
Trillion $	2.55	1.81

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ RE+ Base 2050



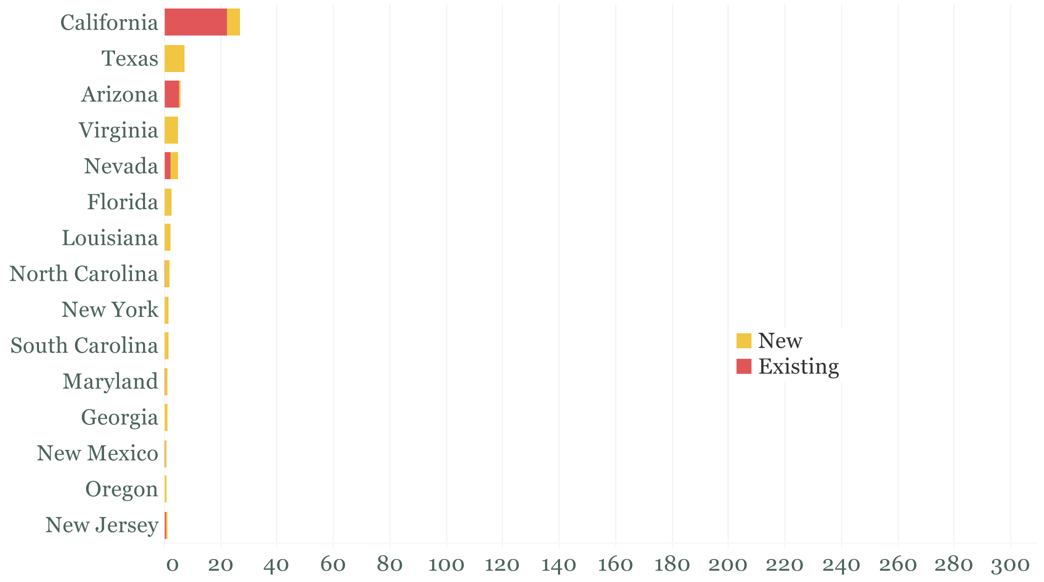


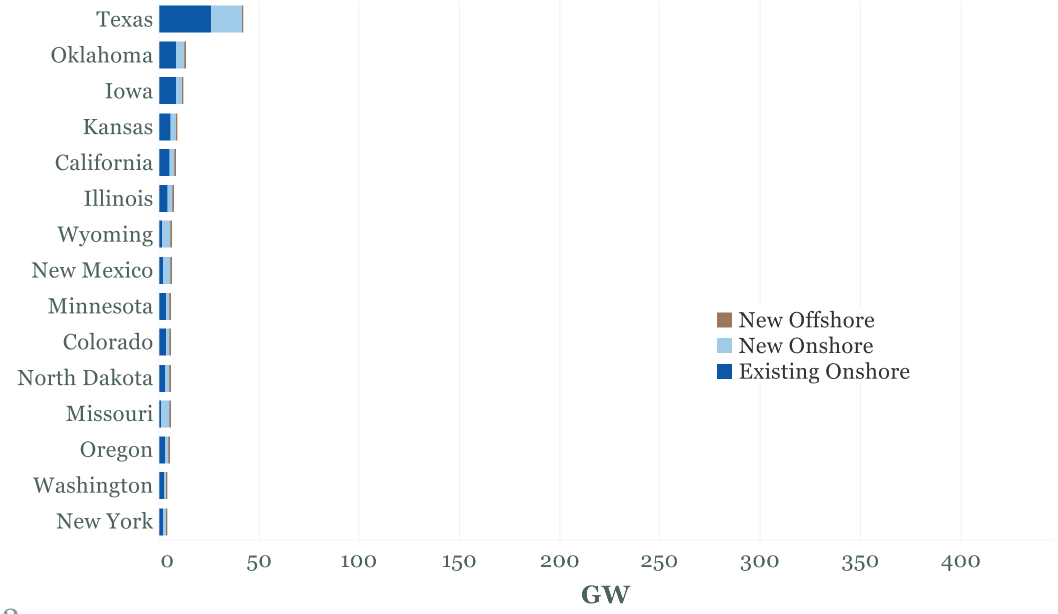


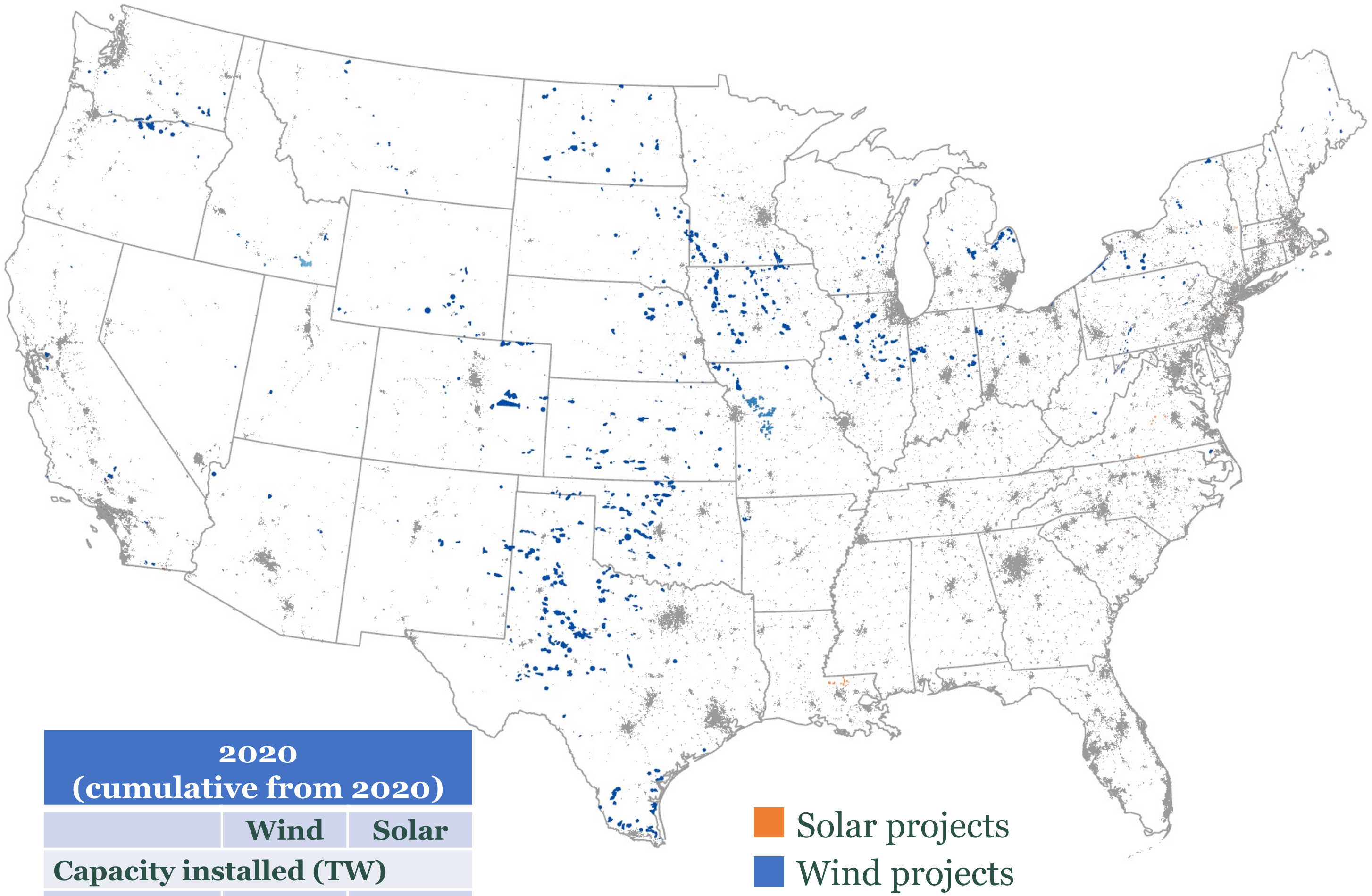
2050 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	3.07	2.75
Land area (1000 km²)		
Total	1,003	61.2
Direct	10.0	55.7
Capital invested (2018$)		
Trillion $	3.60	2.68

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ RE+ Constrained 2020



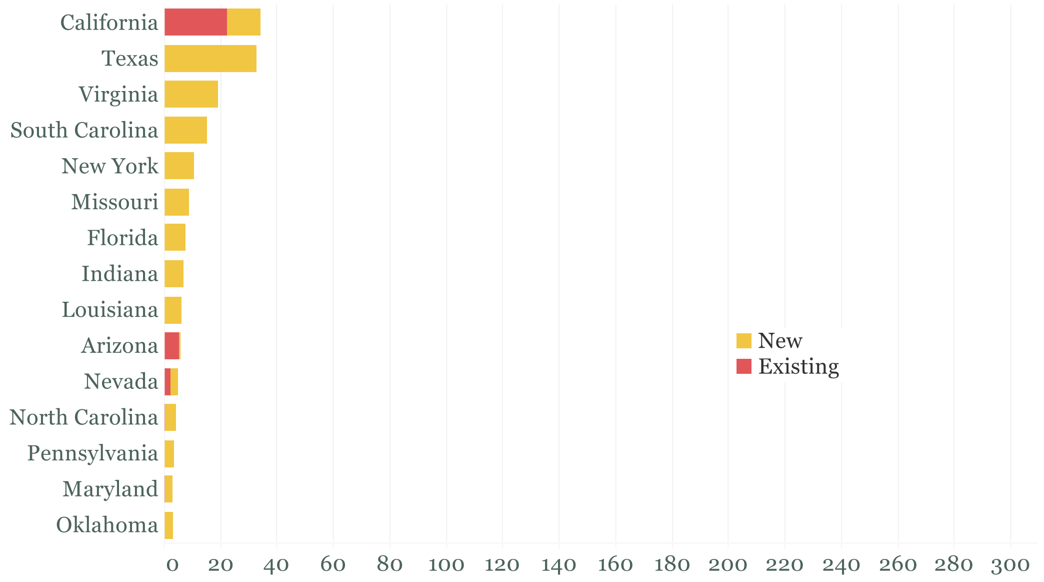


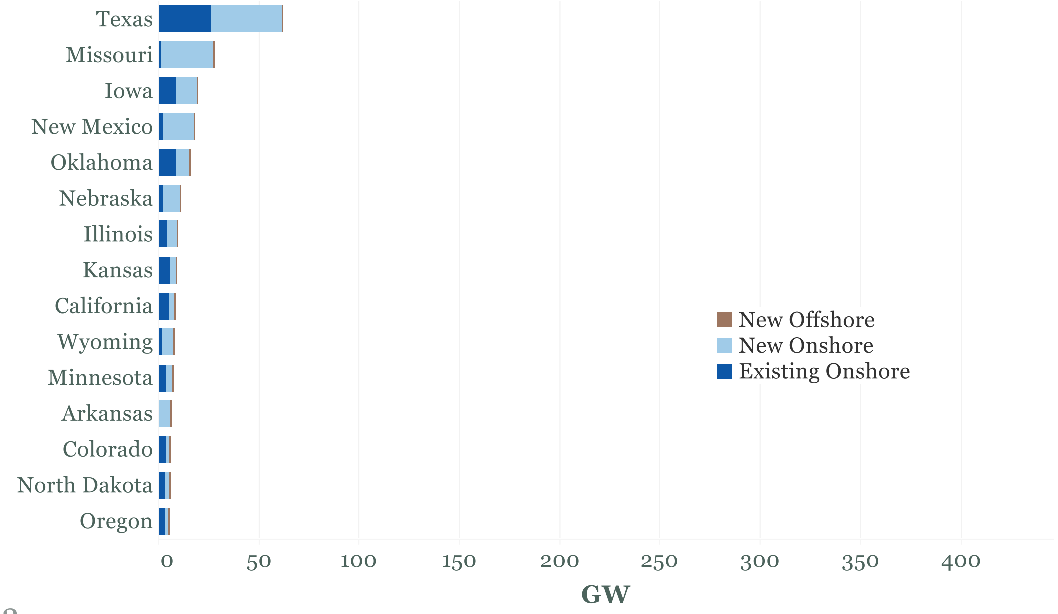


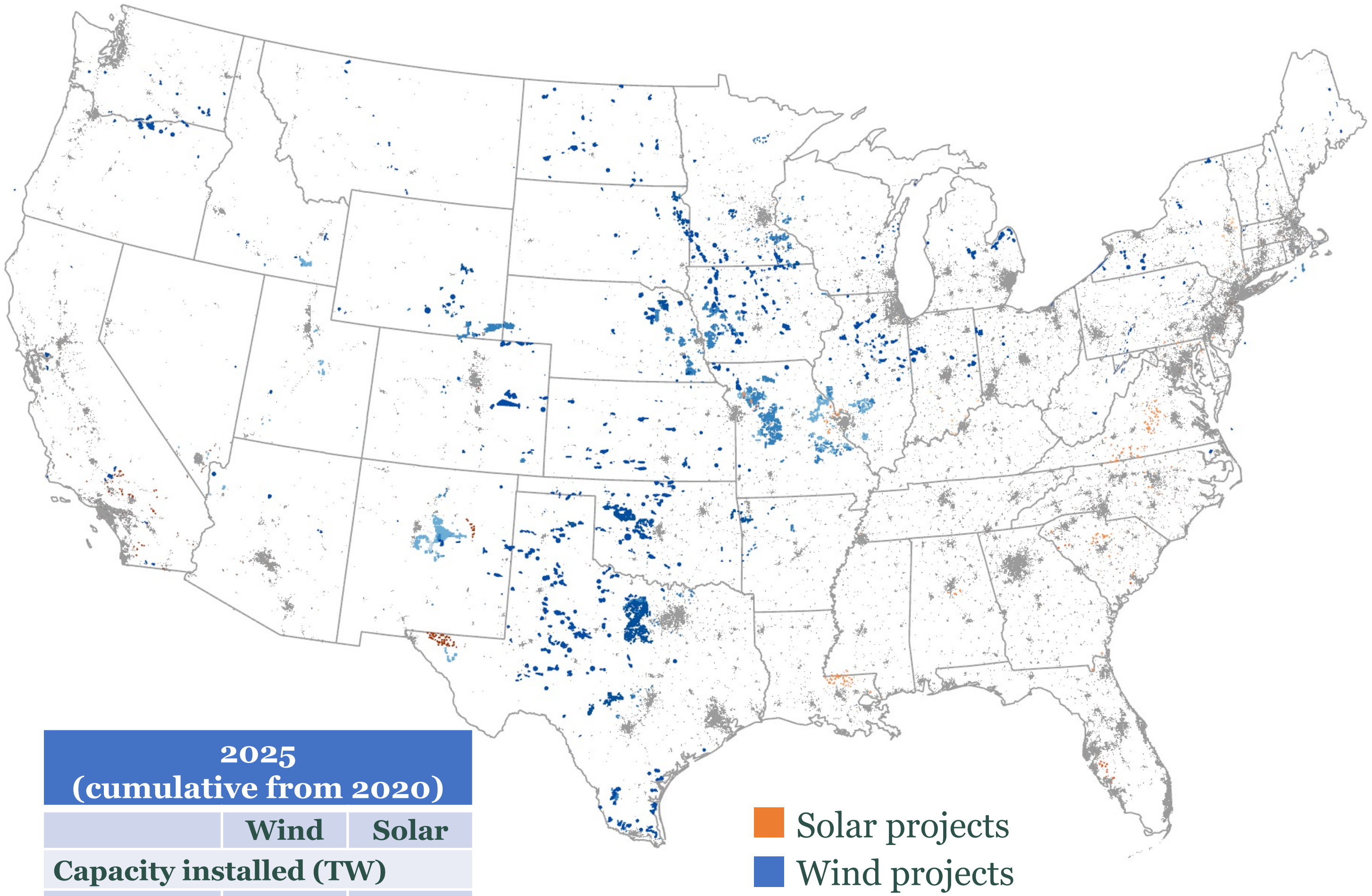
2020 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.16	0.07
Land area (1000 km²)		
Total	58	1.14
Direct	0.58	1.04
Capital invested (2018$)		
Trillion $	0.10	0.05

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ RE+ Constrained 2025



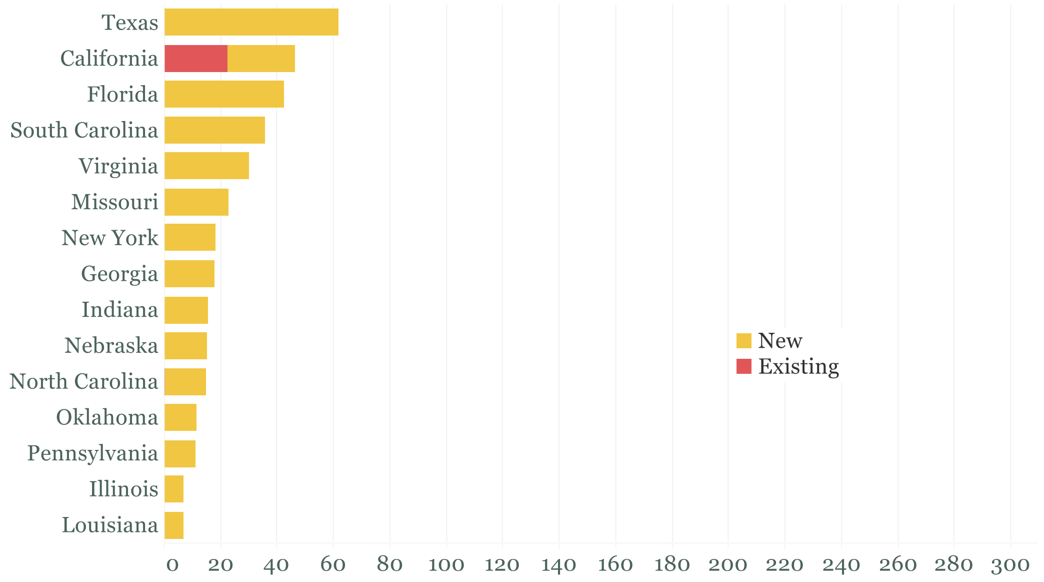


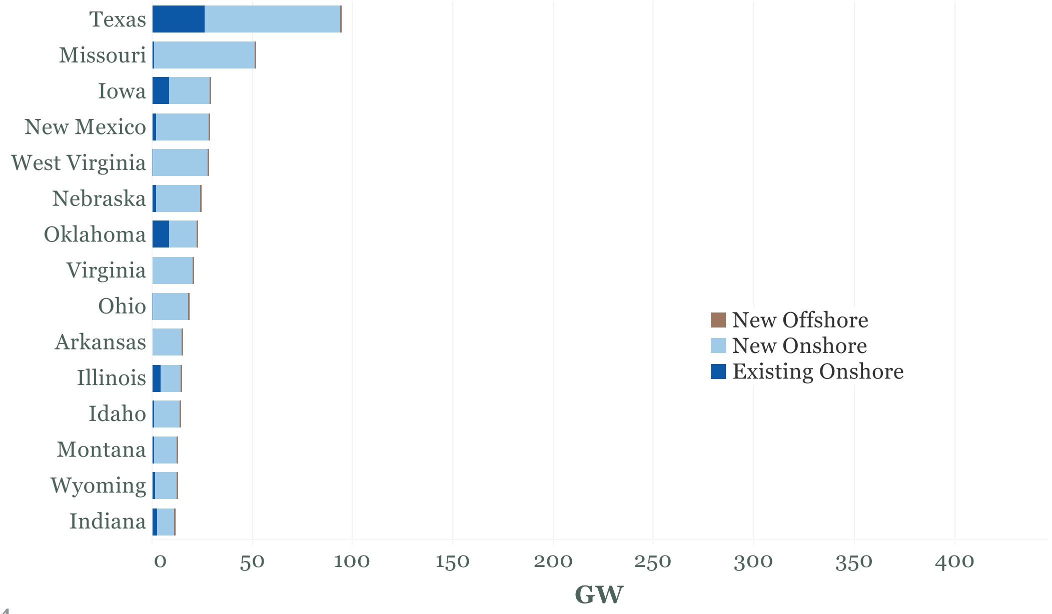


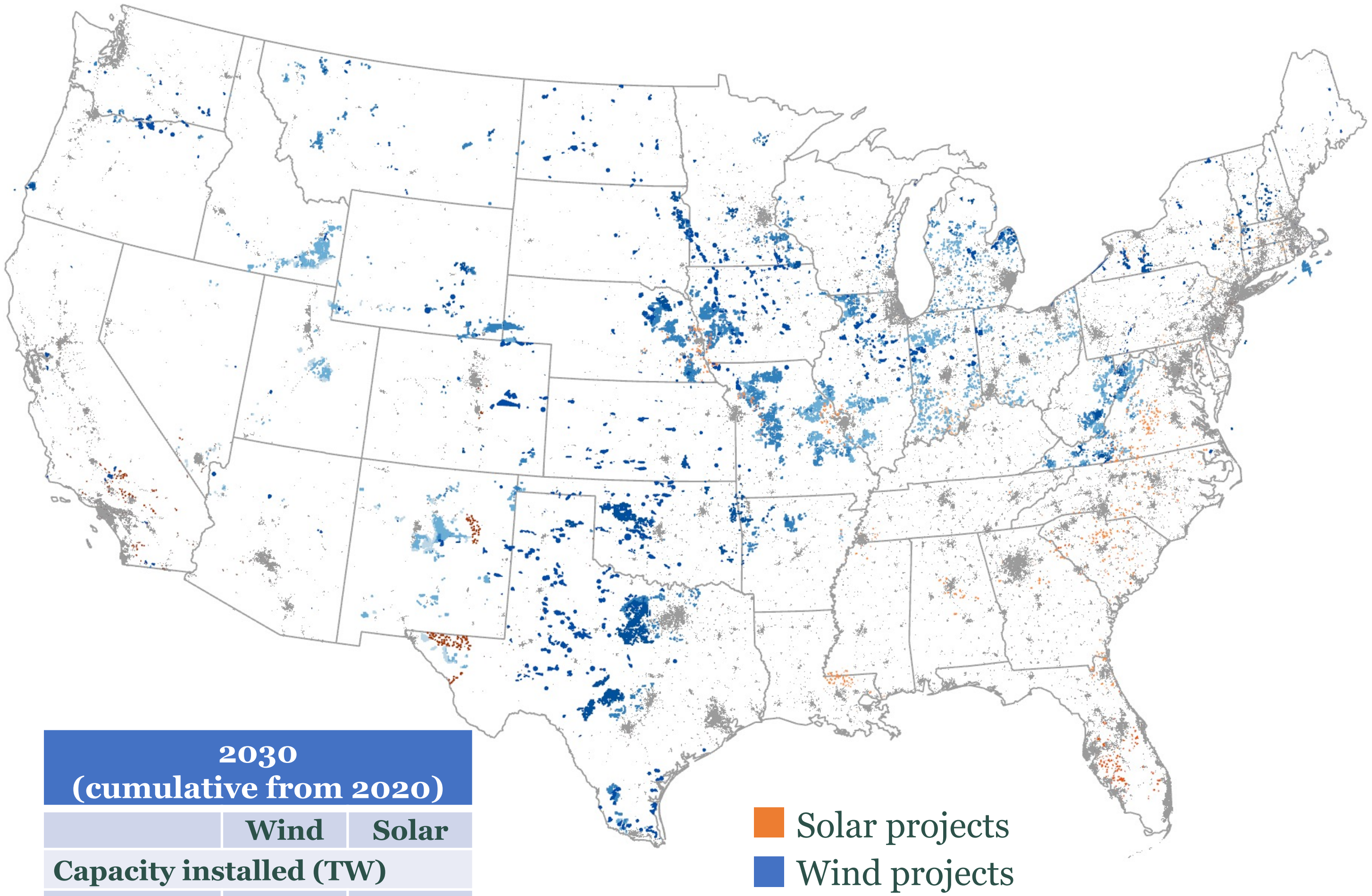
2025 (cumulative from 2020)	Wind	Solar
Capacity installed (TW)		
	0.25	0.19
Land area (1000 km²)		
Total	89	3.84
Direct	0.89	3.50
Capital invested (2018$)		
Trillion $	0.23	0.20

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ RE+ Constrained 2030



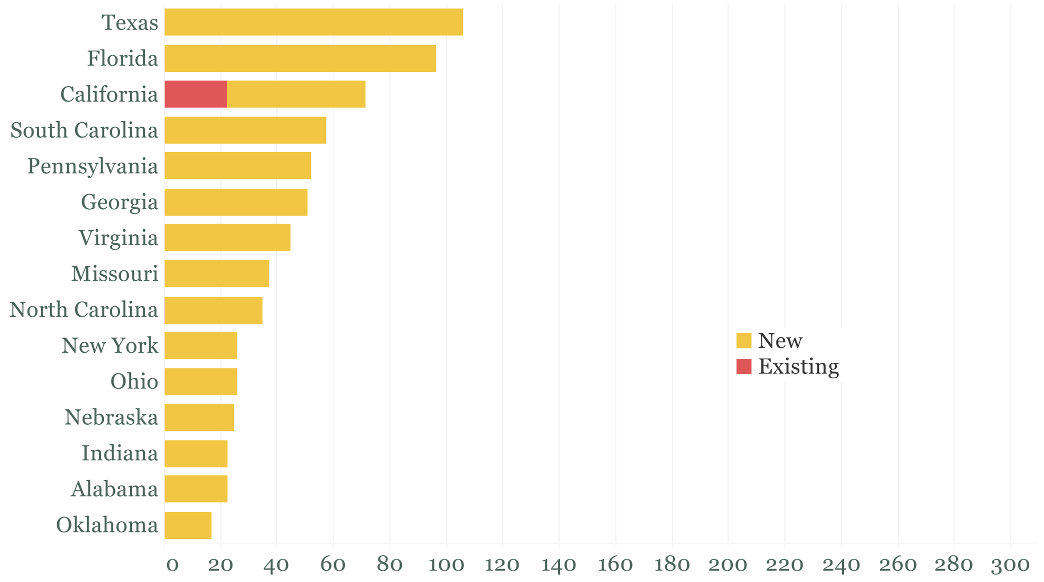


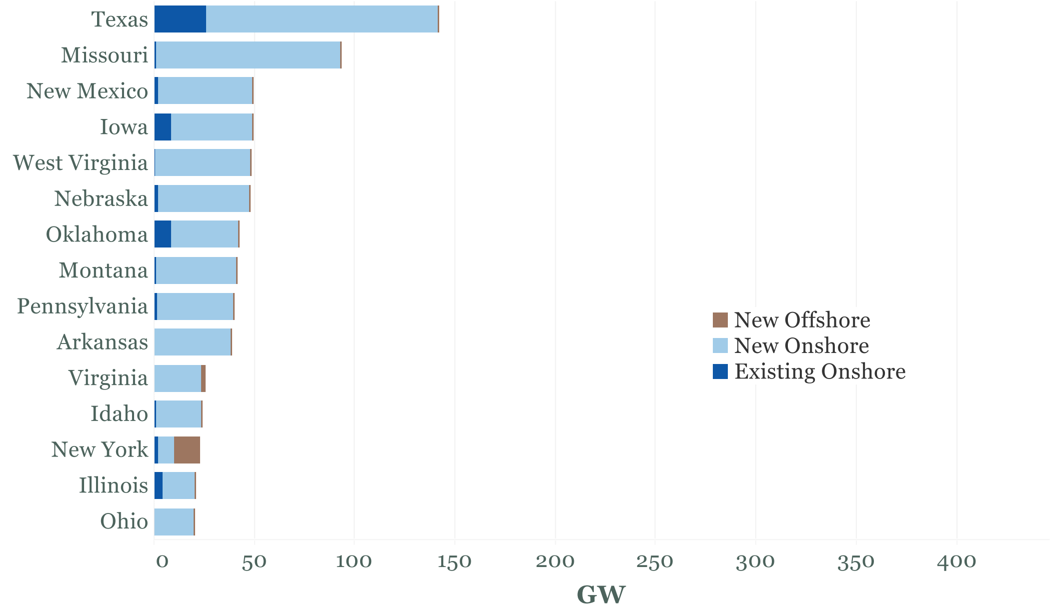


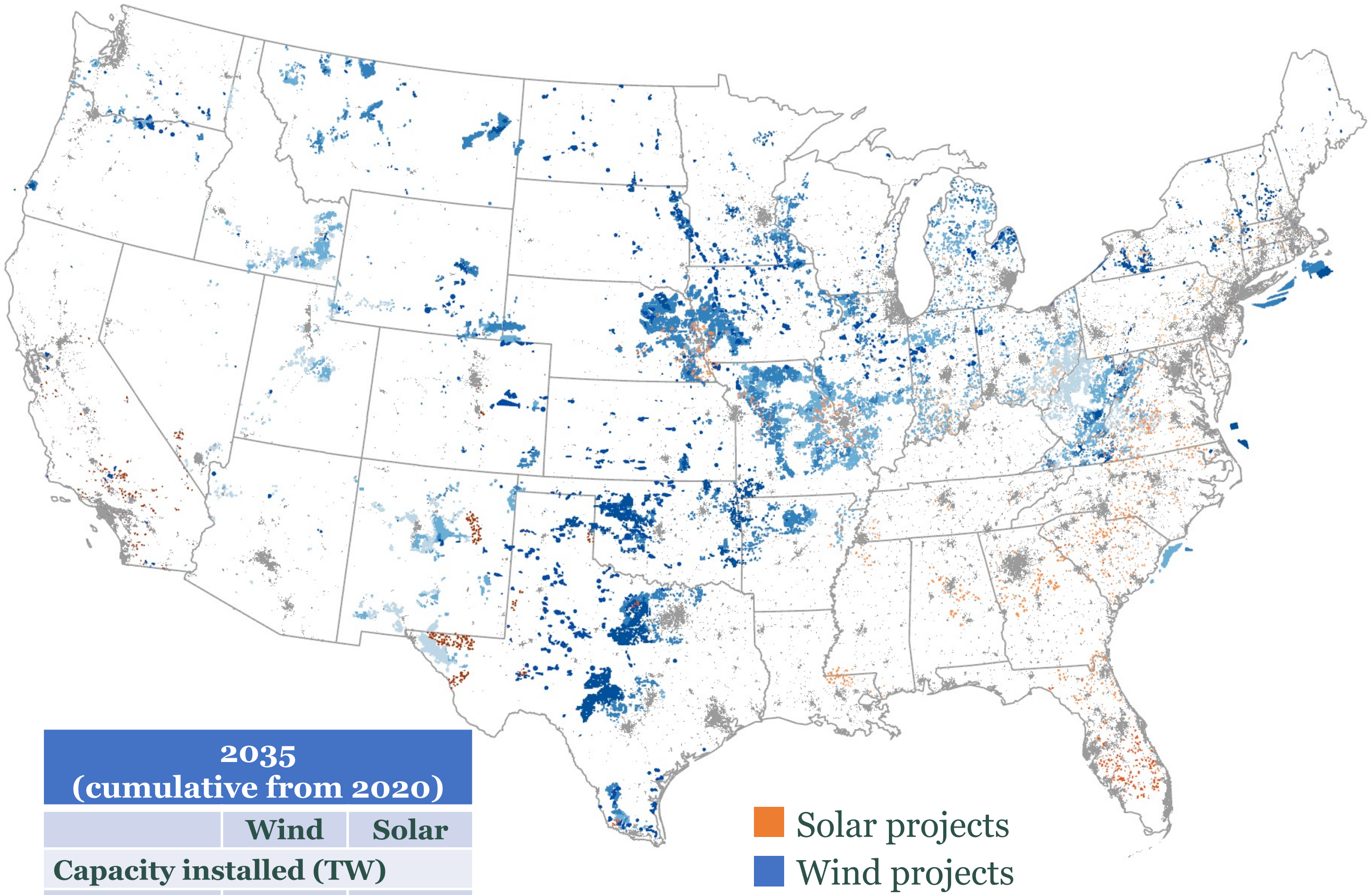
2030 (cumulative from 2020)		
	Wind	Solar
Capacity installed (TW)		
	0.50	0.42
Land area (1000 km²)		
Total	181	9.39
Direct	1.81	8.54
Capital invested (2018$)		
Trillion $	0.56	0.47

Note: *Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).*

E+ RE+ Constrained 2035



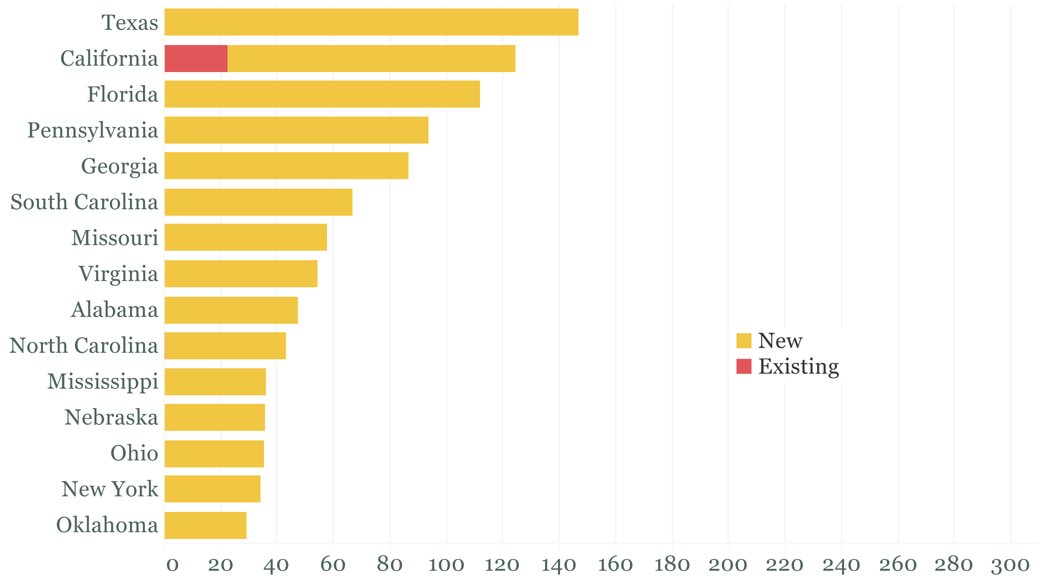


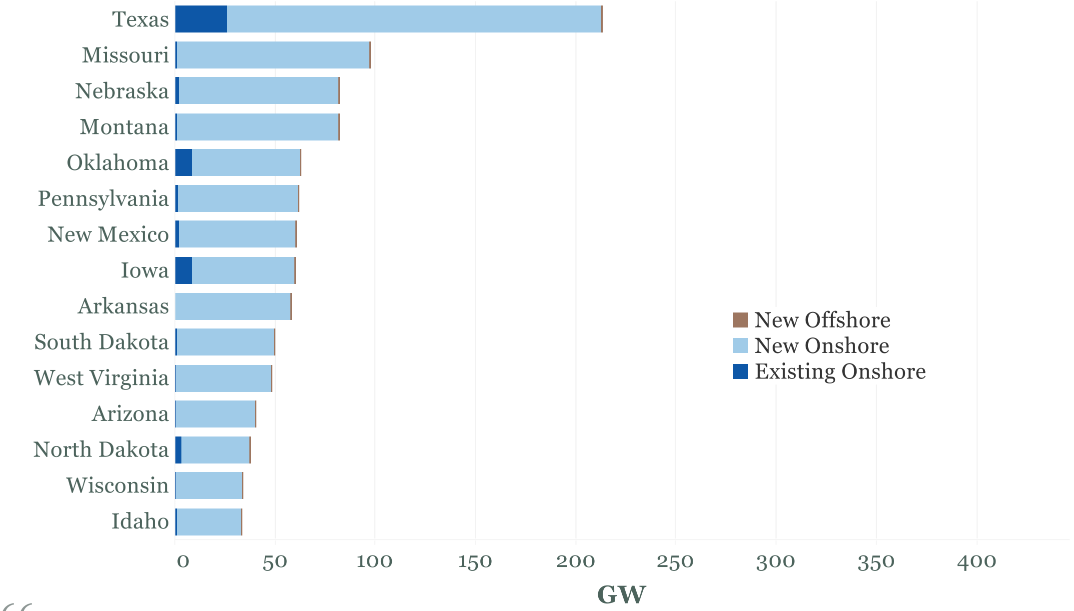


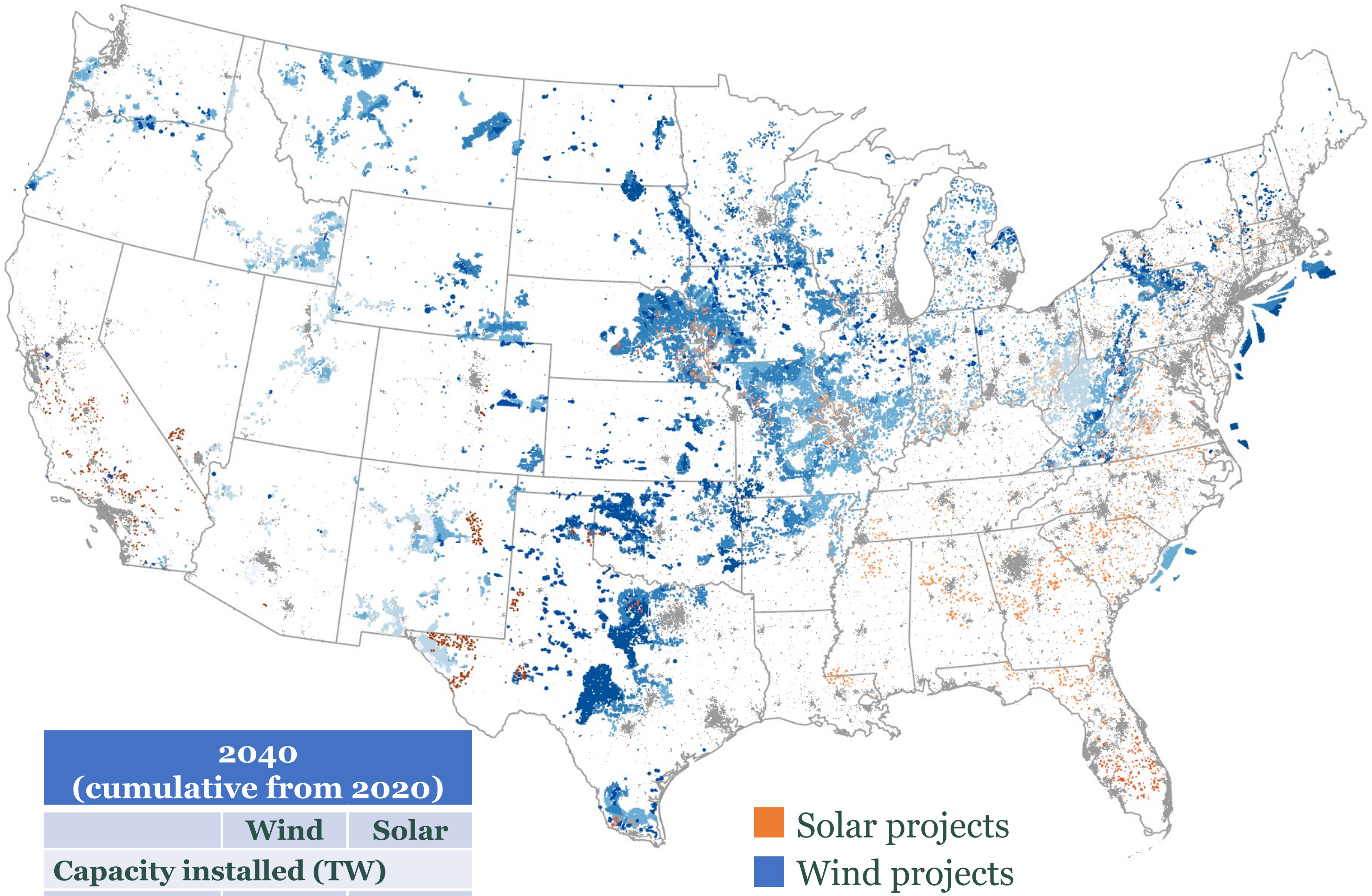
2035 (cumulative from 2020)		
	Wind	Solar
Capacity installed (TW)		
	0.93	0.82
Land area (1000 km²)		
Total	328	18.7
Direct	3.28	17.1
Capital invested (2018$)		
Trillion $	1.17	0.89

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ RE+ Constrained 2040



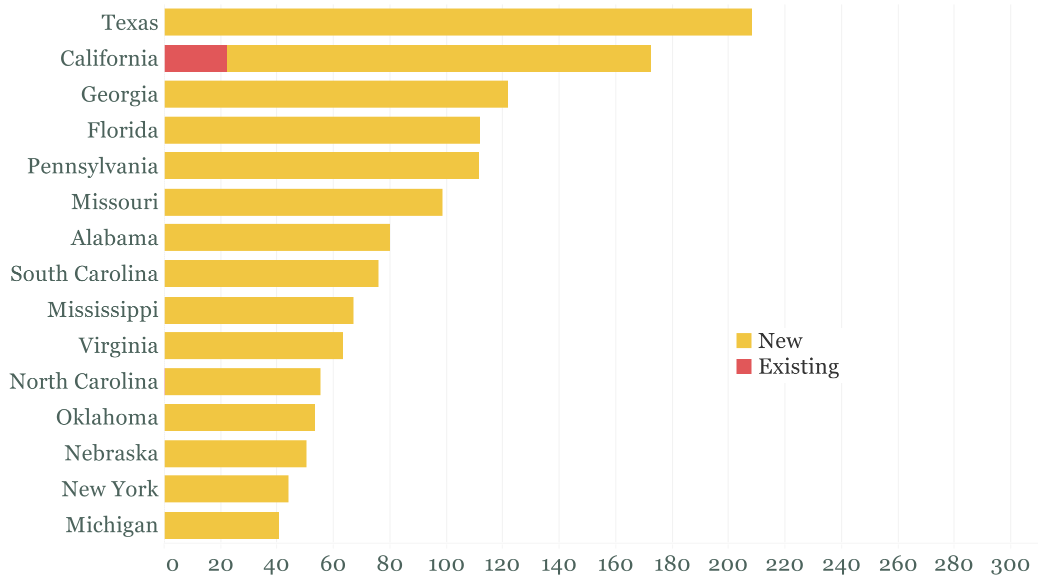


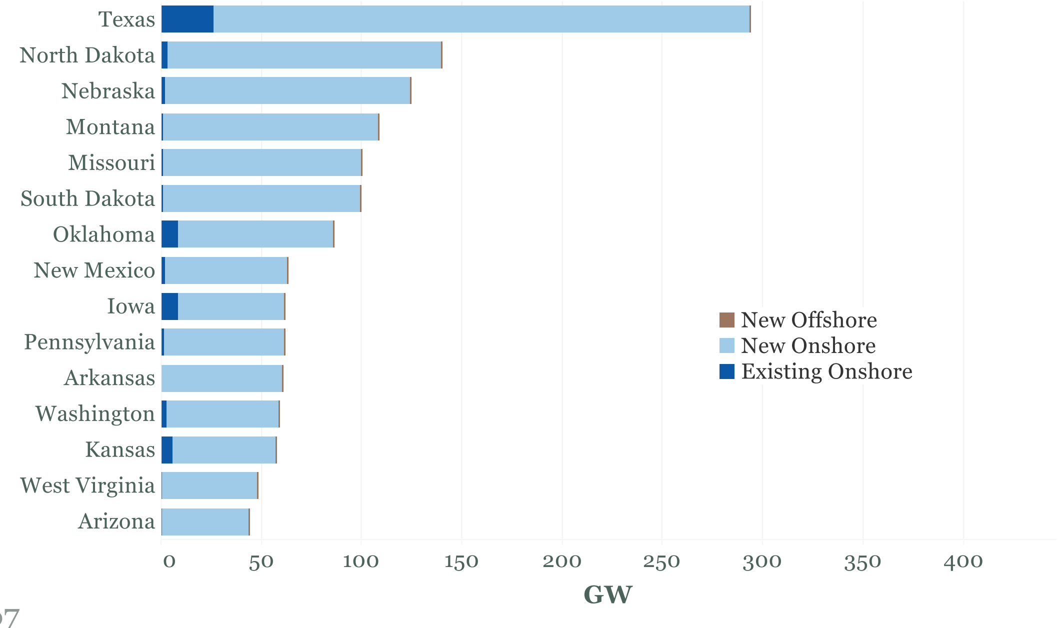


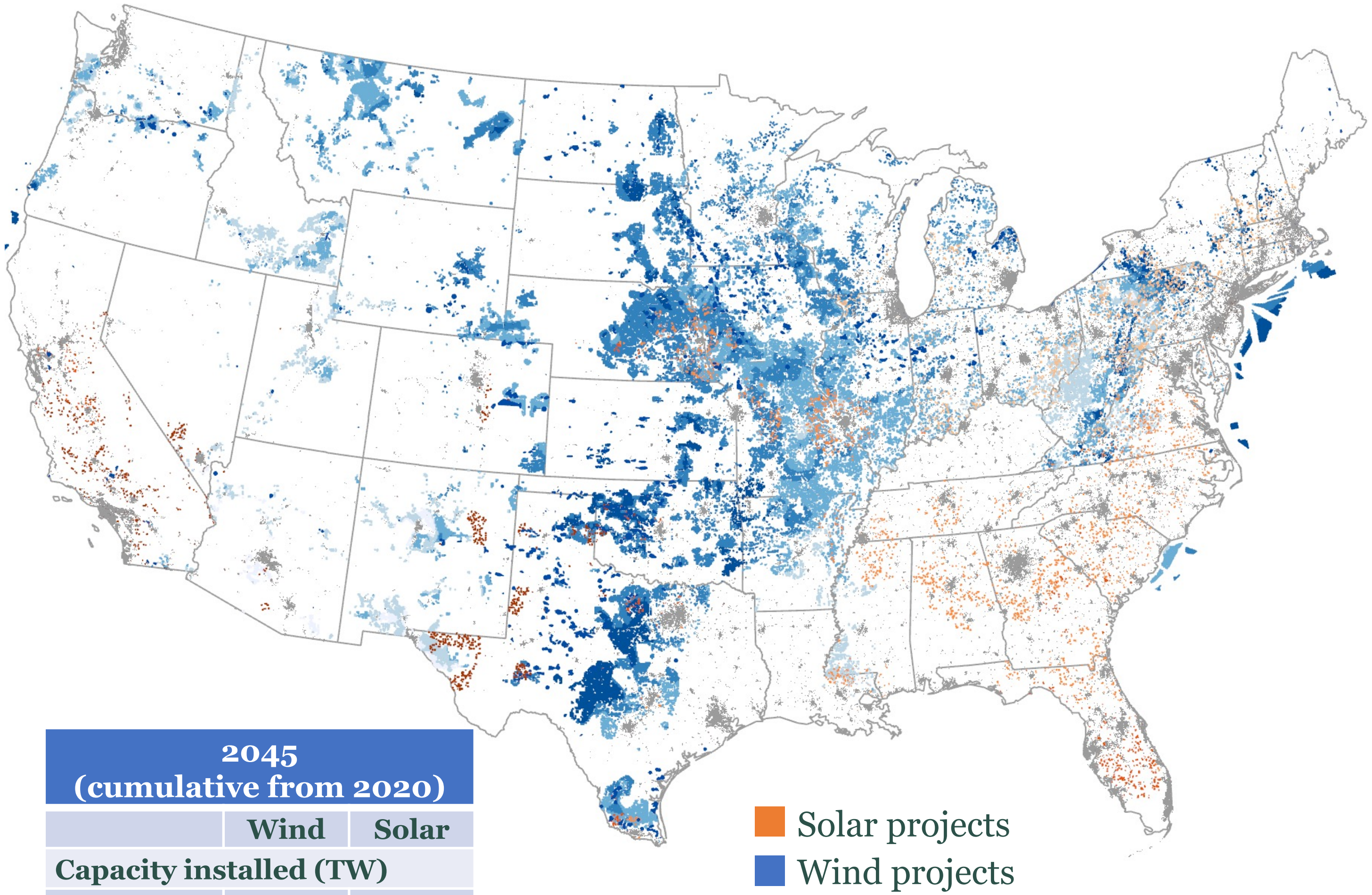
2040 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	1.41	1.23
Land area (1000 km²)		
Total	490	28.2
Direct	4.90	25.7
Capital invested (2018$)		
Trillion $	1.77	1.30

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ RE+ Constrained 2045



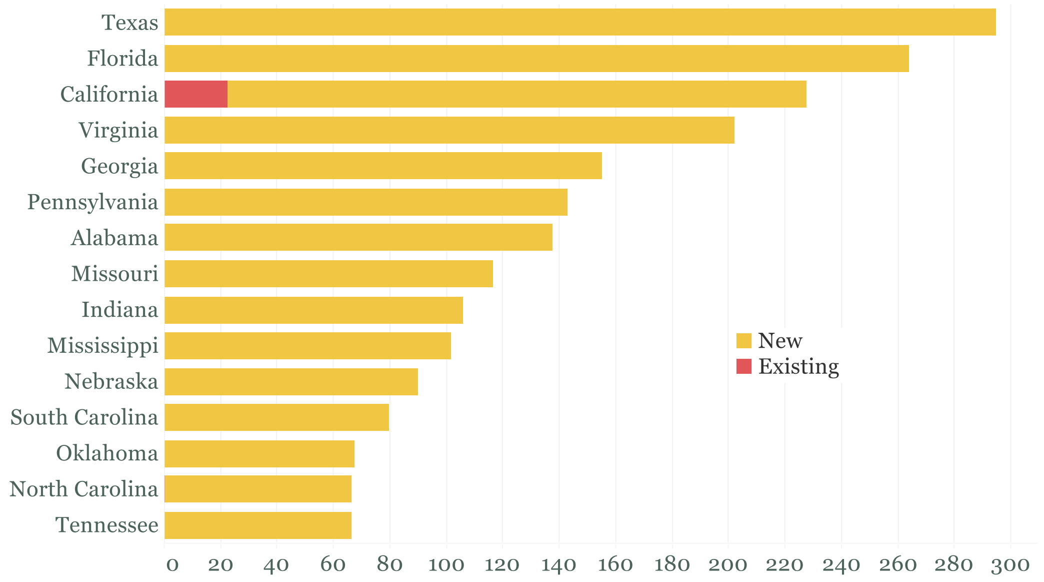


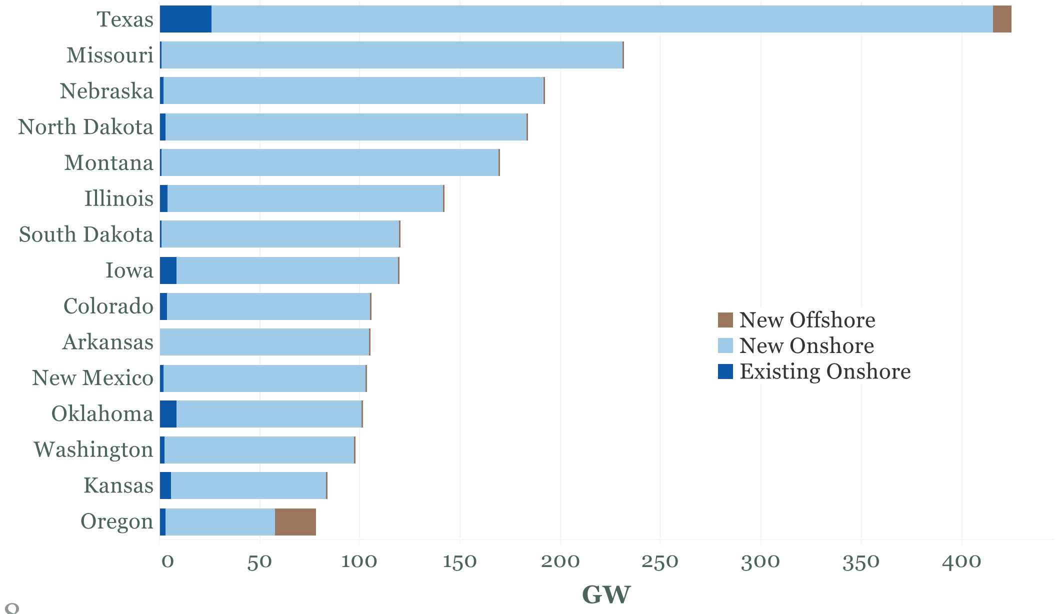


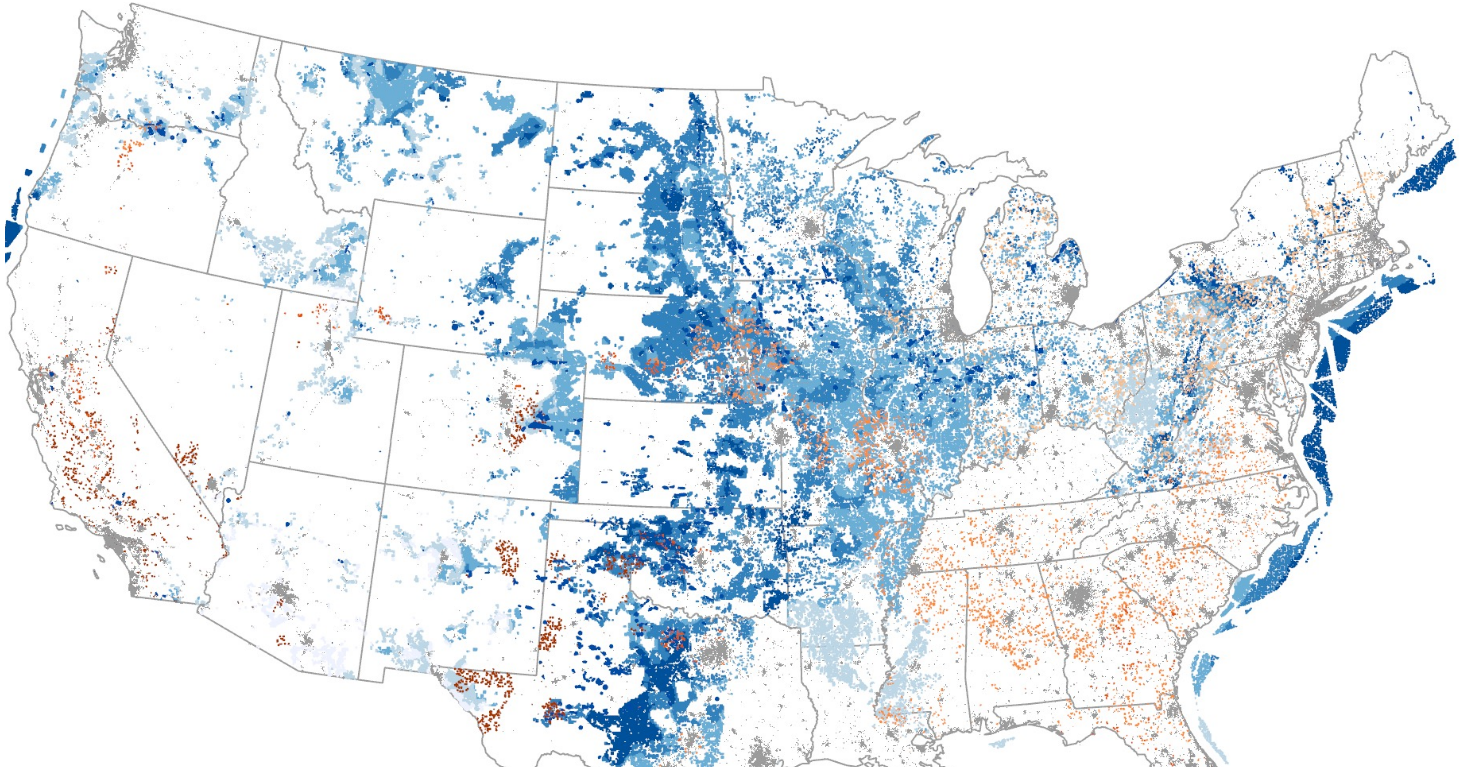
2045 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	1.89	1.71
Land area (1000 km²)		
Total	658	39.5
Direct	6.58	36.0
Capital invested (2018$)		
Trillion $	2.30	1.76

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ RE+ Constrained 2050



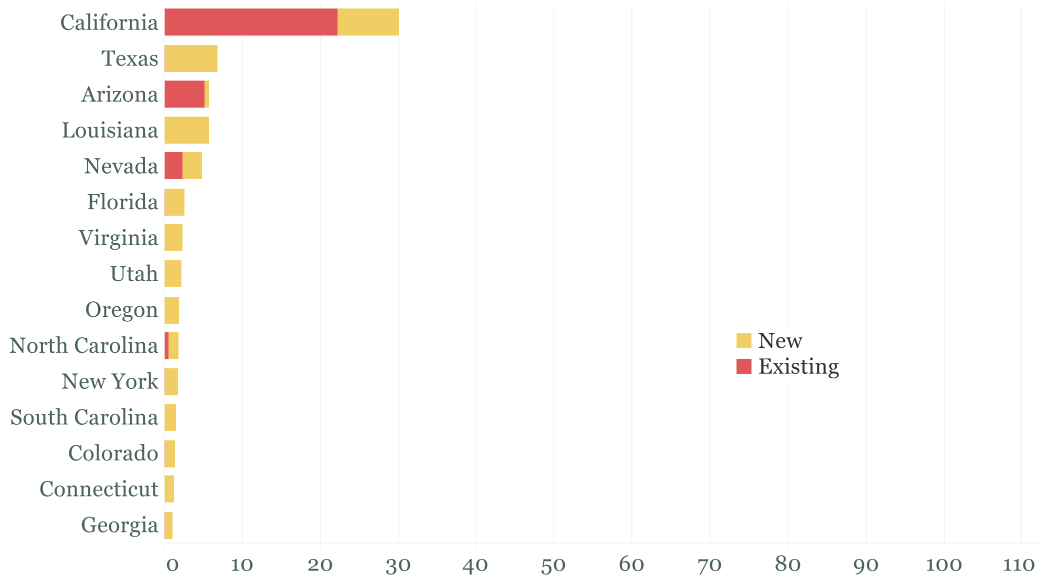


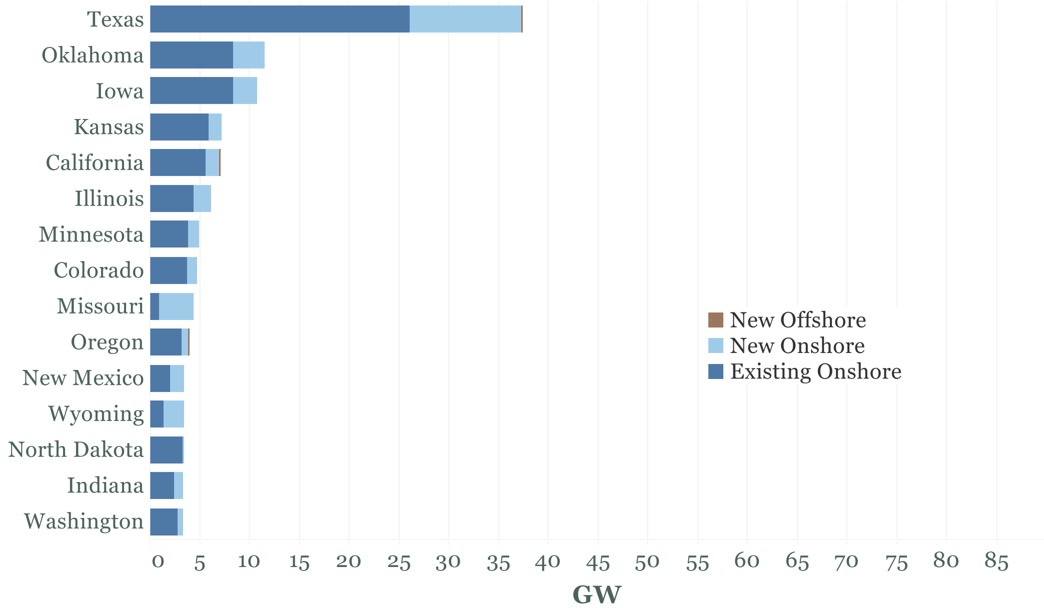


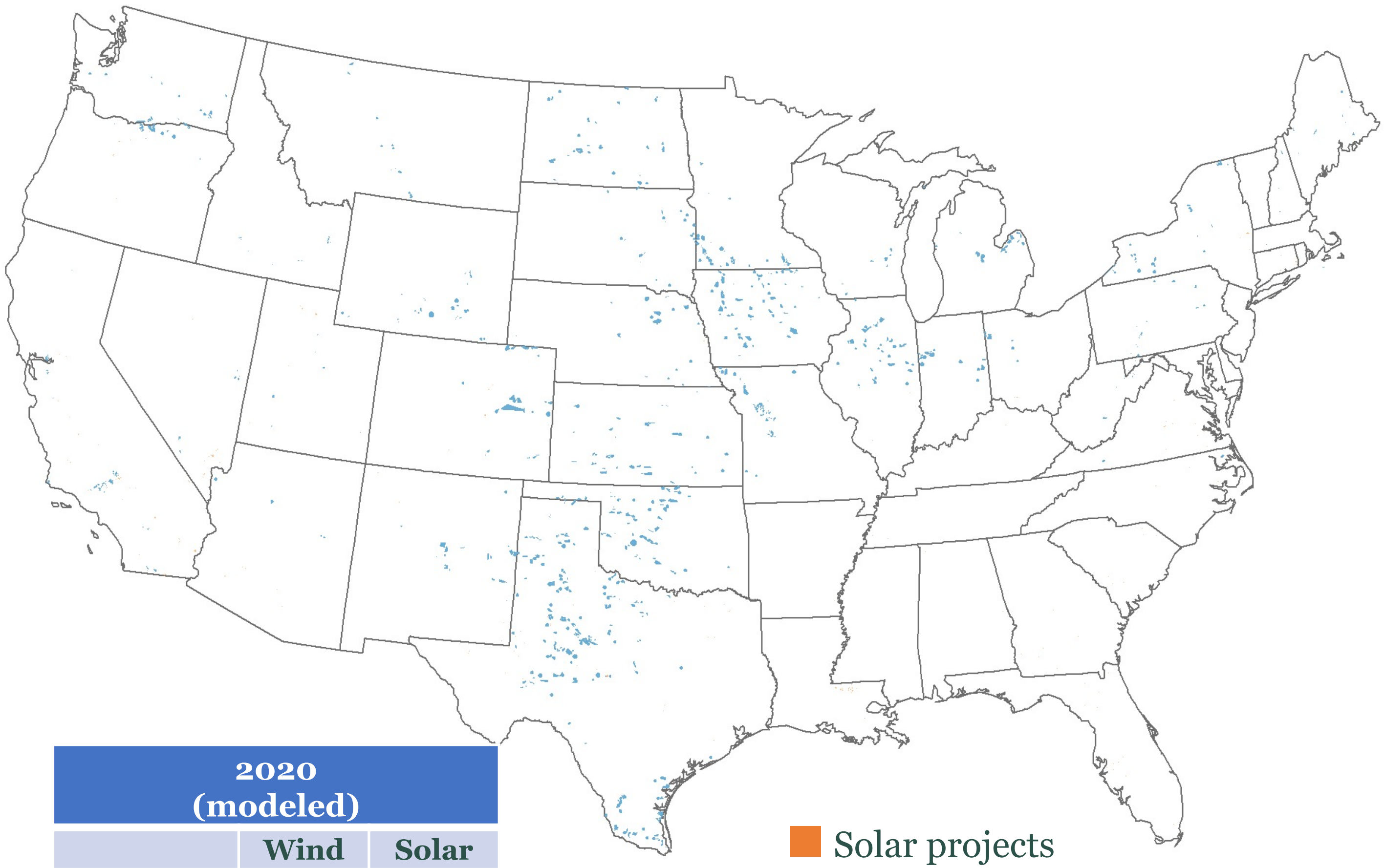
2050 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	3.25	2.77
Land area (1000 km²)		
Total	1,015	63.8
Direct	10.2	58.0
Capital invested (2018$)		
Trillion $	3.78	2.70

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ RE- Base 2020







2020 (modeled)		
	Wind	**Solar**
Capacity installed (TW)		
	0.14	0.08
Land area (1000 km²)		
Total	56	1.39
Direct	0.56	1.04
Capital invested (2018$)		
Trillion $	0.06	0.06

Solar projects
Wind projects

Note: *Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).*

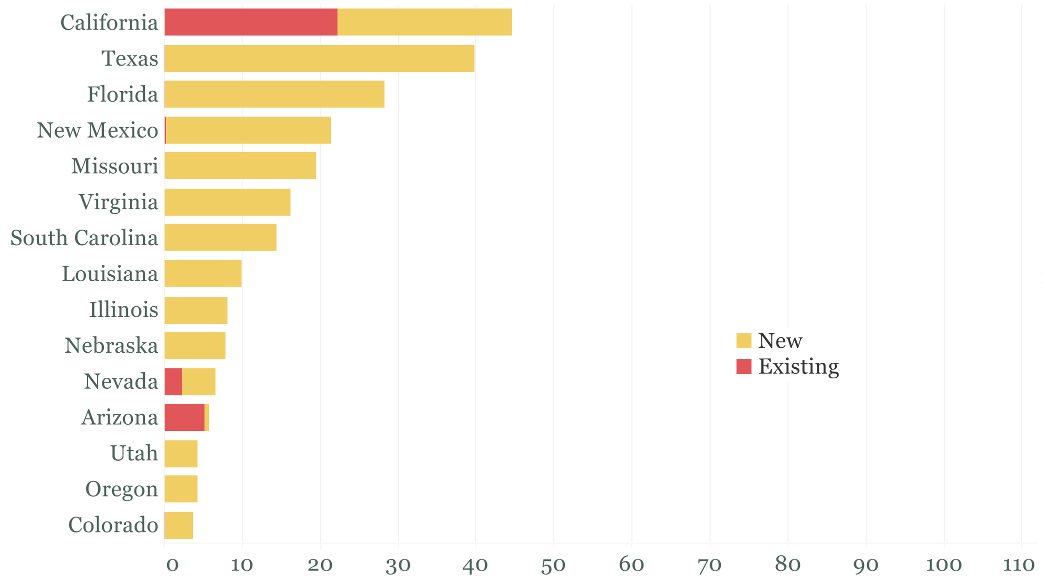
E+ RE- Base 2025

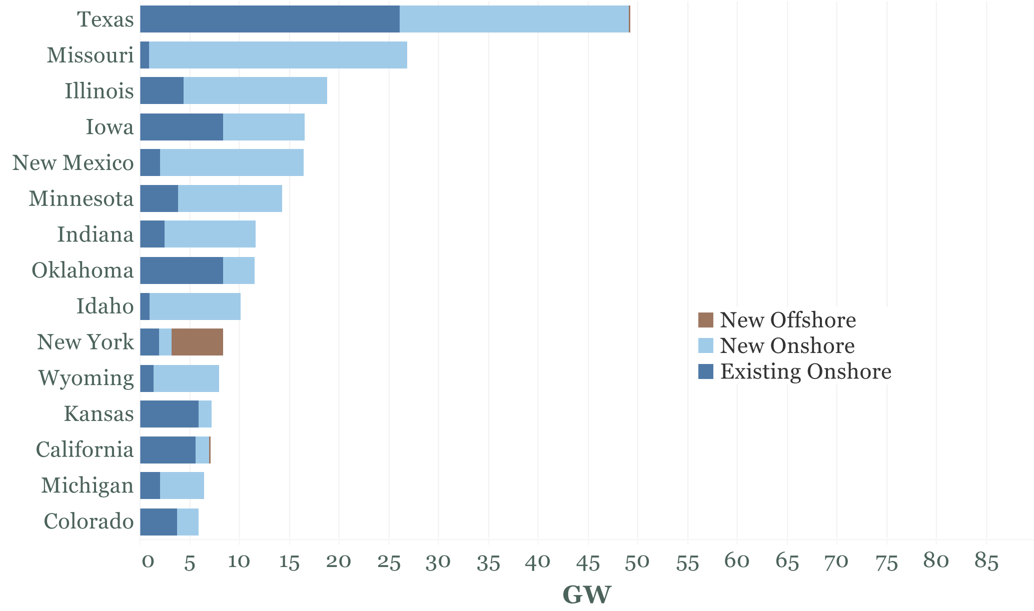
NOT GRAPHED

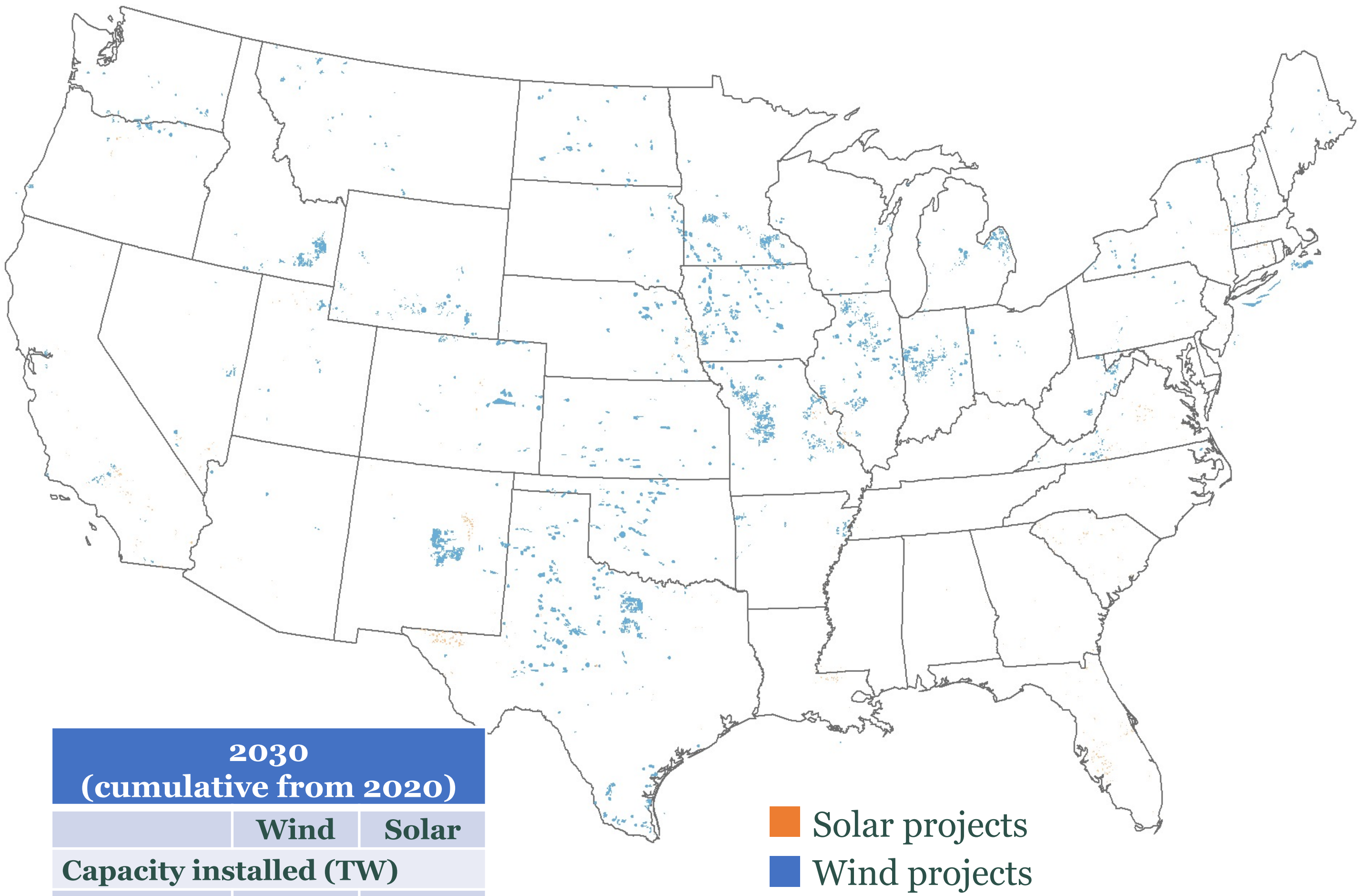
NOT MAPPED

2025 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.19	0.18
Land area (1000 km²)		
Total	73	3.60
Direct	0.73	3.27
Capital invested (2018$)		
Trillion $	0.14	0.19

E+ RE- Base 2030







2030 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.27	0.27
Land area (1000 km²)		
Total	102	5.79
Direct	1.02	5.27
Capital invested (2018$)		
Trillion $	0.26	0.29

Note: *Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).*

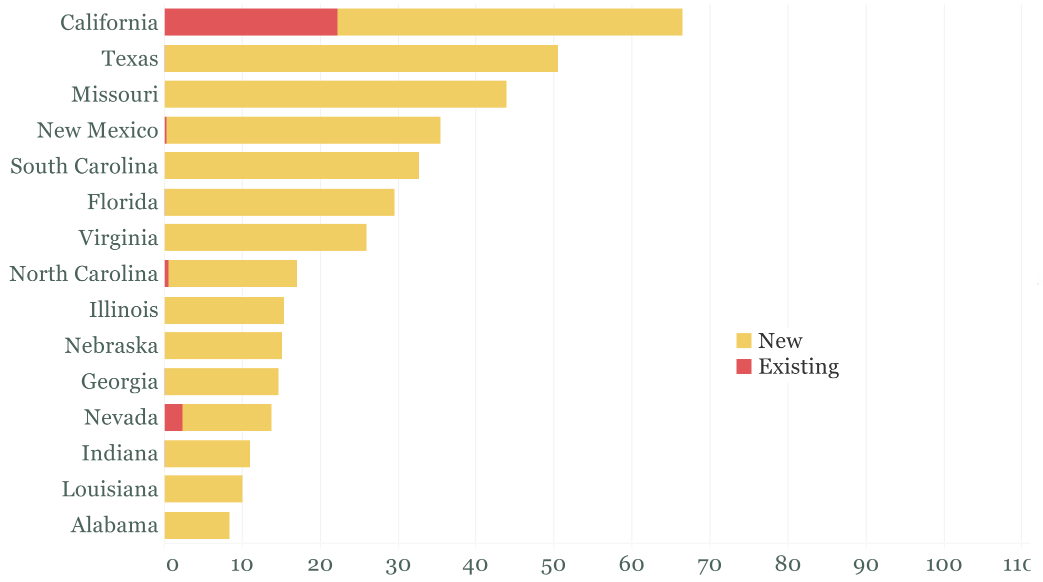
E+ RE- Base 2035

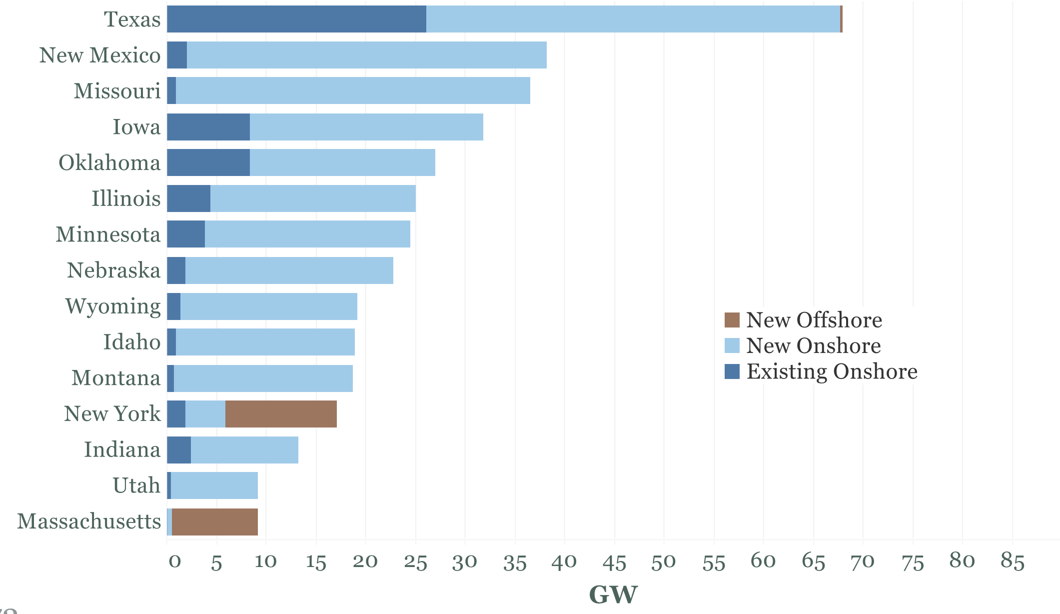
NOT GRAPHED

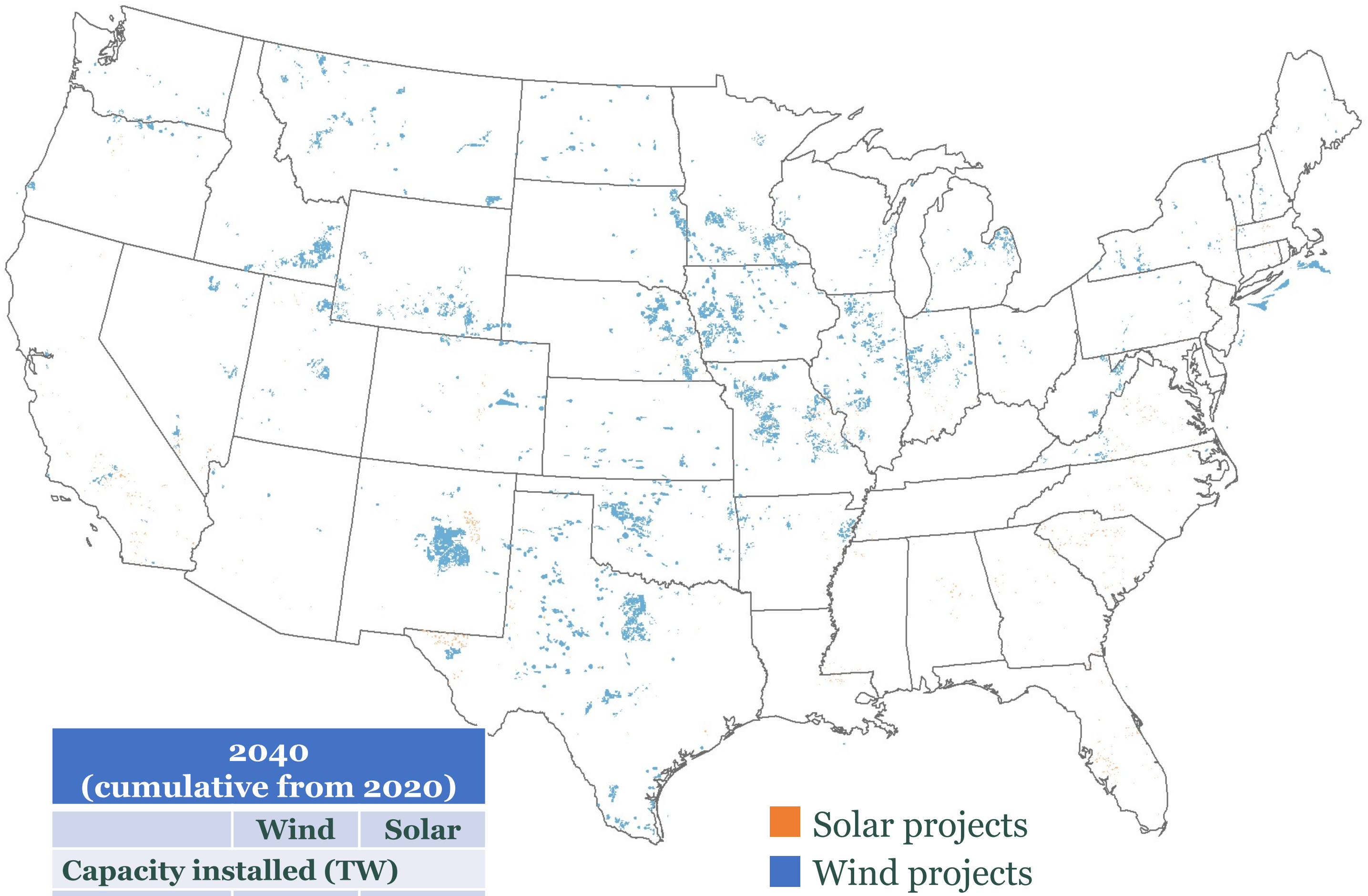
NOT MAPPED

2035 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.34	0.35
Land area (1000 km²)		
Total	126	7.78
Direct	1.26	7.08
Capital invested (2018$)		
Trillion $	0.36	0.38

E+ RE- Base 2040







2040 (cumulative from 2020)		
	Wind	Solar
Capacity installed (TW)		
	0.47	0.46
Land area (1000 km²)		
Total	170	10.1
Direct	1.70	9.19
Capital invested (2018$)		
Trillion $	0.50	0.49

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

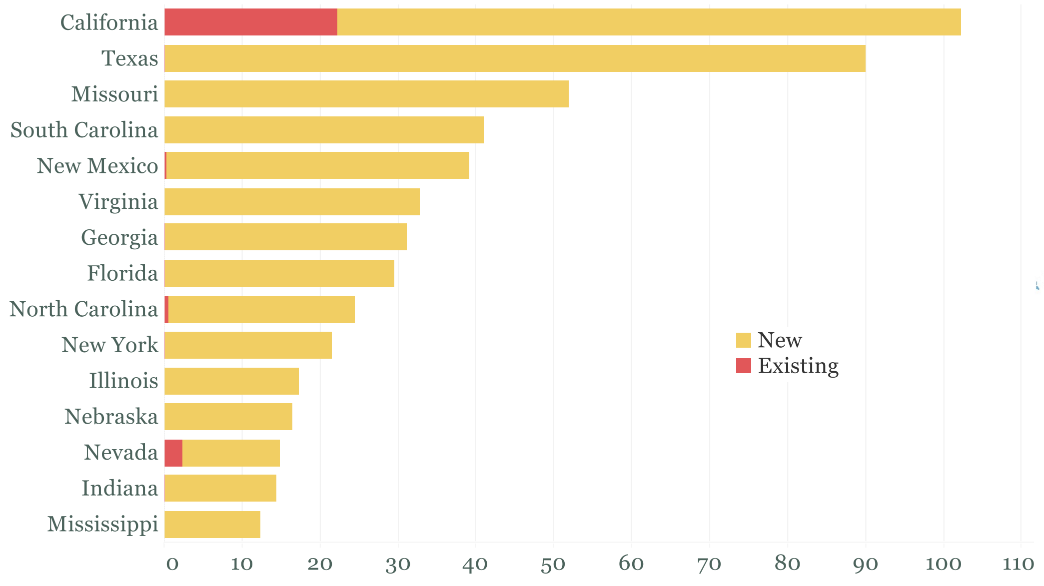
E+ RE- Base 2045

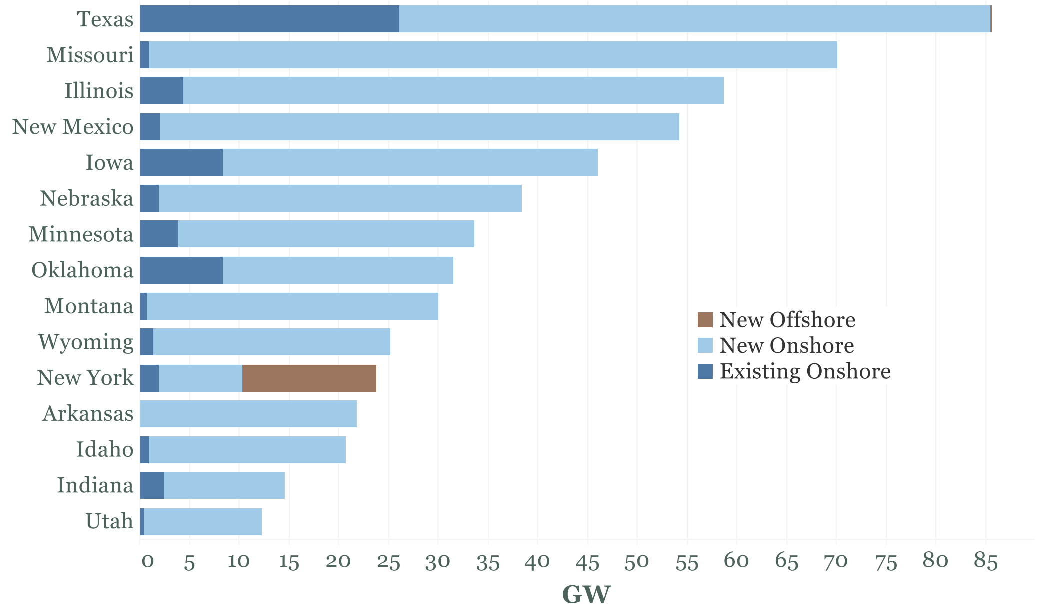
NOT GRAPHED

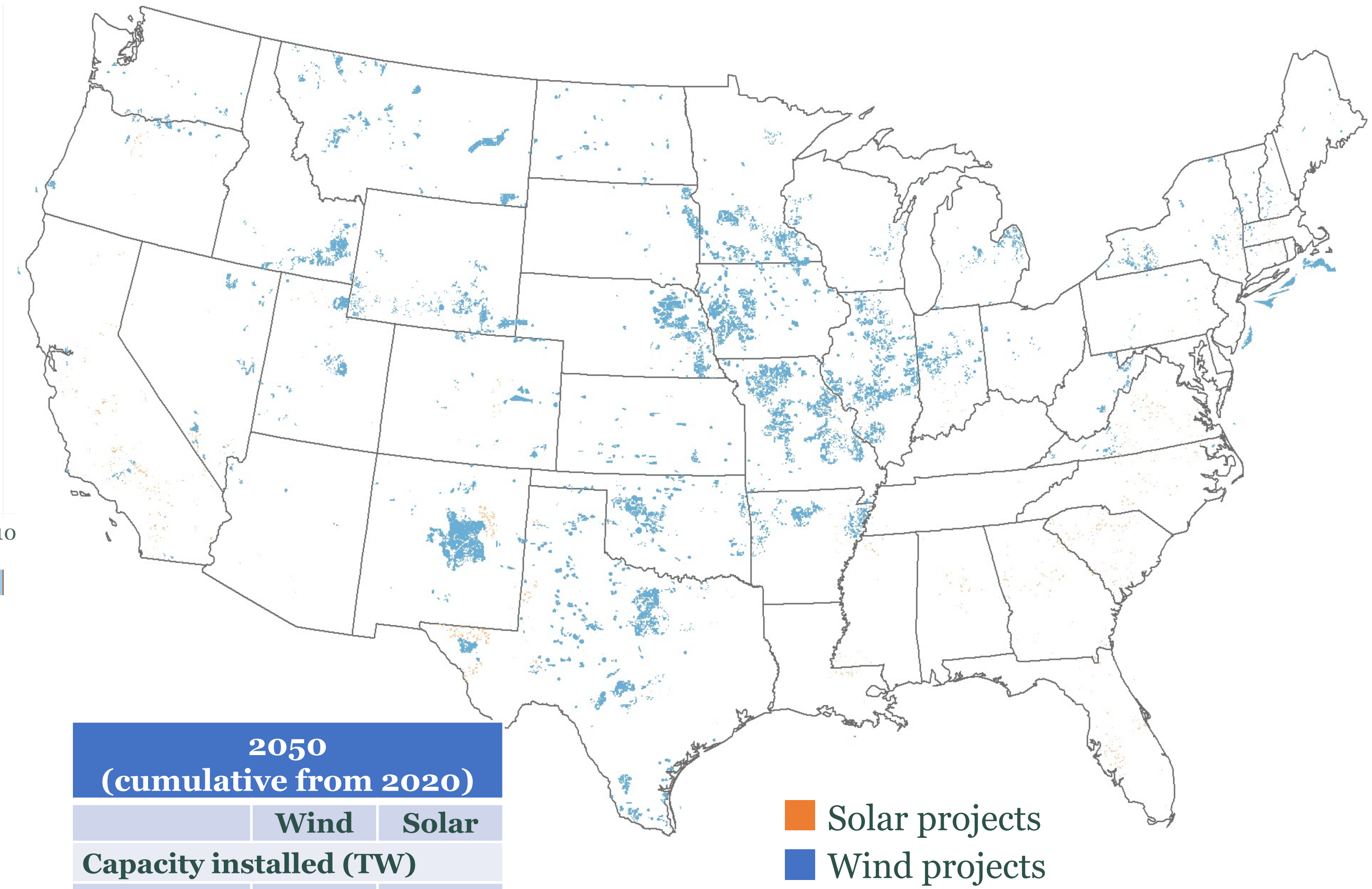
NOT MAPPED

2045 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.59	0.56
Land area (1000 km²)		
Total	214	12.4
Direct	2.14	11.3
Capital invested (2018$)		
Trillion $	0.63	0.59

E+ RE- Base 2050



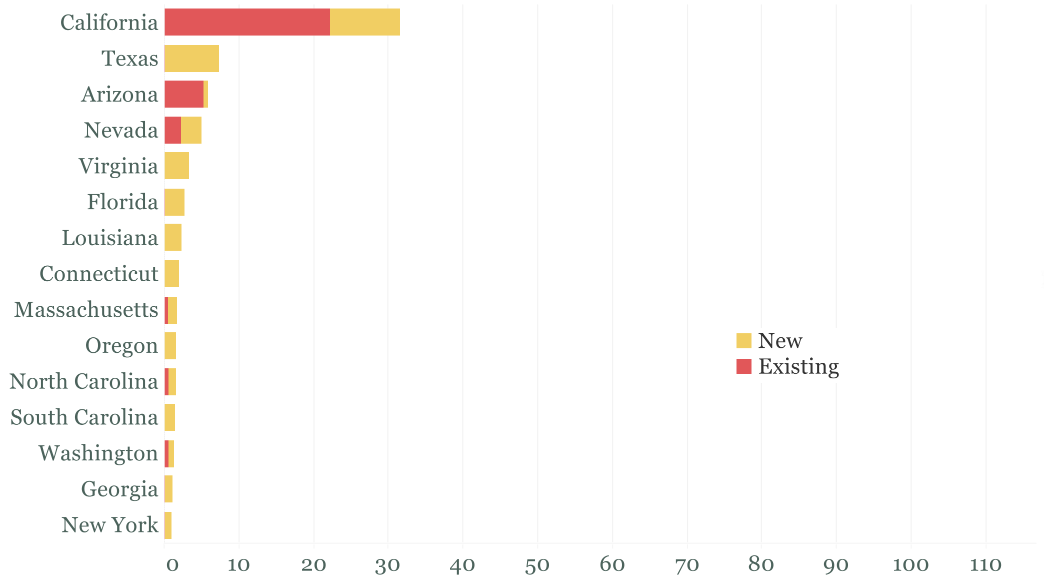


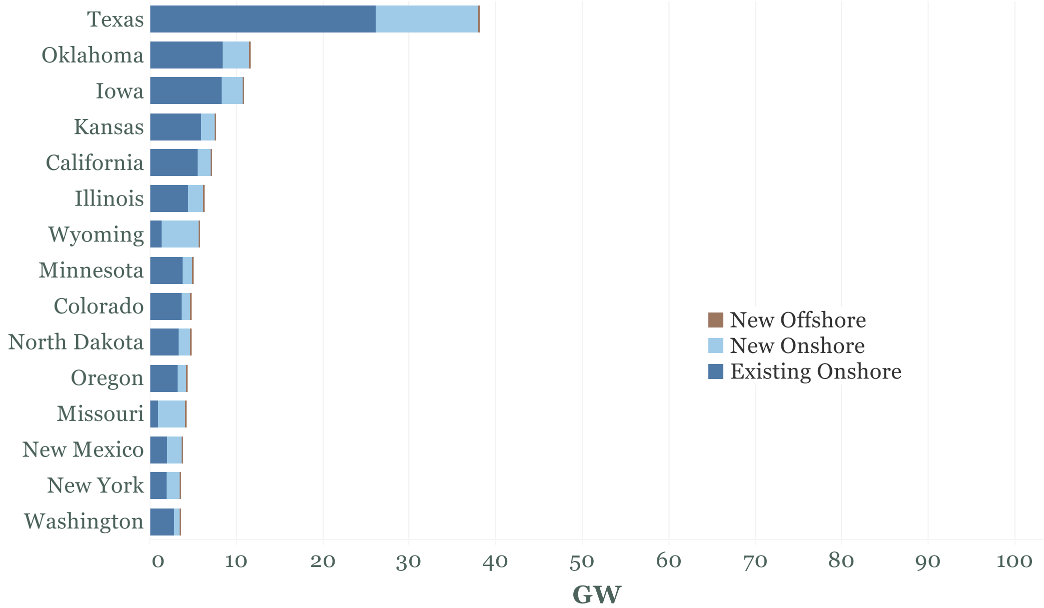


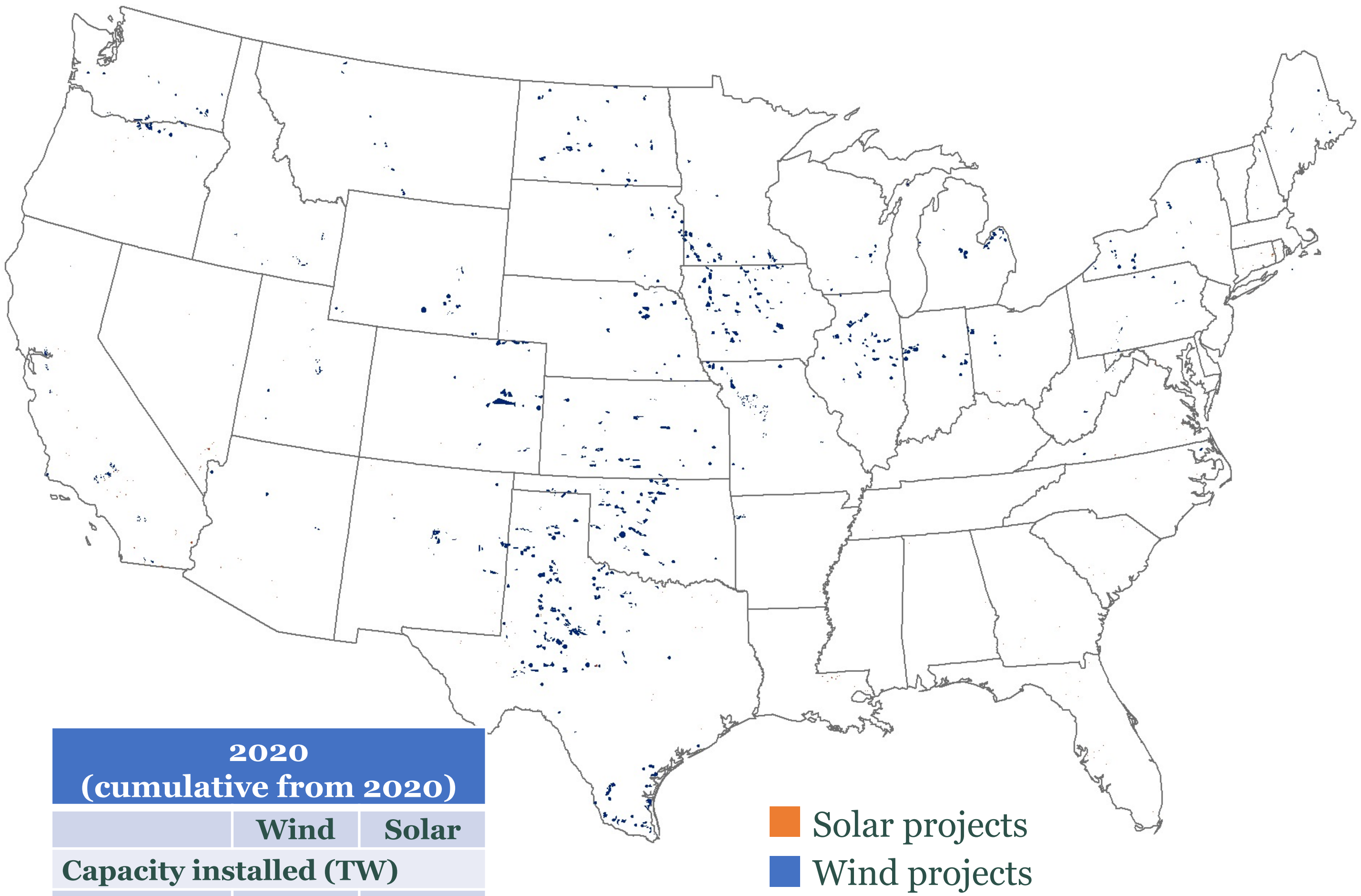
2050 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.67	0.64
Land area (1000 km²)		
Total	244	14.2
Direct	2.44	13.0
Capital invested (2018$)		
Trillion $	0.73	0.66

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

E+ RE- Constrained 2020







2020 (cumulative from 2020)		
	Wind	Solar
Capacity installed (TW)		
	0.14	0.08
Land area (1000 km²)		
Total	56	1.31
Direct	0.56	1.19
Capital invested (2018$)		
Trillion $	0.07	0.06

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

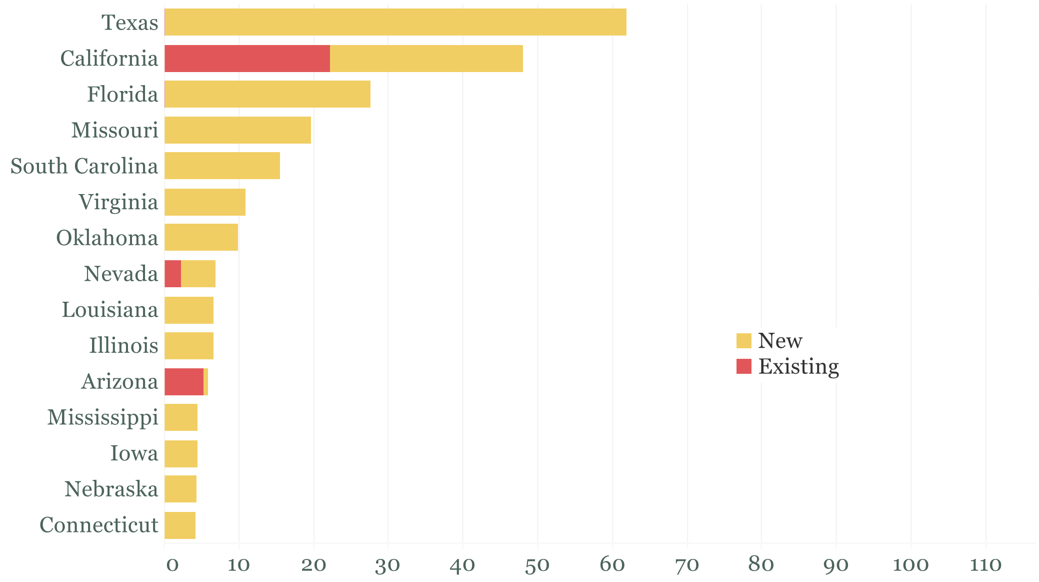
E+ RE- Constrained 2025

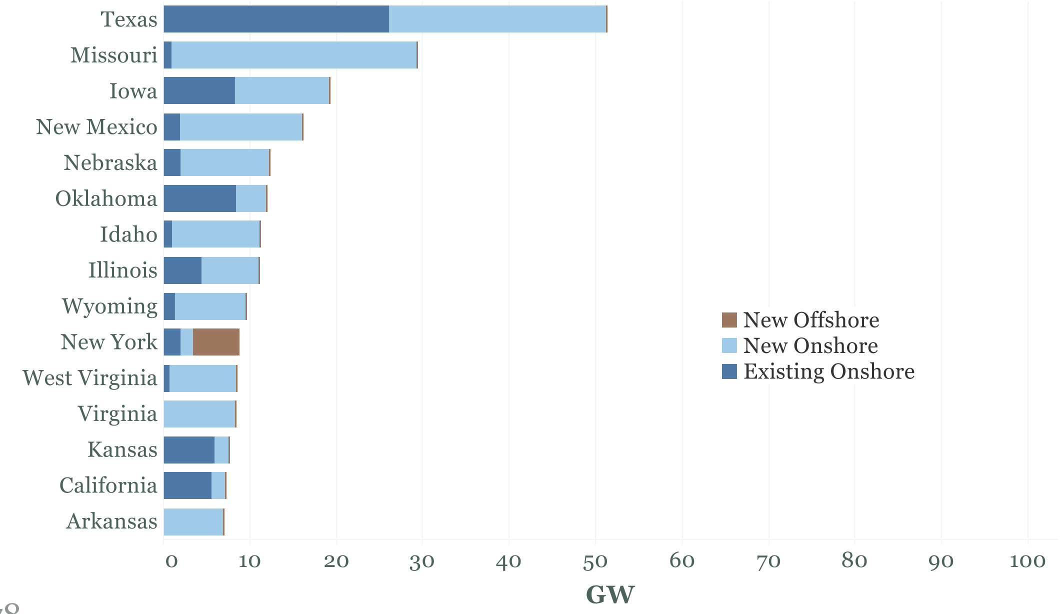
NOT GRAPHED

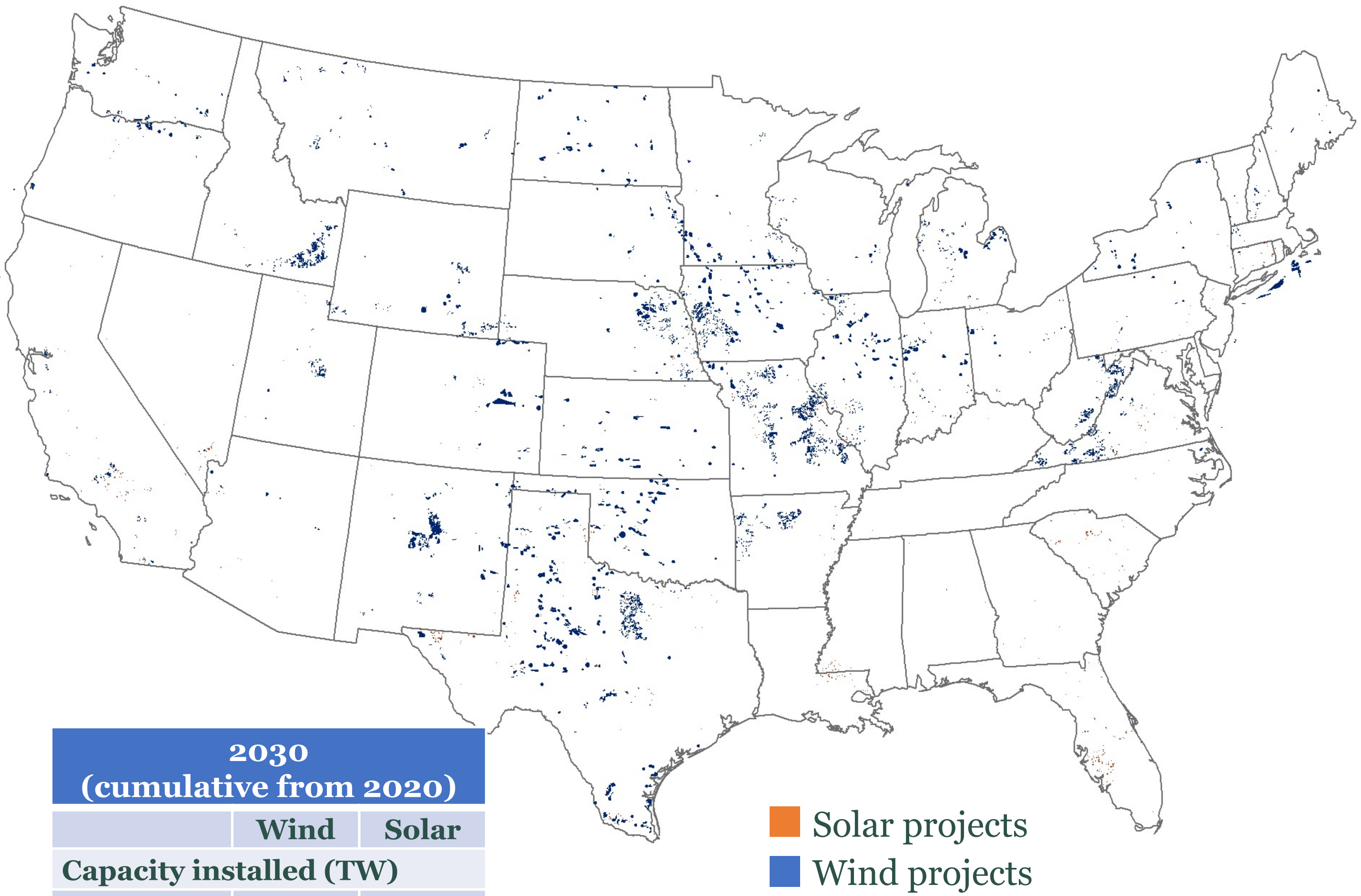
NOT MAPPED

2025 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.19	0.17
Land area (1000 km²)		
Total	73	3.45
Direct	0.73	3.14
Capital invested (2018$)		
Trillion $	0.16	0.18

E+ RE- Constrained 2030







2030 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.28	0.27
Land area (1000 km²)		
Total	104	5.65
Direct	1.04	5.14
Capital invested (2018$)		
Trillion $	0.28	0.30

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

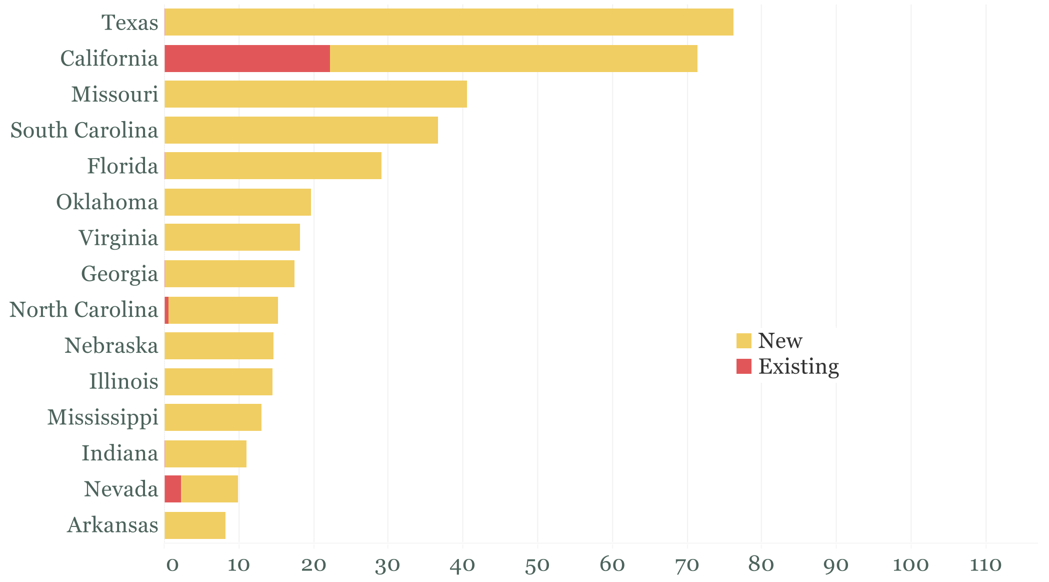
E+ RE- Constrained 2035

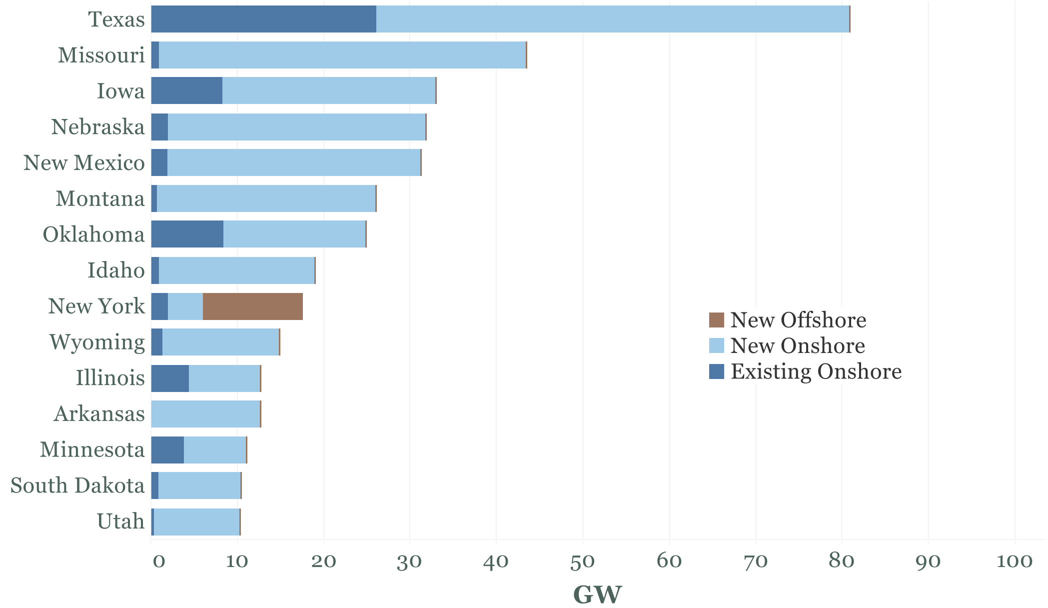
NOT GRAPHED

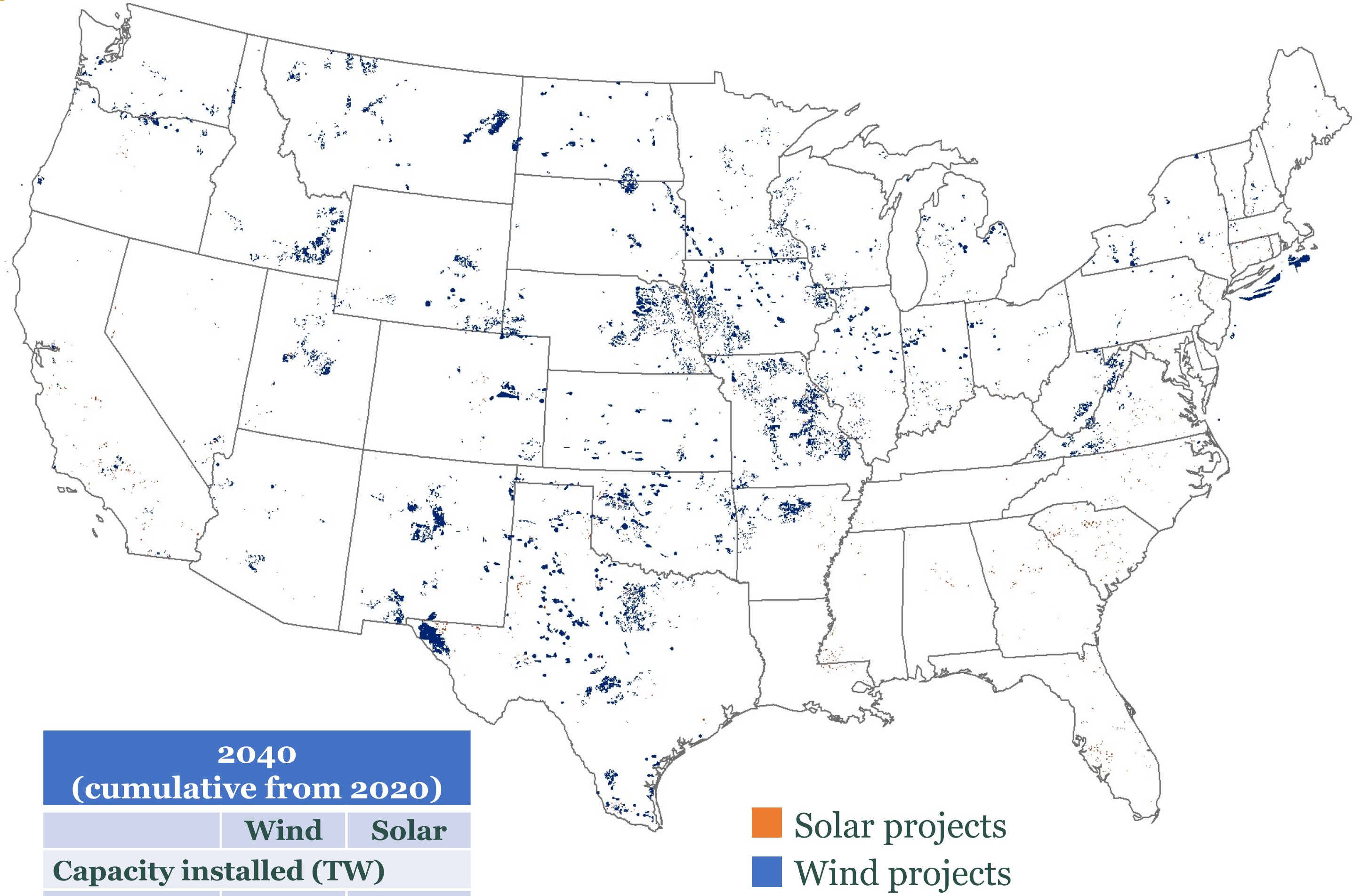
NOT MAPPED

2035 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.36	0.37
Land area (1000 km²)		
Total	129	7.74
Direct	1.29	7.04
Capital invested (2018$)		
Trillion $	0.38	0.40

E+ RE- Constrained 2040







2040 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.49	0.48
Land area (1000 km²)		
Total	176	10.2
Direct	1.76	9.32
Capital invested (2018$)		
Trillion $	0.53	0.51

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color)

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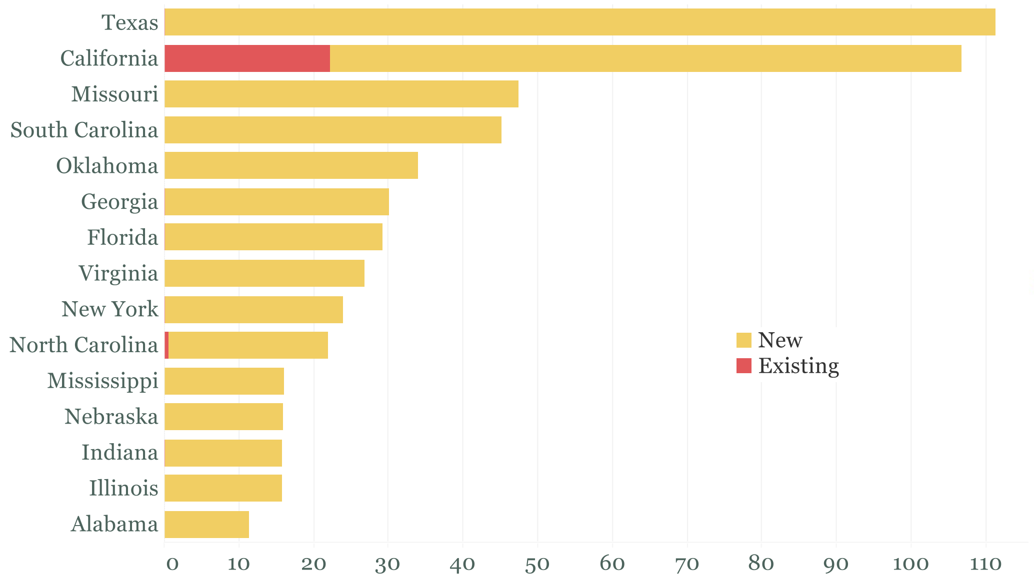
E+ RE- Constrained 2045

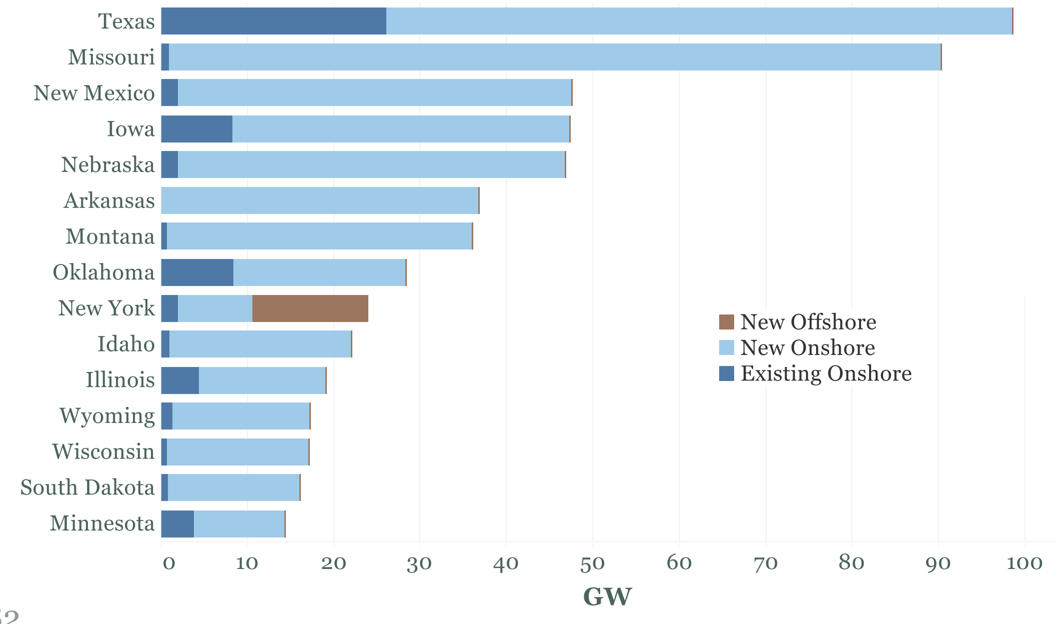
NOT GRAPHED

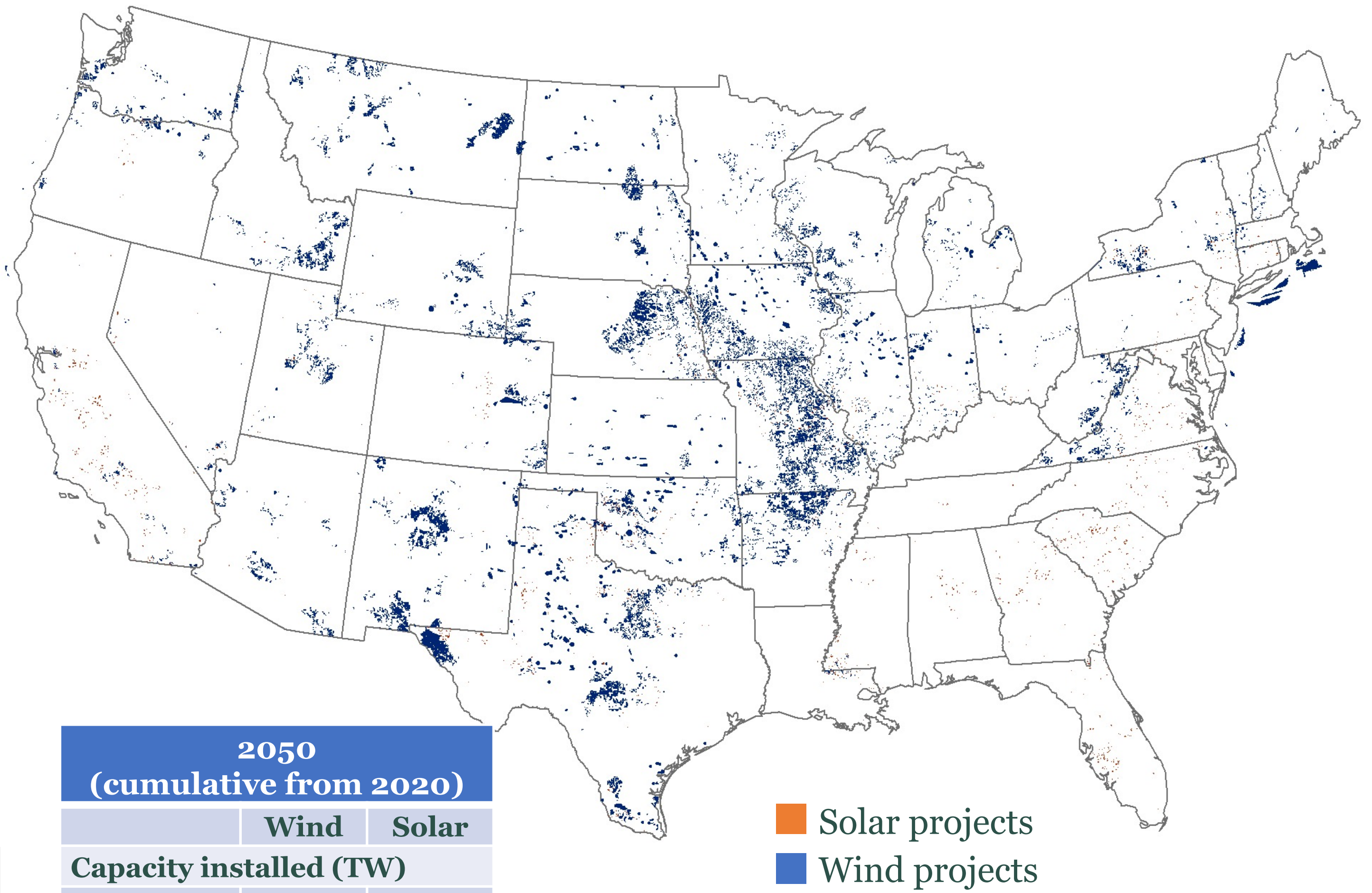
NOT MAPPED

2045 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.62	0.59
Land area (1000 km²)		
Total	222	12.9
Direct	2.22	11.7
Capital invested (2018$)		
Trillion $	0.68	0.61

E+ RE- Constrained 2050

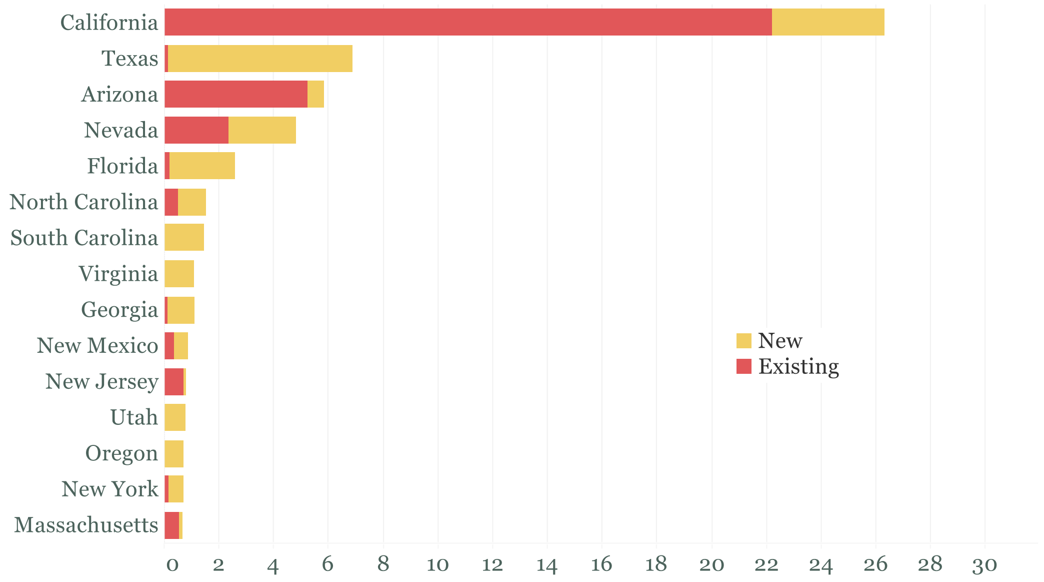


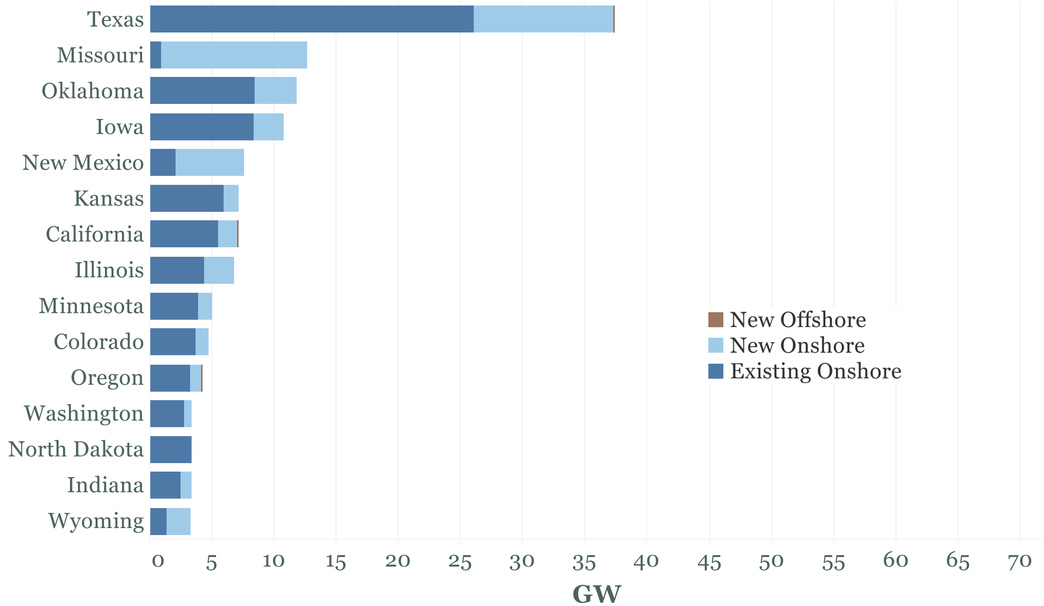


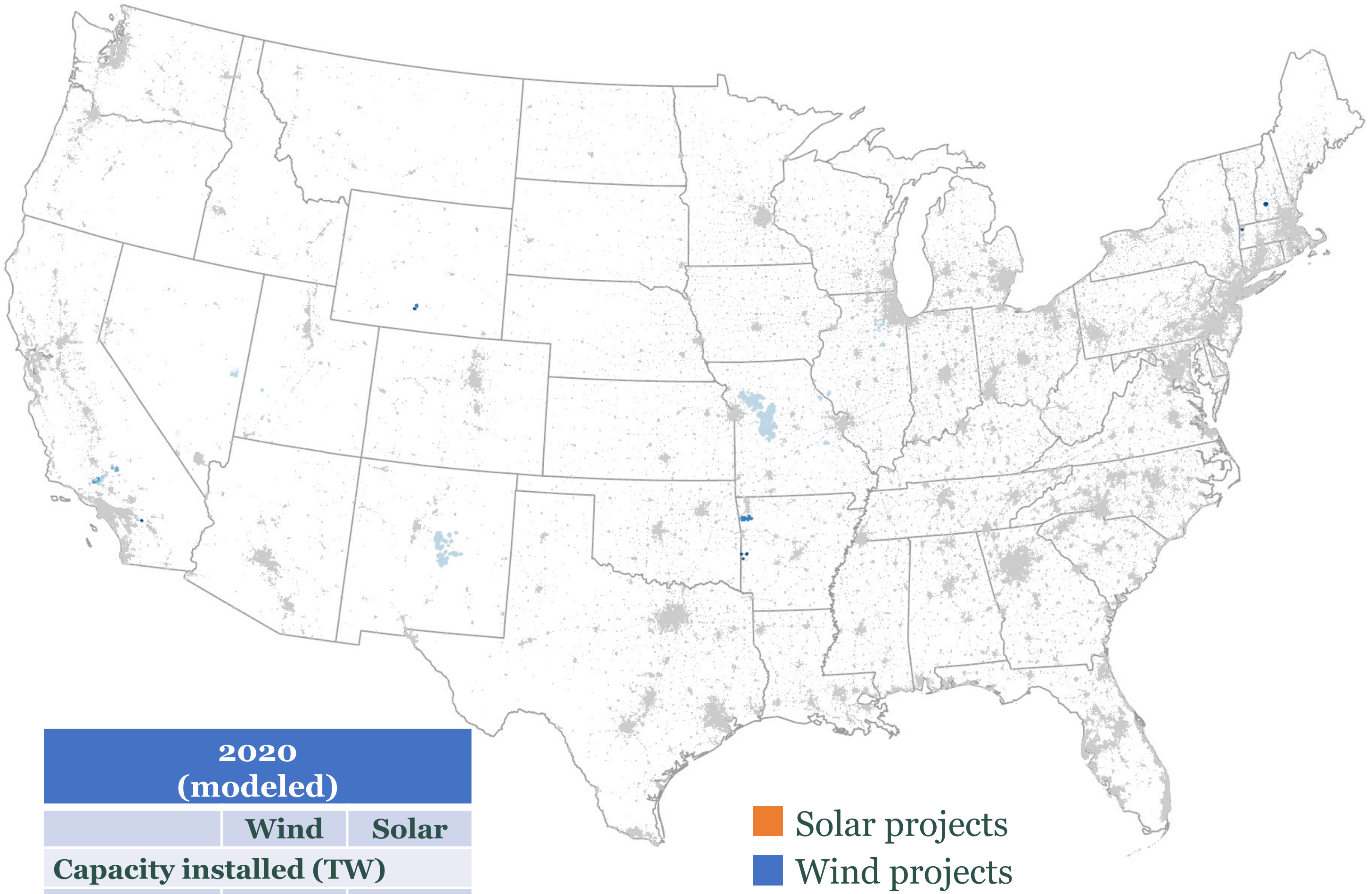


2050 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.71	0.67
Land area (1000 km²)		
Total	256	14.8
Direct	2.56	13.5
Capital invested (2018$)		
Trillion $	0.78	0.68

REF Base 2020







2020 (modeled)		
	Wind	**Solar**
Capacity installed (TW)		
	0.15	0.06
Land area (1000 km²)		
Total	62	0.95
Direct	0.62	0.86
Capital invested (2018$)		
Trillion $	0.08	0.04

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

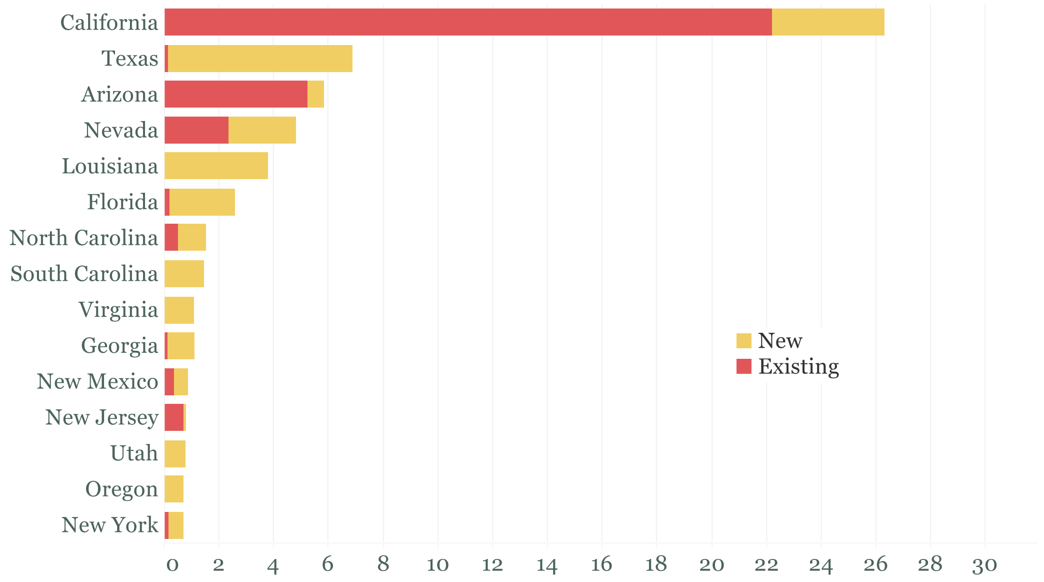
REF Base 2025

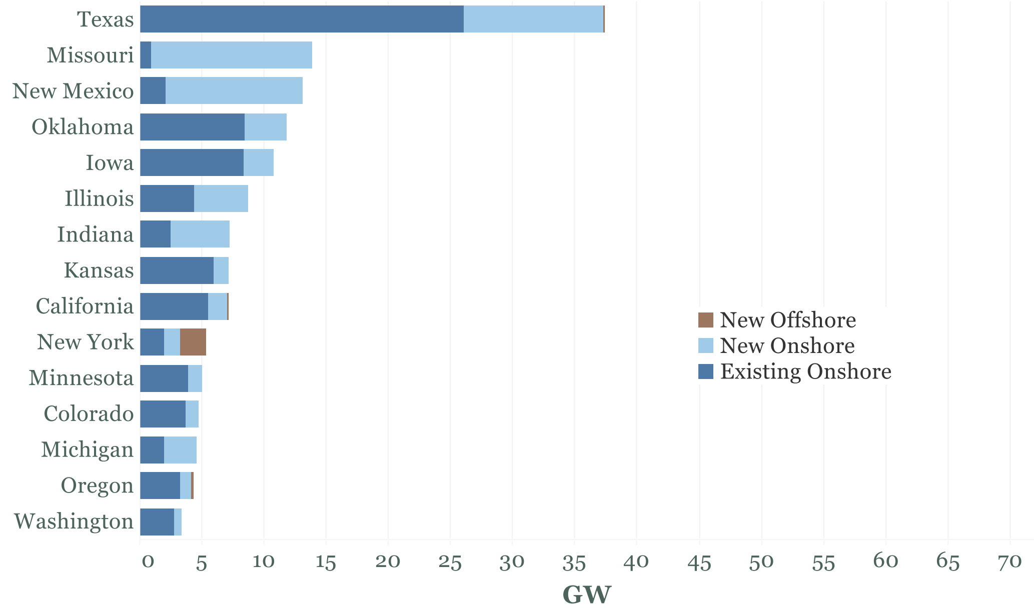
NOT GRAPHED

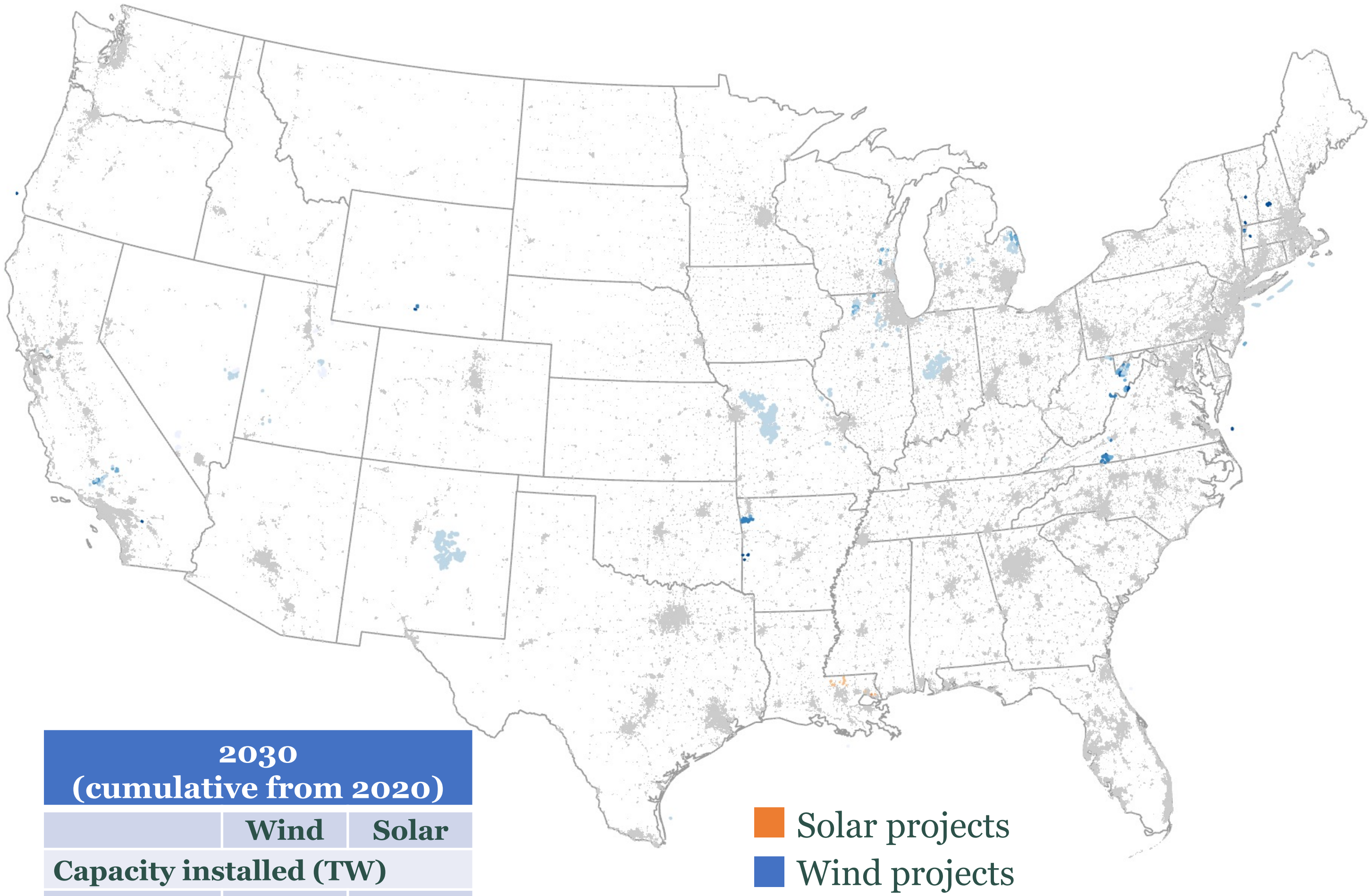
NOT MAPPED

2025 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.15	0.06
Land area (1000 km^2)		
Total	62	0.95
Direct	0.62	0.62
Capital invested (2018$)		
Trillion $	0.09	0.04

REF Base 2030







2030 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.17	0.06
Land area (1000 km²)		
Total	69	1.02
Direct	0.69	0.92
Capital invested (2018$)		
Trillion $	0.12	0.04

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

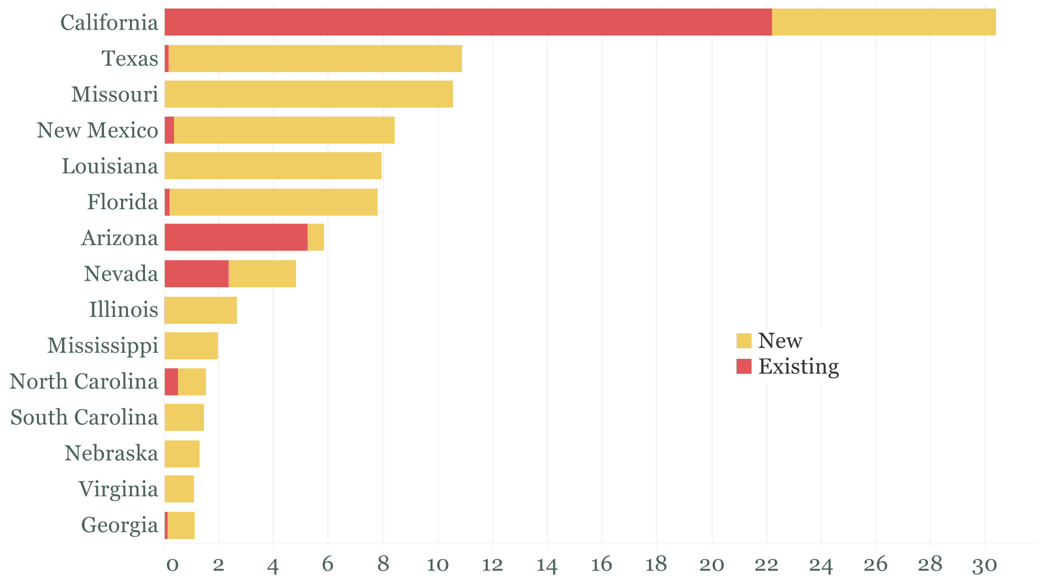
REF Base 2035

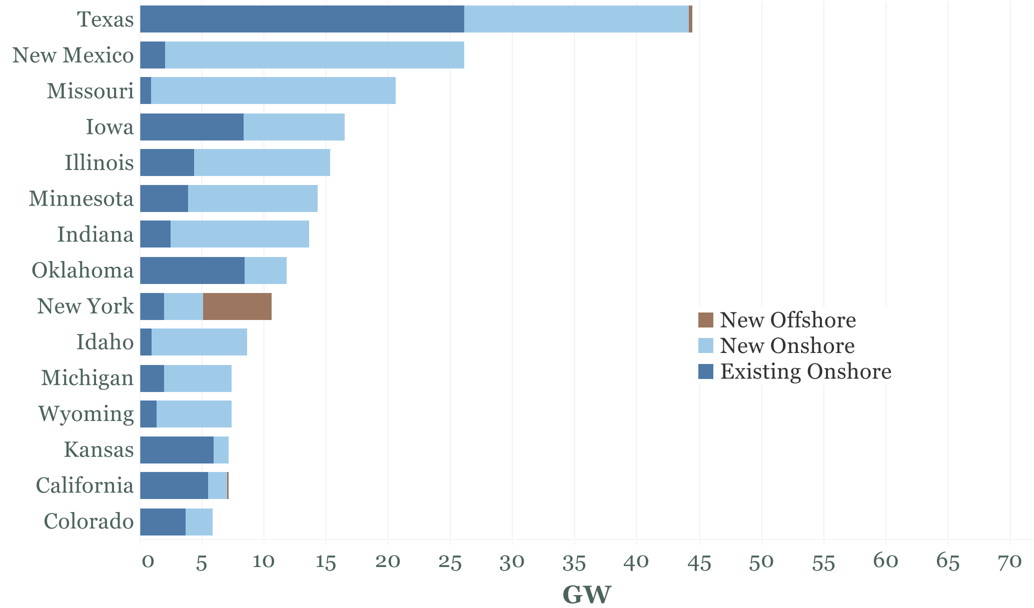
NOT GRAPHED

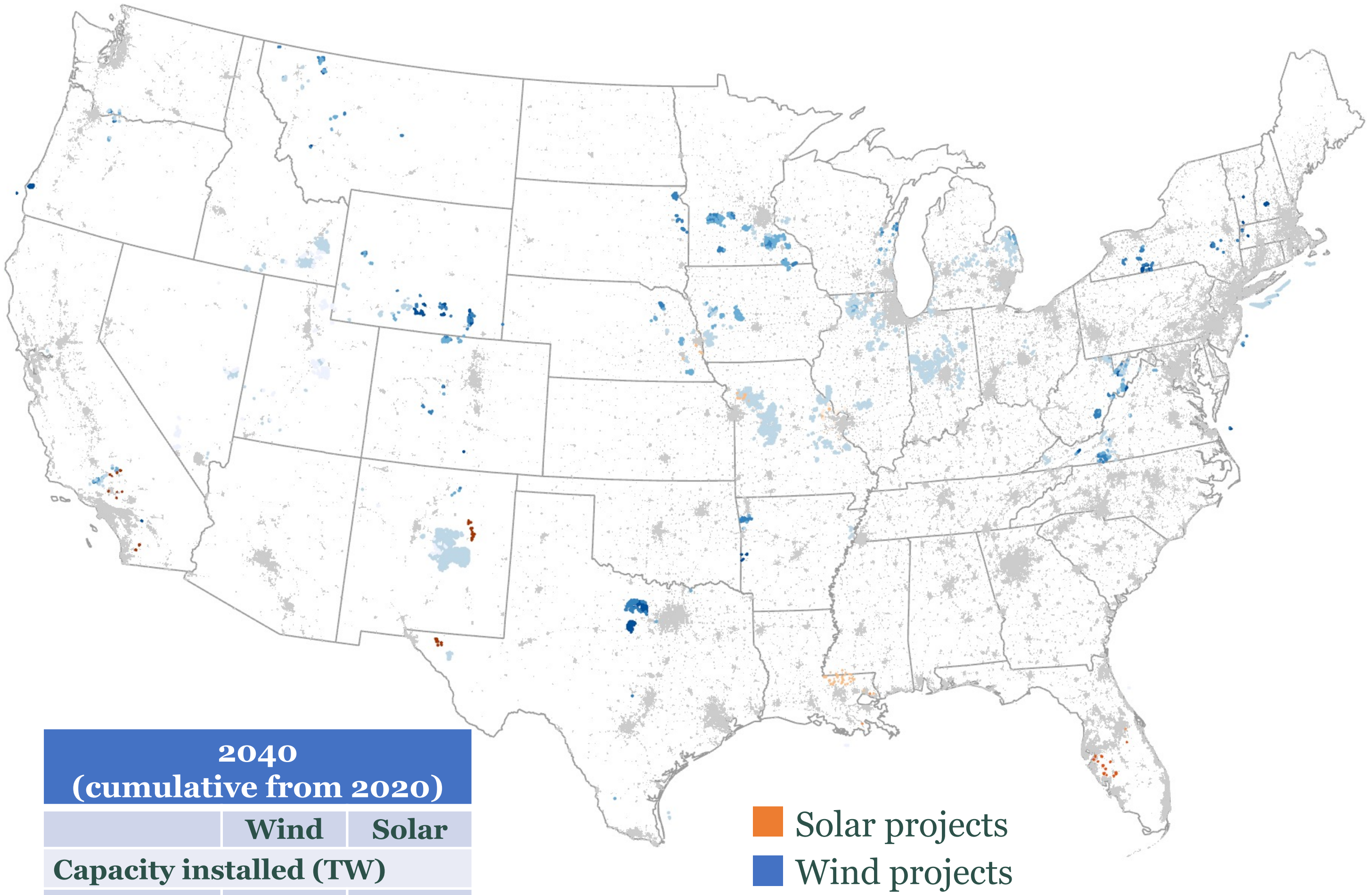
NOT MAPPED

2035 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.19	0.08
Land area (1000 km^2)		
Total	75	1.26
Direct	0.75	1.15
Capital invested (2018$)		
Trillion $	0.15	0.06

REF Base 2040







2040 (cumulative from 2020)		
	Wind	Solar
Capacity installed (TW)		
	0.27	0.11
Land area (1000 km²)		
Total	102	1.87
Direct	1.02	1.70
Capital invested (2018$)		
Trillion $	0.23	0.08

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).

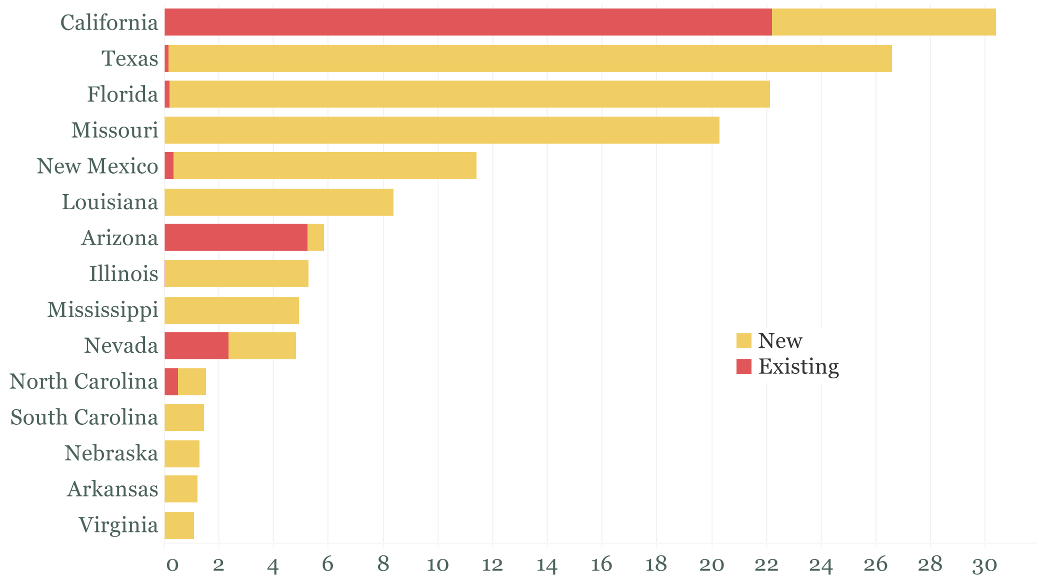
REF Base 2045

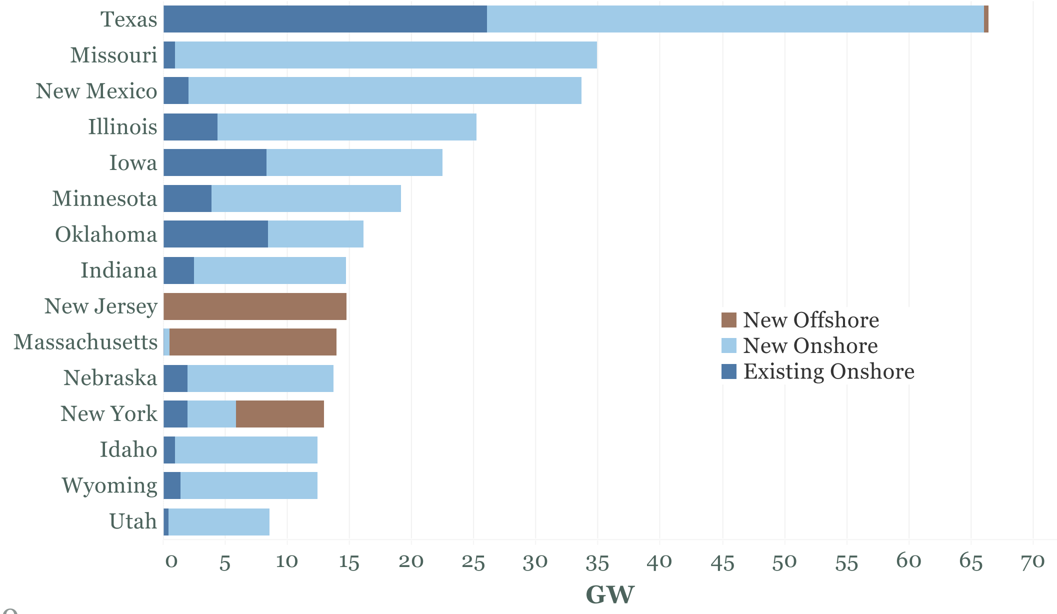
NOT GRAPHED

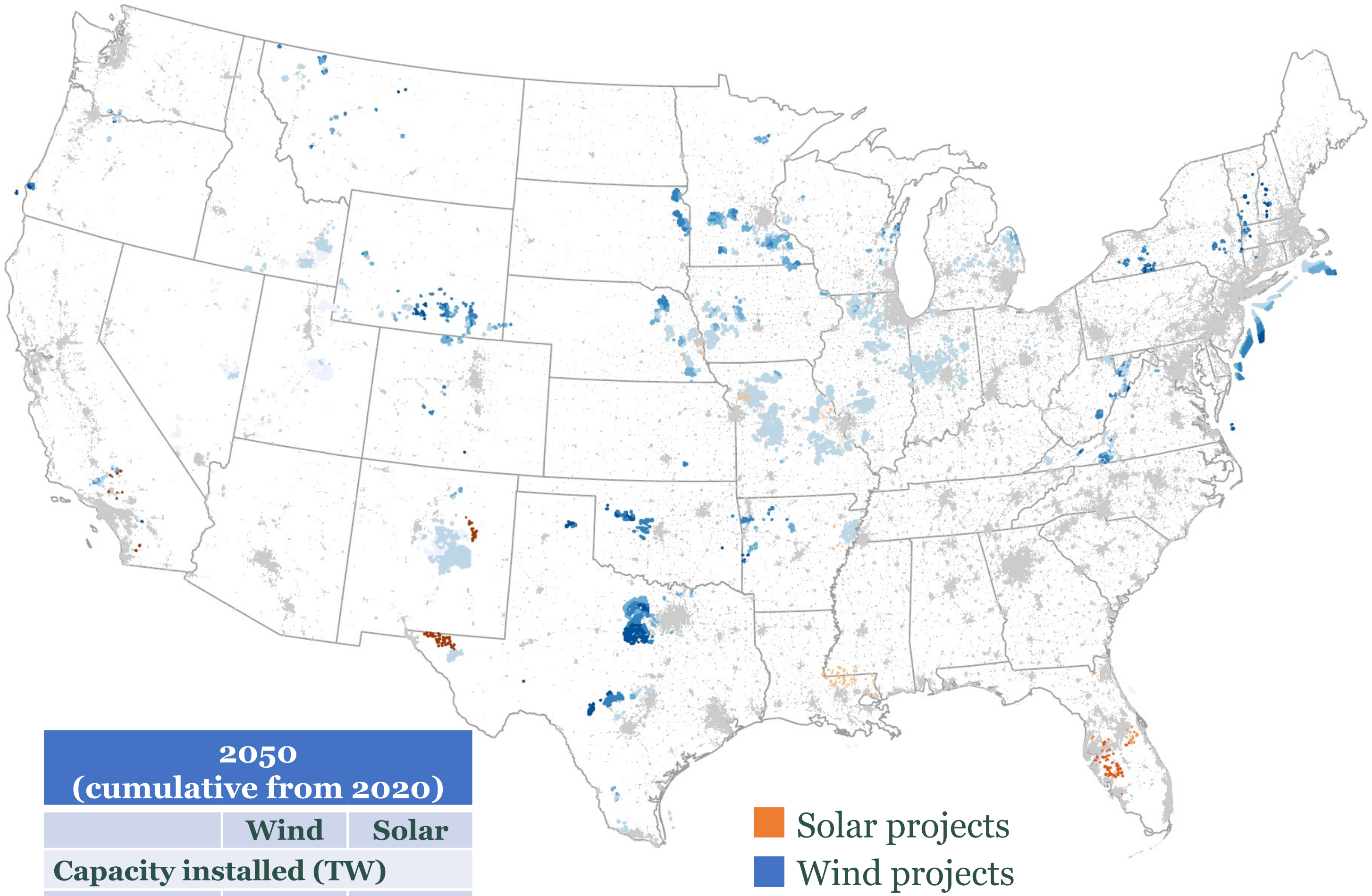
NOT MAPPED

2045 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.34	0.12
Land area (1000 km²)		
Total	127	2.29
Direct	1.27	2.08
Capital invested (2018$)		
Trillion $	0.31	0.10

REF Base 2050







2050 (cumulative from 2020)		
	Wind	**Solar**
Capacity installed (TW)		
	0.41	0.16
Land area (1000 km²)		
Total	142	3.05
Direct	1.42	2.77
Capital invested (2018$)		
Trillion $	0.39	0.13

Note: Site capacity factors are reflected in color intensity (Highest capacity factor = darkest color).