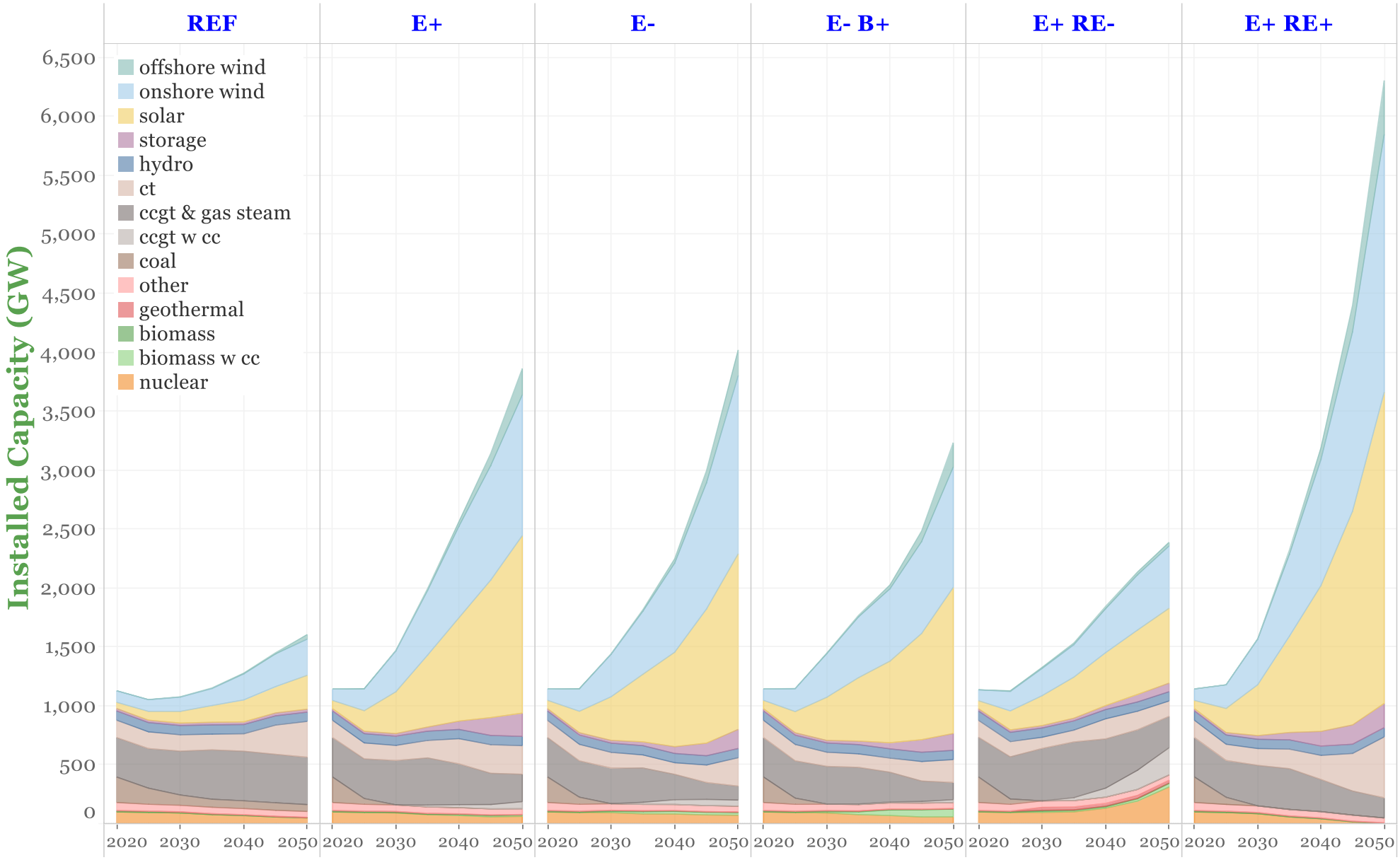
By 2050 installed solar capacity is 9 to 39 times larger than today, and installed wind capacity is 6 to 28 times larger.



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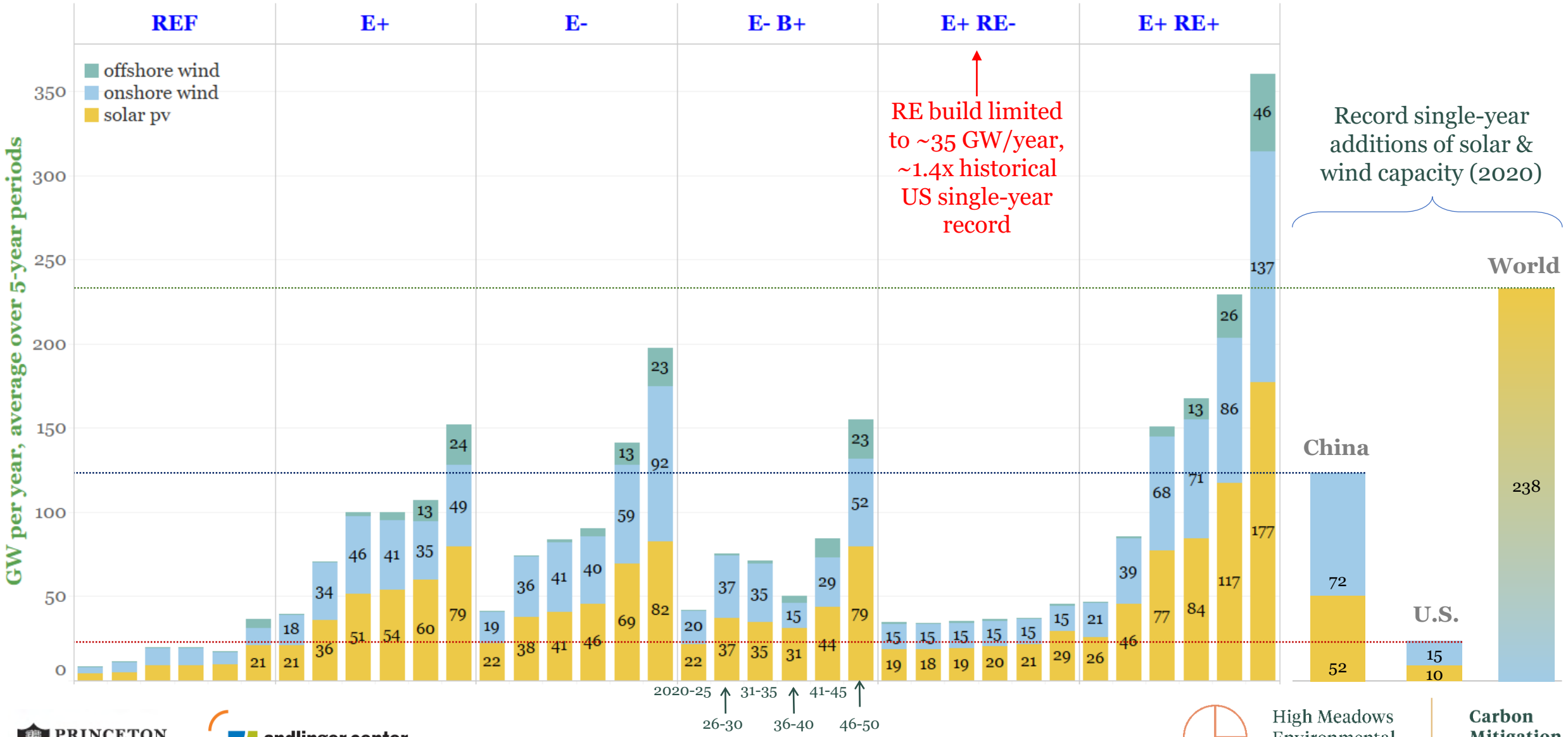
Annual wind and solar capacity additions are sustained over multiple decades at historically-unprecedented rates



PRINCETON UNIVERSITY

andlinger center for energy+the environment

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High Meadows Environmental Institute

Carbon Mitigation Initiative

Downscaling methodology for solar and wind and transmission siting in net-zero pathways

Summary of this section

- Wind and solar capacity is deployed extensively across the United States in all cases. Finding sites suitable to develop projects presents a potential bottleneck to wind and solar deployment.
- To assess availability of lands for wind and solar development, we conduct a high resolution (4km x 4km) evaluation of the entire continental U.S. (and offshore wind development areas) using ~50 total geospatial screens to exclude areas with potentially conflicting land uses, including high population density areas, protected lands (e.g. parks, wilderness), the most productive farm lands, or areas with high environmental conservation value, as well as areas unsuitable for construction (e.g. wetlands, mountain slopes).
- To visualize the extent of wind and solar deployment and supporting transmission expansion over time, we downscale RIO's coarse-resolution model results (14-regions for continental U.S.). "Candidate project areas" (CPA) that pass all land use screens are selected in order of least delivered electricity cost (including approximated transmission costs) from solar or wind farms at those CPAs to demand centers until sufficient capacity has been selected to meet the regional level of solar and wind generation modeled by RIO.
- We also visualize a notional expansion of the transmission capacity required to connect wind and solar projects sites to demand centers (e.g. major metropolitan areas).
- These downscaling results, driven by least-cost objectives, are only one of many possible siting configurations for generation projects and transmission lines. Configurations whose siting is driven by other objectives, e.g., minimizing land-use conflicts and/or maximizing local benefits, would be different from these results.
- Annexes D and F provide additional details of methodology and results.

Candidate solar and onshore wind project sites mapped for "base" and "constrained" land availability.

Methodology similar to Wu, *et al.*, *Power of Place: Land Conservation and Clean Energy Pathways for California*, The Nature Conservancy, 2019.

	Solar	Onshore Wind
NREL capacity factor map resolution, km	**10**	**2**
Average power density (MW/km²)	**45**	**2.7**
Land areas excluded from siting of wind / solar projects		
Slope	**> 17%**	**> 34%**
Intactness: Theobald Human Modification index*	**HMI < 0.082 for CONSTRAINED only**	
Population density	> 100 people/km² excluded; density of solar/wind projects in other areas is restricted in inverse proportion to population density	
Urban areas + buffer, km	**0.5**	**1**
Water bodies + buffer, km	**0.25**	**0.25**
Military installations + buffer, km	**1**	**3**
Active mines + buffer, km	**1**	**1**
Airports and runways + buffer, km	**1**	**3**
Railways + buffer, km	**0.25**	**0.25**
Prime soils (prime farmland)	**Not allowed**	**Allowed in BASE. Not allowed in CONSTRAINED**
FEMA 1% annual flood hazard areas	**Not allowed**	
Areas of critical environmental concern	**Not allowed**	
National forests (except for wind on ridgecrests), parks, wilderness, recreation, and other federal protected areas	**Not allowed**	
State parks, forests, wilderness & other protected areas	**Not allowed**	
Wetlands and watershed protected areas	**Not allowed**	
Private conservation & forest stewardship areas	**Not allowed, except for wind on ridge crests**	
Native American areas	**Not allowed**	
BLM *High* and *Moderate* sensitivity areas	**Not allowed**	
~50 total environmental, cultural, and economic exclusions. See full list here		

* Exclusion categories that distinguish Base from Constrained land availability are shown in red.

Constrained scenarios are designed to limit development on intact landscapes. Theobald's HMI is used to quantify intactness. HMI is derived from analysis of North America at 0.09 km² resolution, with each cell assigned a value from 0 to 1 based on multiple metrics. HMI values < 0.082 identify highly intact landscapes.

Constrained scenarios also restrict onshore wind development on prime farmlands (this is permitted in Base).

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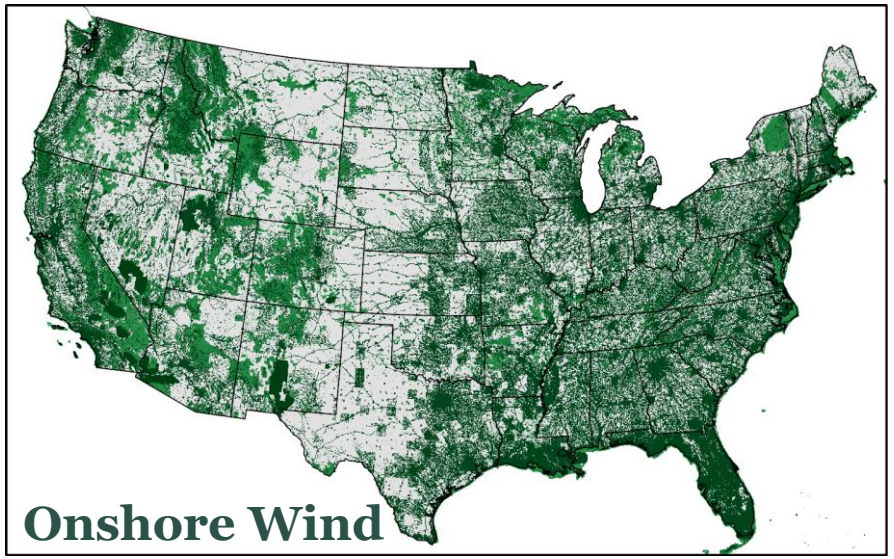
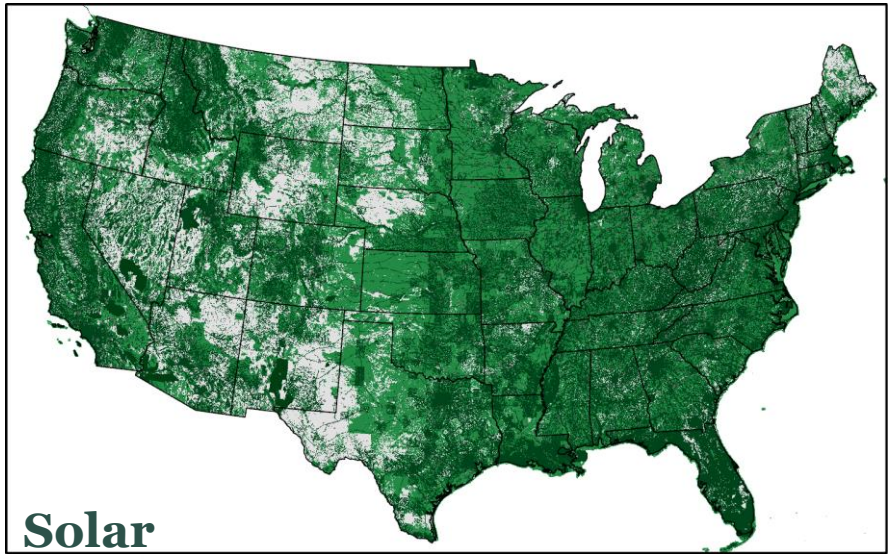
Other land use priorities limit where solar and wind projects can be sited and built.

Base siting options

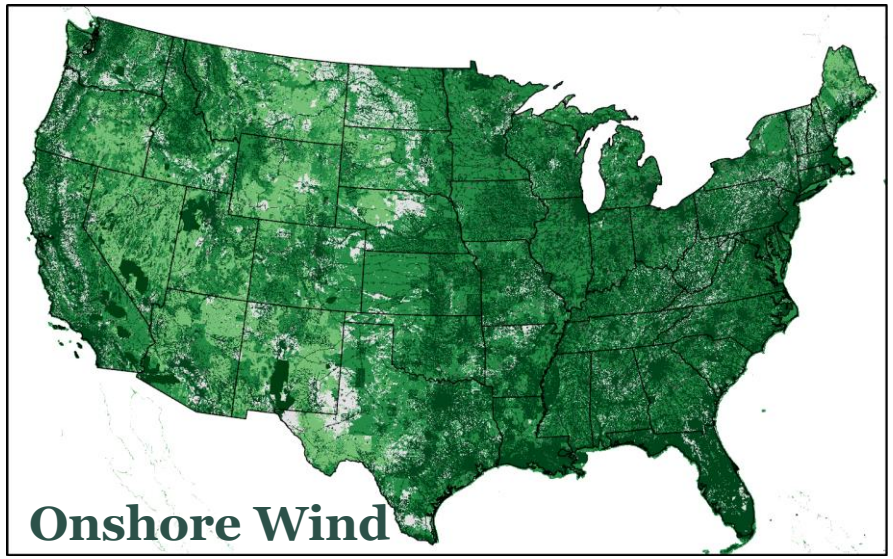


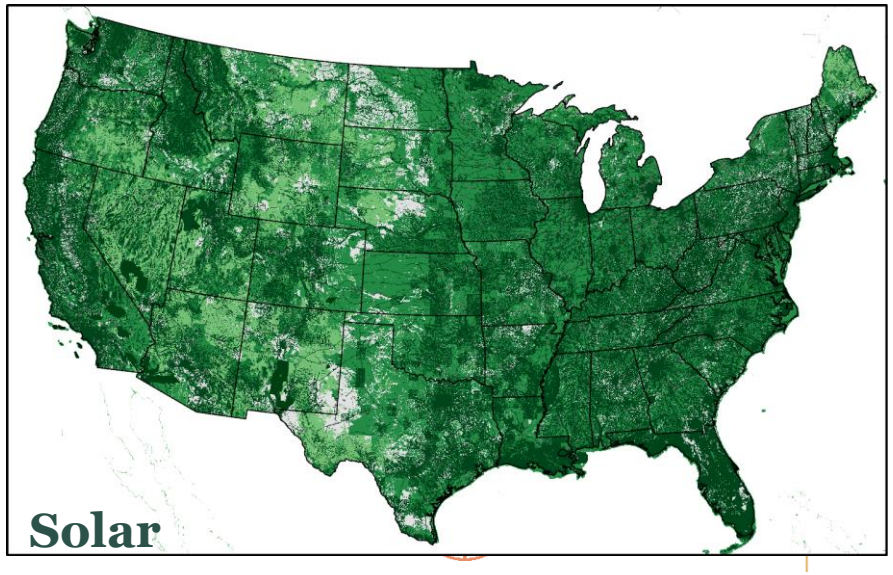


Shaded regions are excluded from development.

Unshaded regions are suitable for siting projects (candidate project areas)

Constrained siting options





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Offshore wind exclusion areas and capacity siting process

Exclusion areas

- Shipping lanes
- Marine protected areas
- Gap status 1 for West, Gulf, and East coasts; Gap status 2 for West and Gulf coasts only (gap status relates to level of sensitivity/administrative protection)
- Military installations + 3 km buffer
- Military danger zones + 3 km buffer
- Outside BOEM-designated zones, candidate area further reduced by 40% (at random) to account for uncertainty about additional exclusions not explicitly geo-specified
- Areas closer than 30 km to shore or greater than 100 km from shore (similar to current BOEM lease zones)

Wind farm technical characteristics

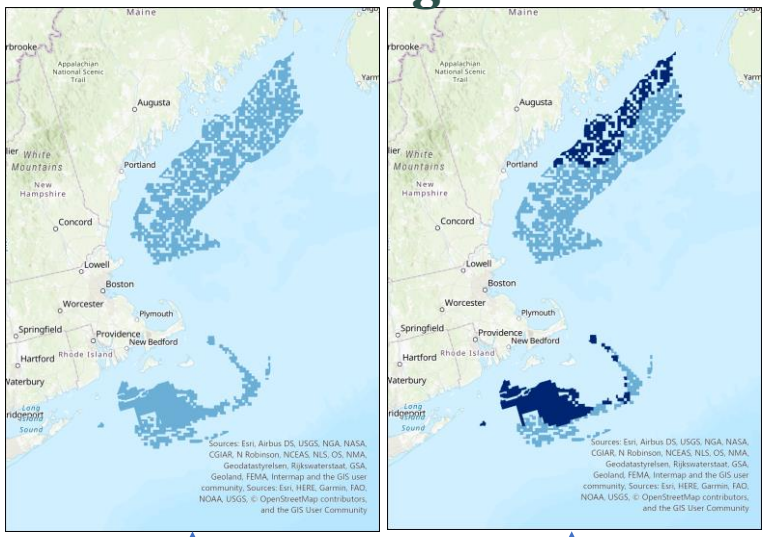
- Power density: West coast, 8 MW/km^2 (floating turbines, seafloor depth > 50 m); East & Gulf coasts: 5 MW/km^2 (fixed turbines, most areas have depth < 50m).
- Capacity factors at 13-km spatial resolution from Vibrant Clean Energy

Sites selected for farms by lowest approximate LCOE until total supply fulfilled

- Turbine capex (avg for 2021-2050 used for ordinal ranking): $3,105/kW (sea depth < 50m); $4,519/kW (> 50 m) (NREL, ATB2019 mid)
- Sub-sea transmission: $20,500/MW-km (< 50m); $28,300/MW-km (> 50m) (ATB2019 mid)

Offshore-wind candidate project areas and selected sites for E+, with base siting constraints

New England

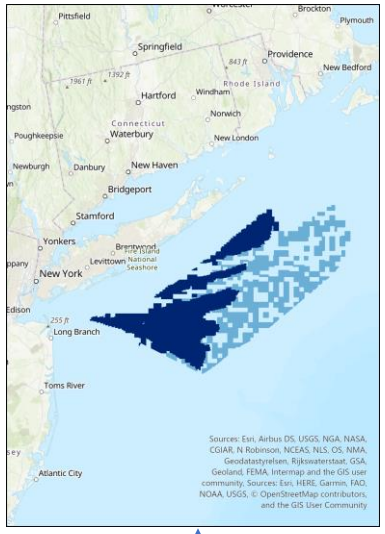


candidate areas, base

selected areas, 2050 E+ base

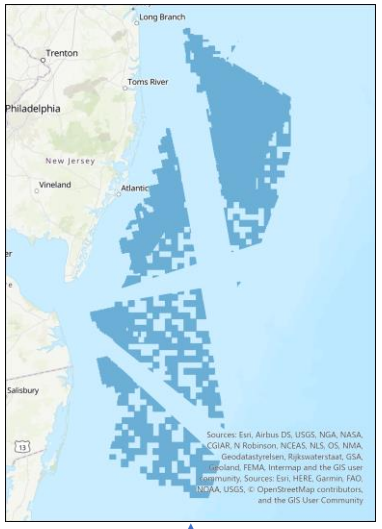
New York

candidate areas, base

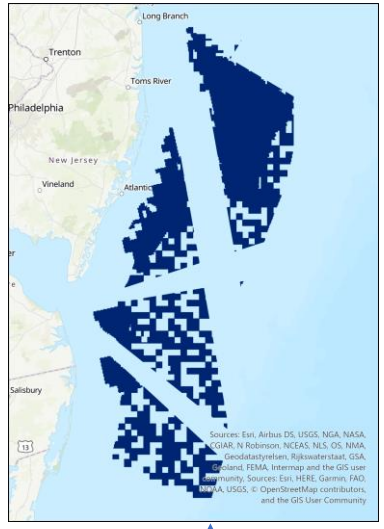


selected areas, 2050 E+ bas

Mid-Atlantic

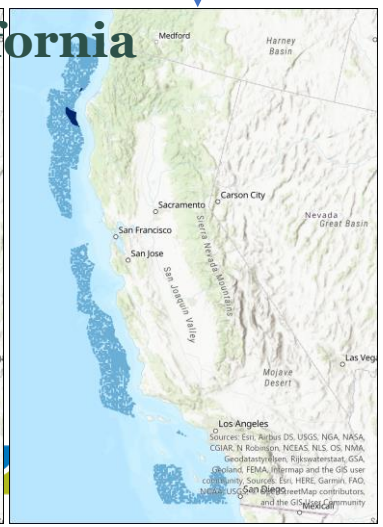


candidate areas, base



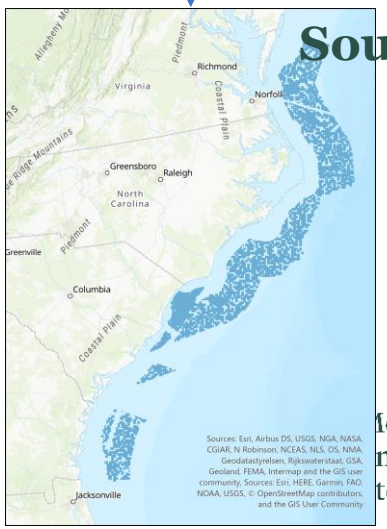
selected areas, 2050 E+

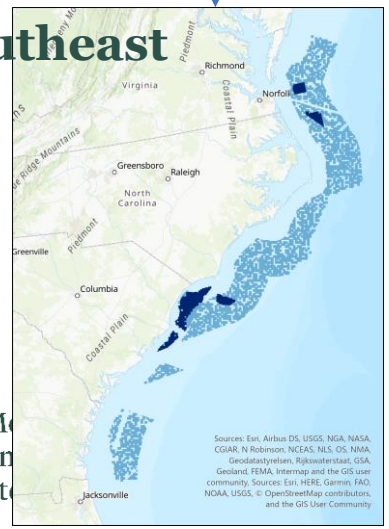
California



Texas, Louisiana

Southeast





Mapping of solar and wind generators and transmission for the E+ pathway with base site availability

Summary of this section

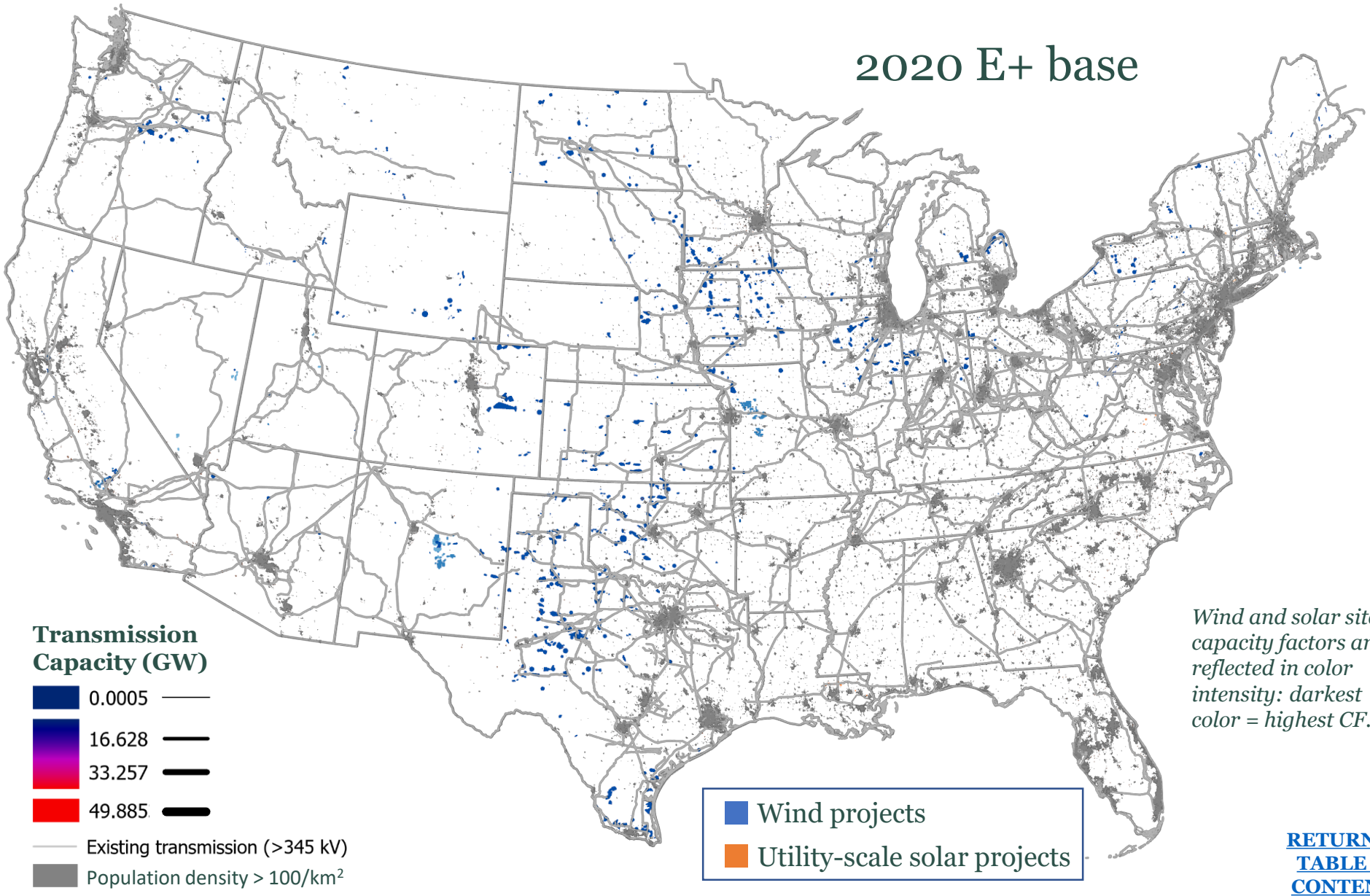
- In E+, over 300 GW of utility-scale solar, 400 GW of onshore wind, and 5 GW of offshore wind capacity are installed across the U.S. by 2030; by 2050, these grow to 1.5 TW, 1.5 TW, and 200 GW, respectively;
- Following a least-cost siting method subject to the Base land availability screen (see Annex D):
  - The top 10 states for wind capacity by 2050 are: Texas, Missouri, Iowa, Illinois, Nebraska, Minnesota, New Mexico, Montana, Oklahoma, and Arkansas
  - The top 10 states for solar capacity by 2050 are: California, Texas, Florida, Georgia, Pennsylvania, South Carolina, Virginia, Alabama, Missouri, Nebraska
  - Over $800 billion is invested in wind and solar capacity through 2030 and $3.5 trillion by 2050.
- Onshore wind and solar farms span a total area of nearly 600,000 km^2; wind farms account for ~94% of this, with extensive visual impact.
- Lands directly impacted by wind and solar farms (e.g., under roads, turbine pads, solar arrays, inverters, and substations) are only a fraction of the total site area: about 40,000 km^2 (an area roughly twice the size of New Jersey), with solar farms accounting for about 85% of this.
- High voltage transmission capacity expands ~60% by 2030 and triples by 2050 to connect wind and solar facilities to demand (see Annex F); total capital invested in transmission is $330 billion through 2030 and $2.2 trillion by 2050.

Modeled 2020 wind and utility-scale solar capacity; Existing transmission lines (≥ 345 kV).

2020 (modeled)		
	Wind	**Solar**
Cumulative capacity (TW)		
	0.13	0.07
Land used (1000 km²)		
Total	57.9	1.08
Direct	0.58	0.98
Cumulative capital (B$$_{2018}$)*		
Solar	-	48
Onshore wind	55	-
Offshore wind	0	-
Existing transmission		
Capacity (GW-km)**		320,000
Increase over 2020		-

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Homeland Infrastructure Foundation-Level Data (HIFLD), 2008, as cited in National Renewable Energy Laboratory, Renewable Electricity Futures Study, 2012.



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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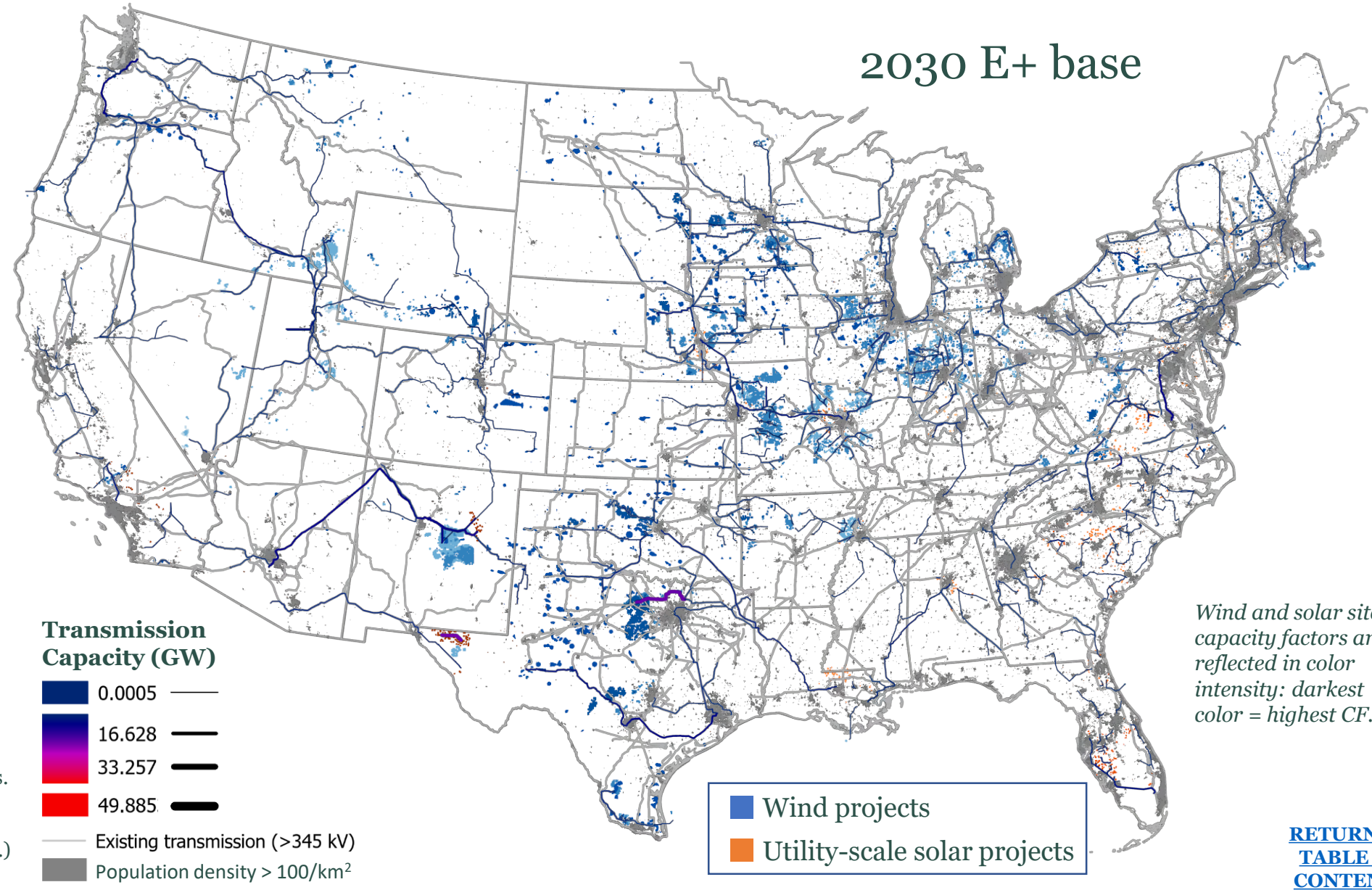
739 GW of wind and solar capacity operating in 2030; transmission capacity grows by 62%.

2030	Wind	Solar
Capacity installed (TW)		
	0.41	0.32
Land used (1000 km²)		
Total	157	7.75
Direct	1.57	7.06
Capital invested (Billion $_{2018}$)*		
Solar	-	353
Onshore wind	427	-
Offshore wind	15	-
Transmission added vs. 2020**		
Capacity (GW-km)		200,000
Increase over 2020		62%
Capital in serv (B$_{2018}$)		330

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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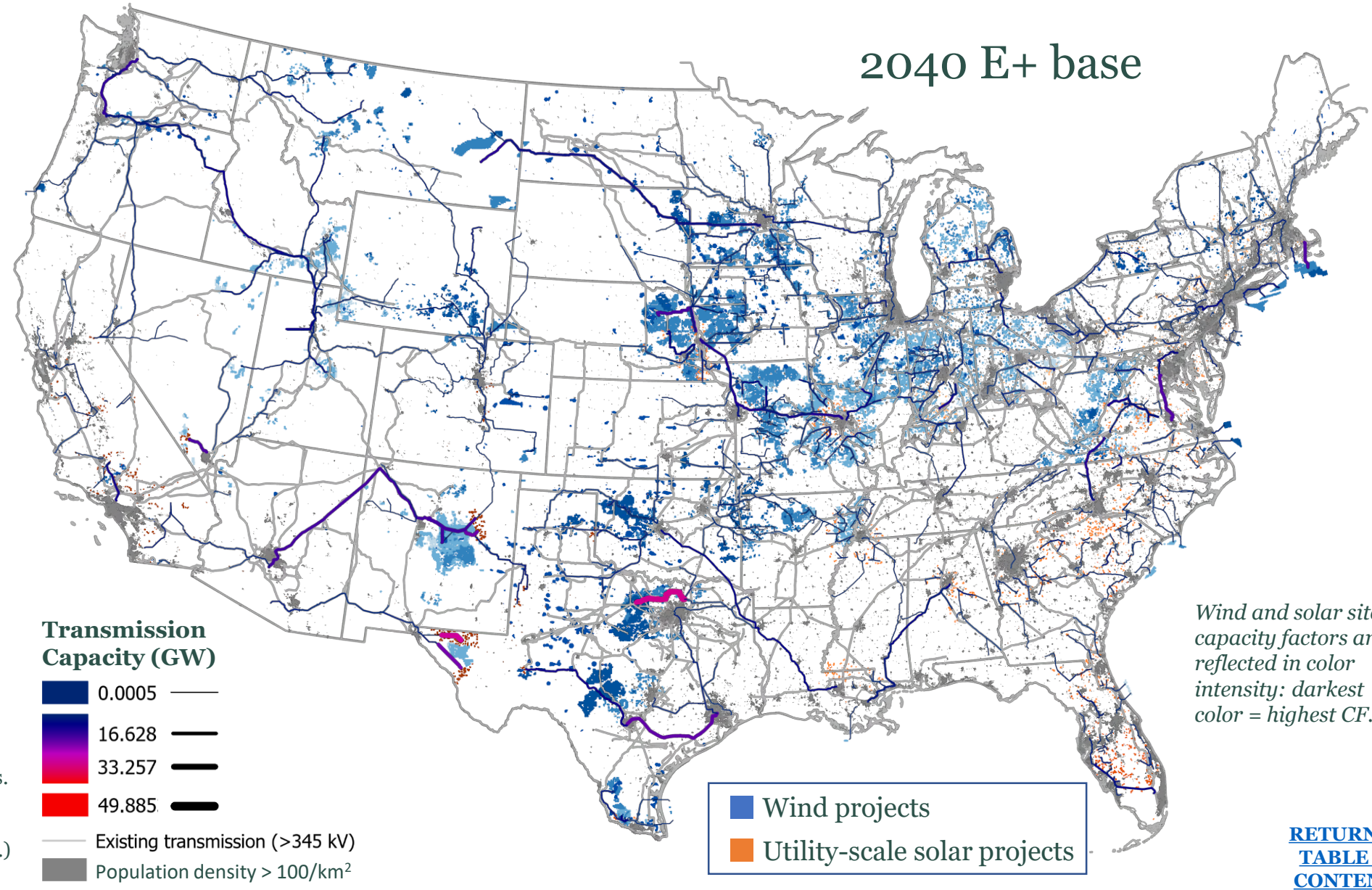
1.8 TW of wind and solar capacity operating in 2040; transmission capacity grows to 1.5x the 2020 level.

2040	Wind	Solar
Capacity installed (TW)		
	0.99	0.85
Land used (1000 km²)		
Total	355	21.5
Direct	3.55	19.6
Capital invested (Billion $_{2018}$)*		
Solar	-	898
Onshore wind	1,053	-
Offshore wind	94	-
Transmission added vs. 2020**		
Capacity (GW-km)		480,000
Increase over 2020		150%
Capital in serv (B$_{2018}$)		1,020

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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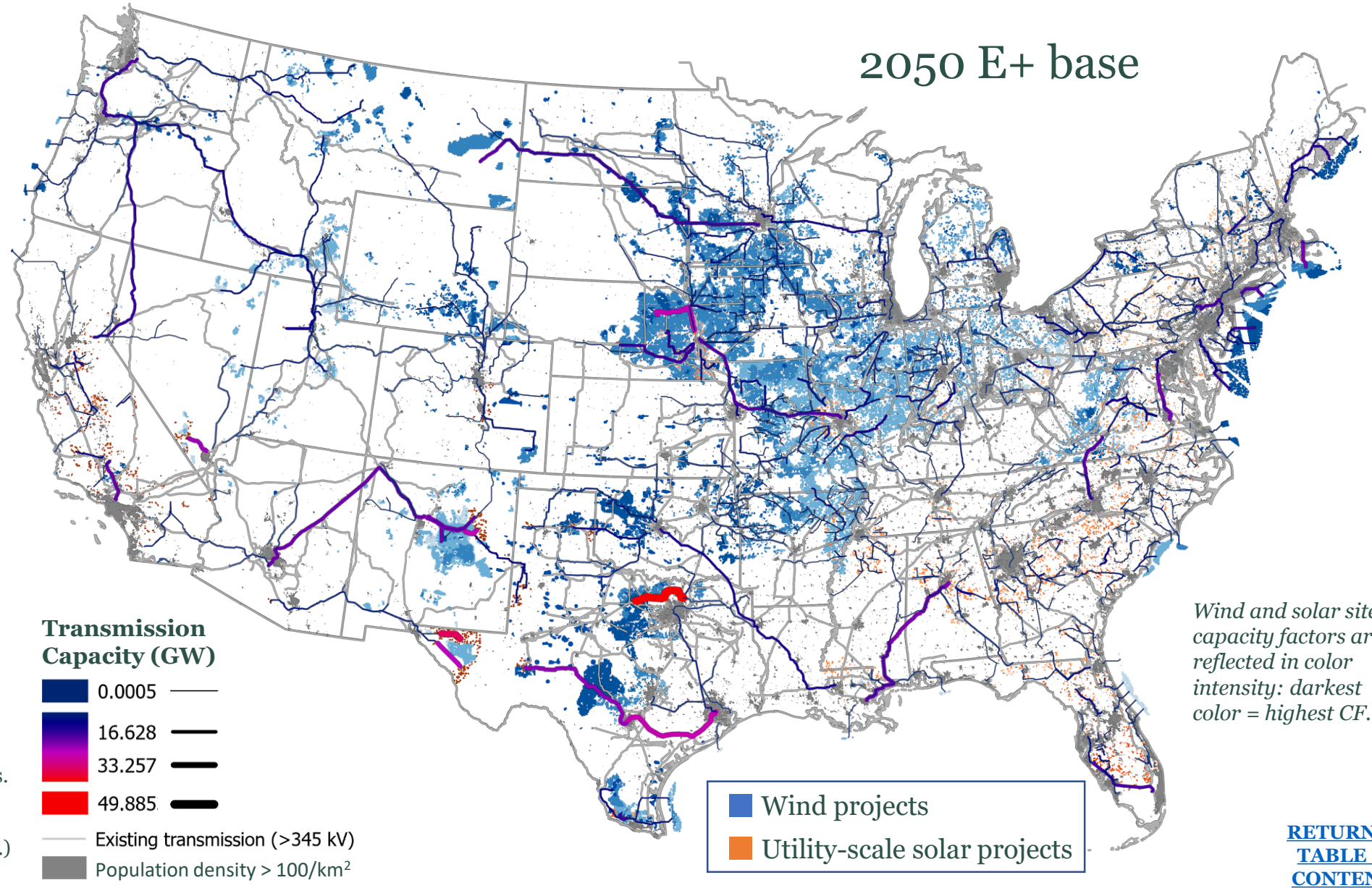
3.2 TW of wind and solar capacity operating in 2050; transmission capacity grows to 3.1x the 2020 level.

2050		
	Wind	**Solar**
Capacity installed (TW)		
	1.67	1.50
Land used (1000 km²)		
Total	551	38.3
Direct	5.51	34.9
Capital invested (Billion $_{2018}$)*		
Solar	-	1,488
Onshore wind	1,609	-
Offshore wind	301	-
Transmission added vs. 2020**		
Capacity (GW-km)		673,000
Increase over 2020		210%
Capital in serv (B$_{2018}$)		2,210

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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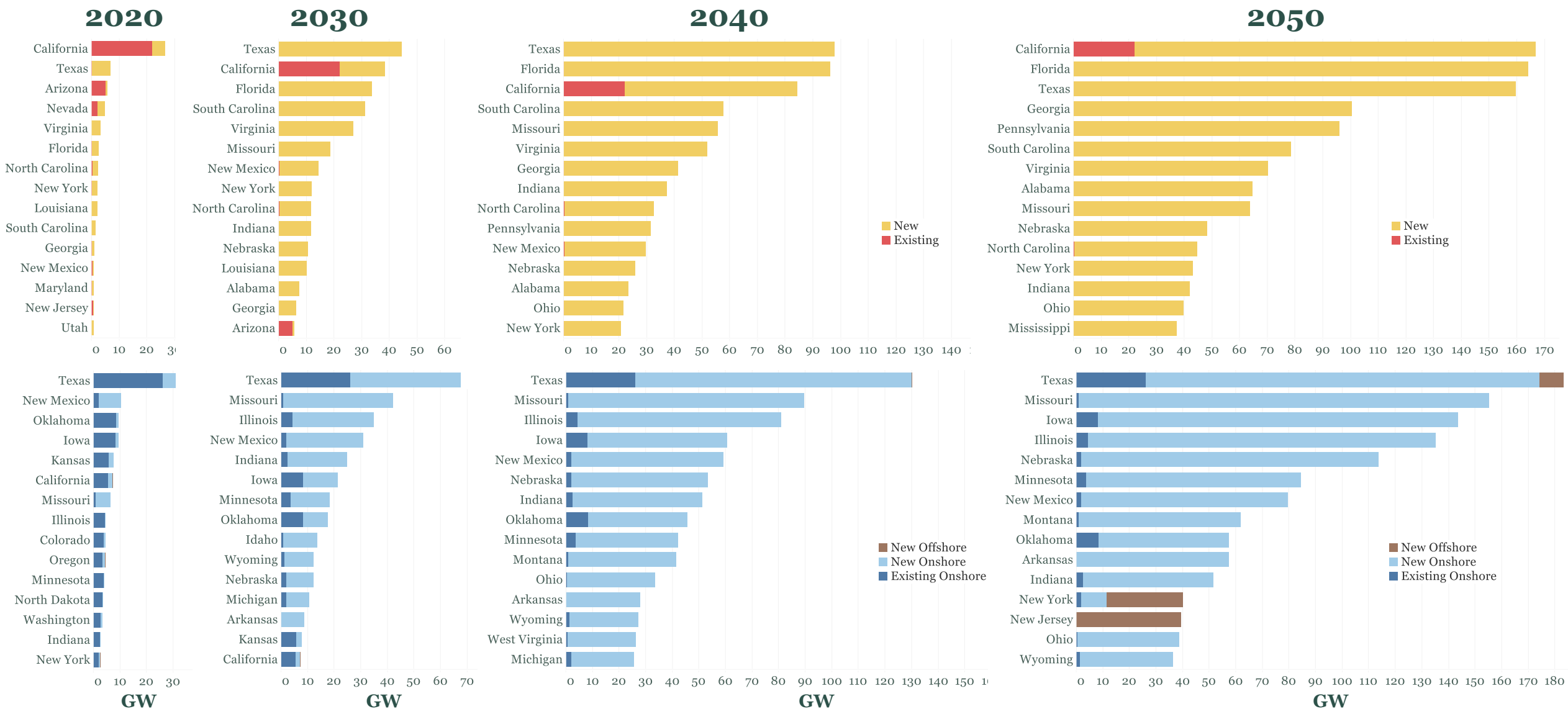
Top 15 states for installed wind and utility-scale solar capacity each decade, E+ (base siting)



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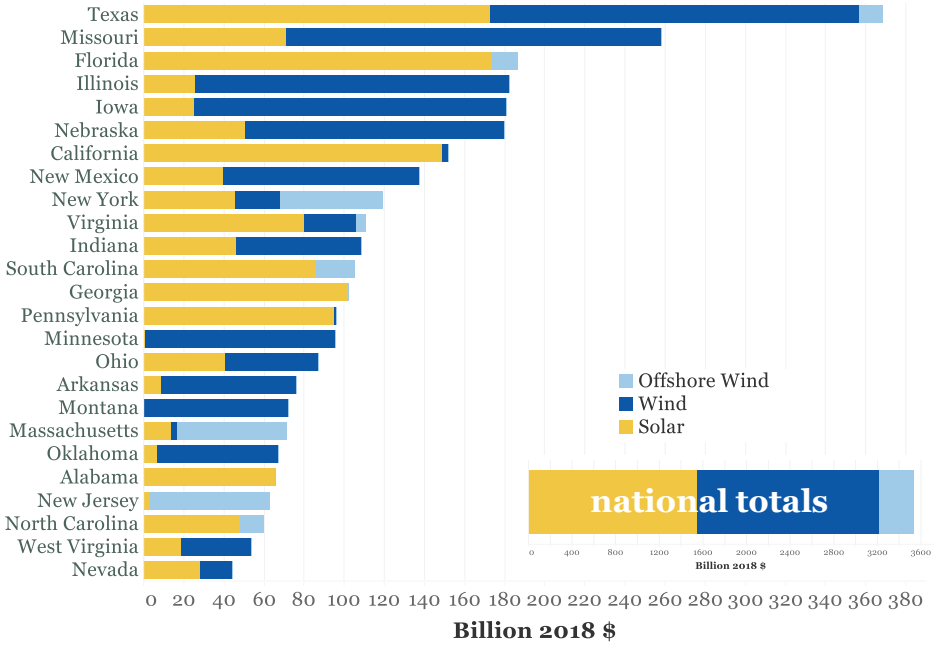
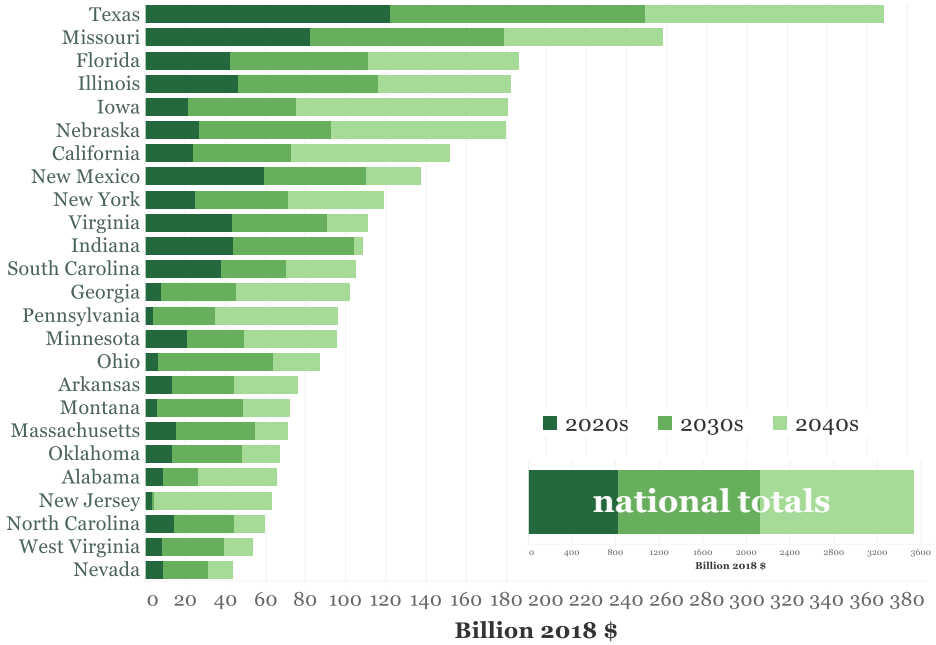
Capital investments by state in wind, utility-scale solar, and associated transmission capacities, E+ (base siting)

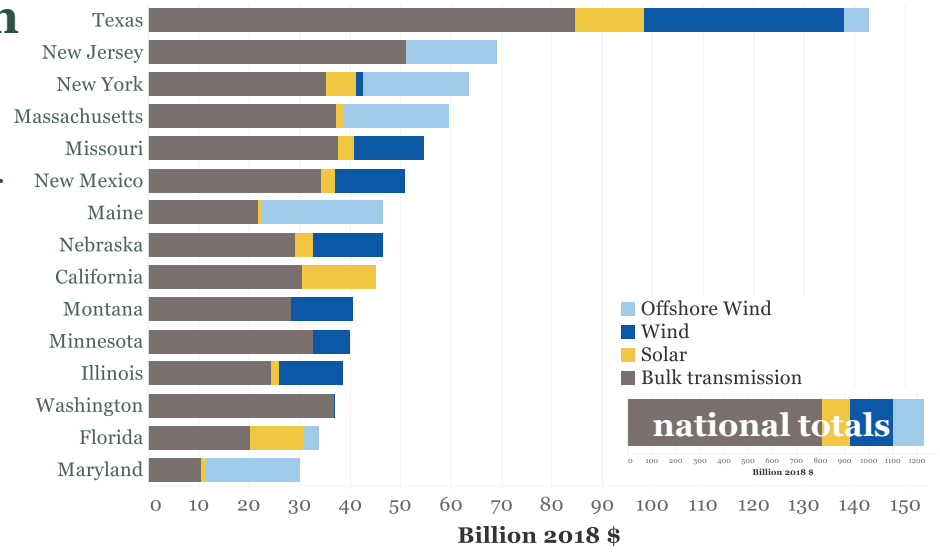
Wind & solar capacity investments, top 25 states

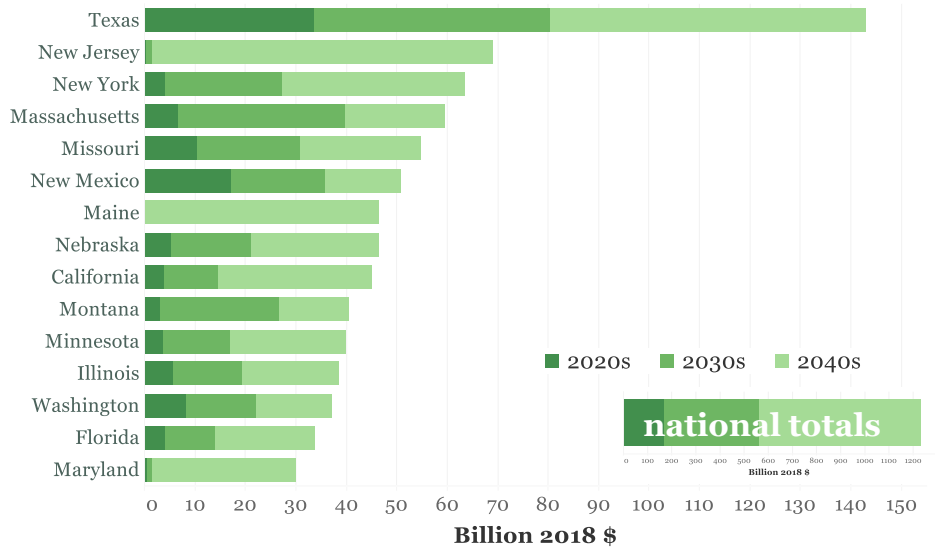




Transmission capacity investments, top 15 states*

* Includes investments in new capacity only. (End-of-life replacement costs, i.e., sustaining capital, is not included in this estimate.) Blue and yellow are investments in spur lines from wind and solar projects to nearest substation.





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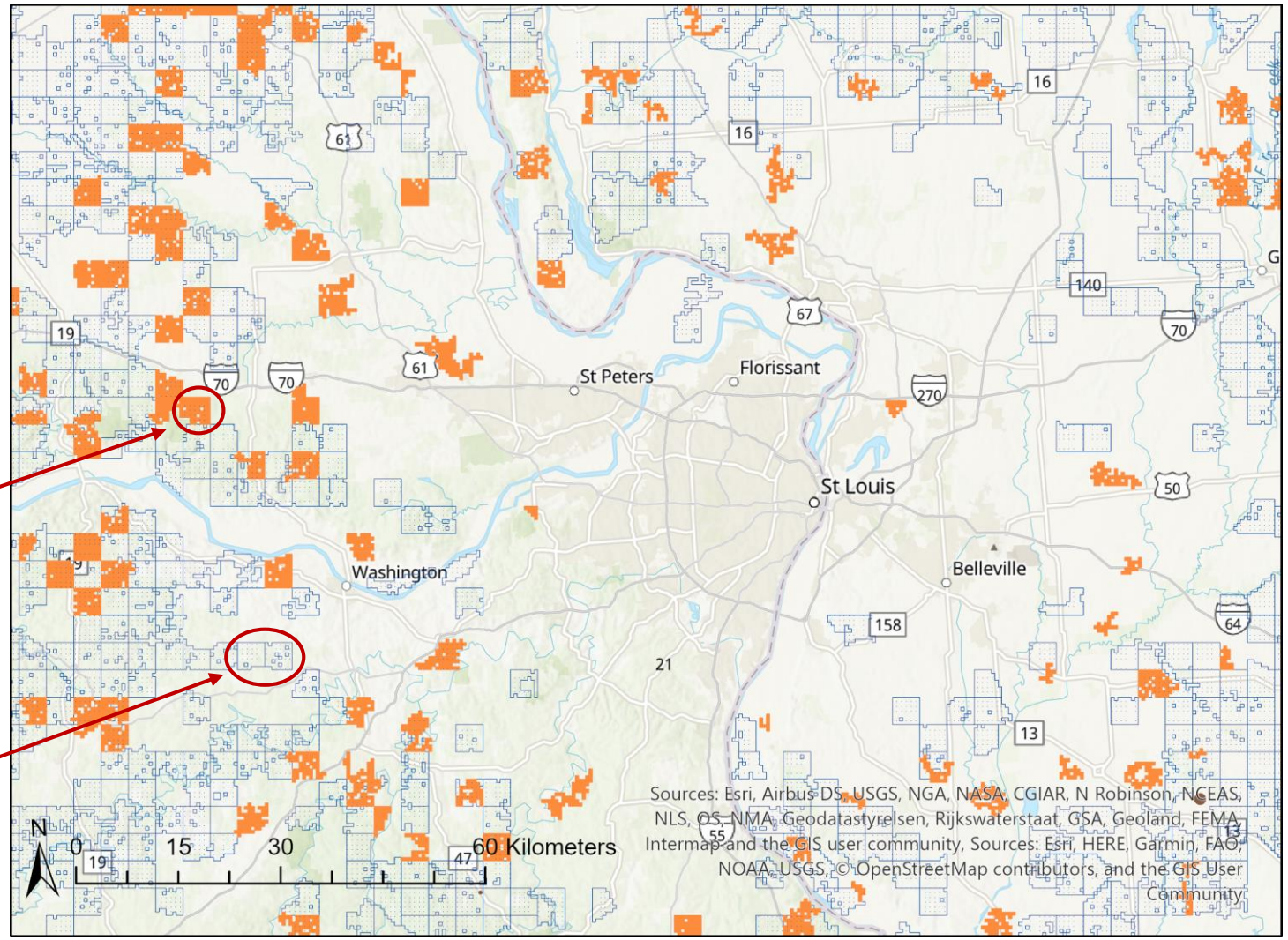
Example area detail: St. Louis, MO
2050 wind and solar farms (E+ base siting)

- Solar, existing and planned
- Solar, additional selected sites 2050 E+ base
- Wind, existing and planned
- Wind, additional selected sites 2050 E+ base
  (dots indicate approximate turbine footprint)

500 MW solar facility
(generic future facility)

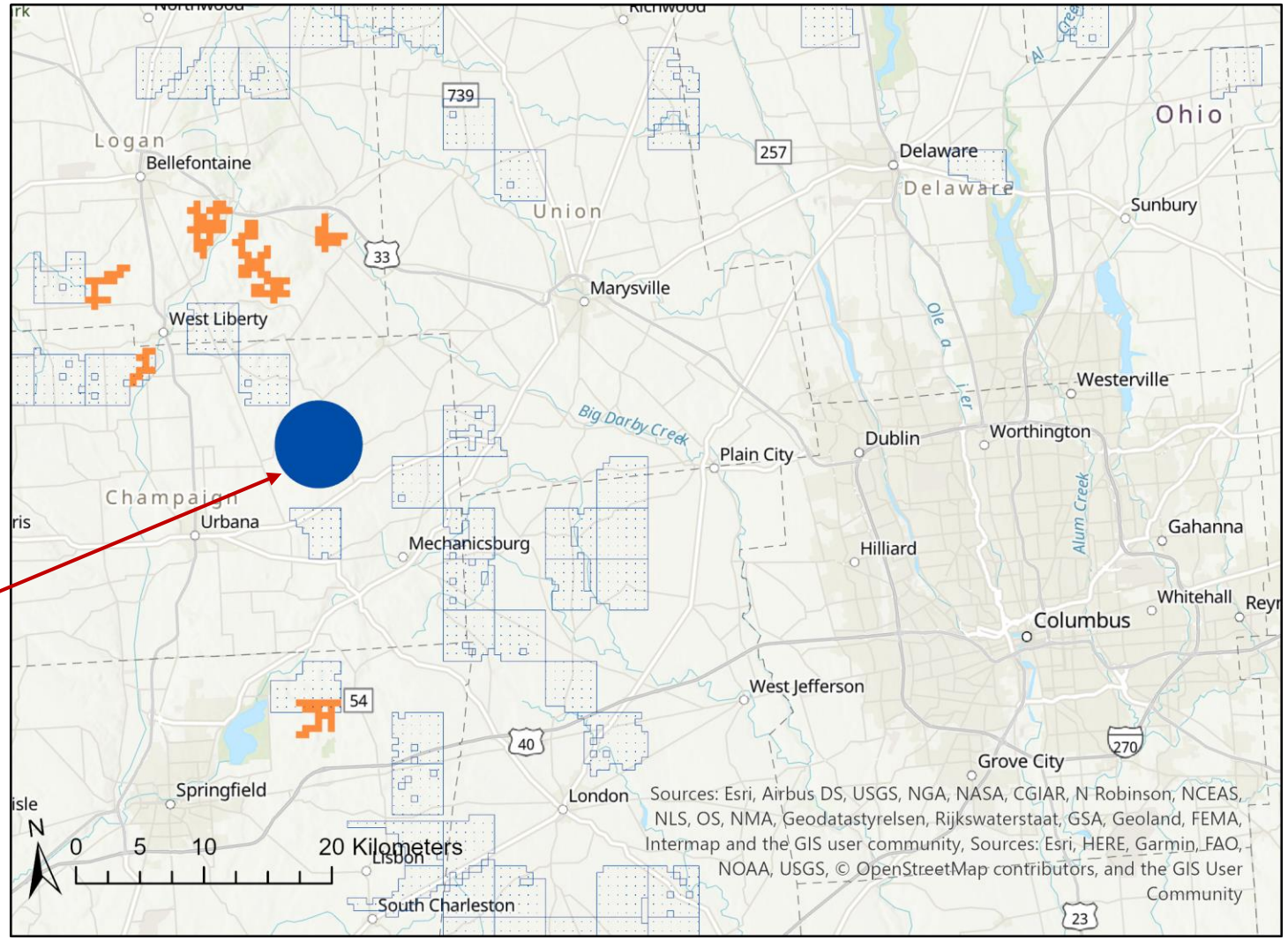
80 MW wind facility
(generic future facility)



Example area detail: Columbus, OH
2050 wind and solar farms (E+ base siting)

- Solar, existing and planned
- Solar, additional selected sites 2050 E+ base
- Wind, existing and planned
- Wind, additional selected sites 2050 E+ base
  (dots indicate approximate turbine footprint)

Buckeye Wind
99 MW proposed facility
Scheduled online date = 2021
Population density = 14 people / km²

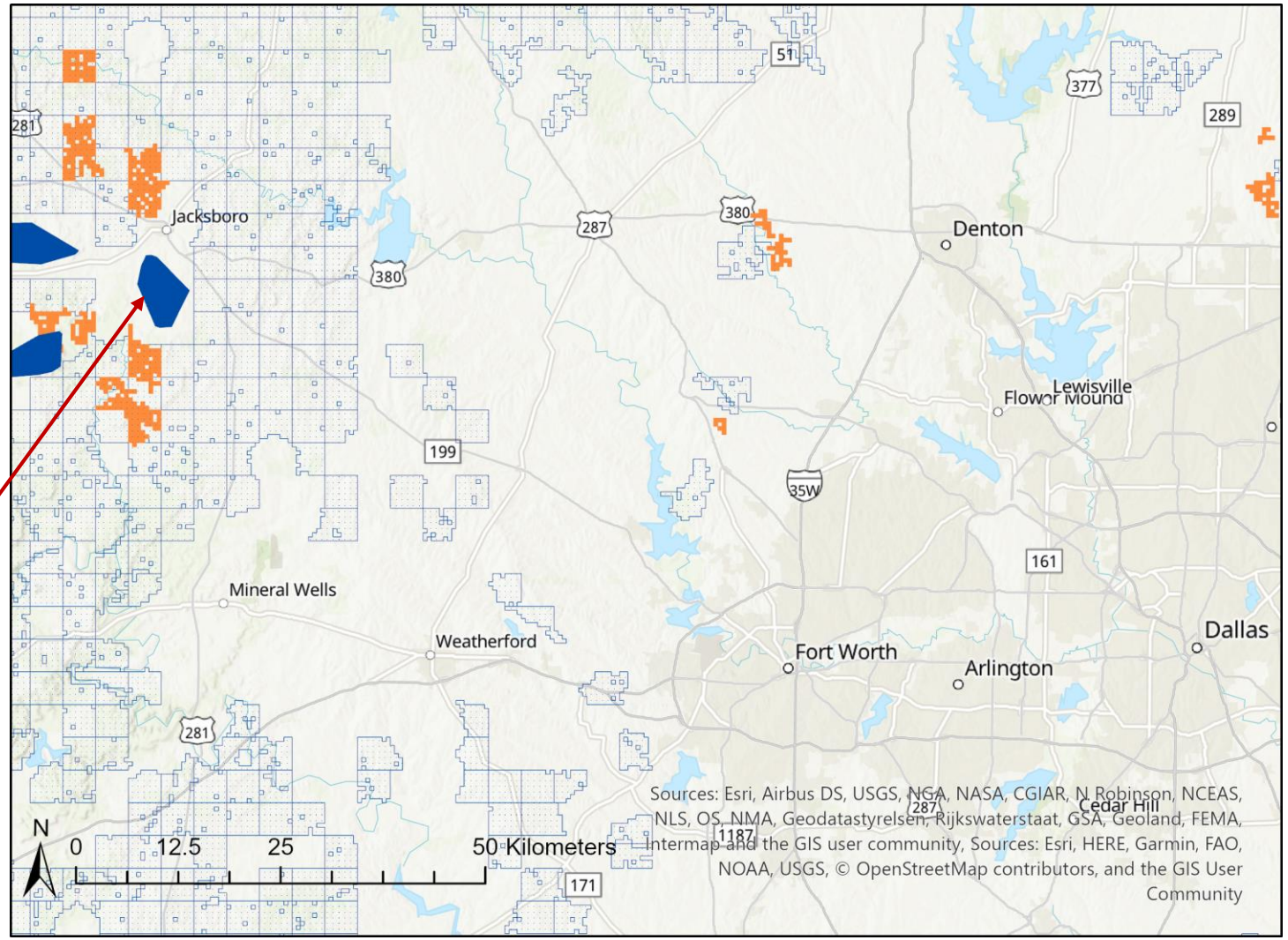


Example area detail: Dallas – Fort Worth, TX
2050 wind and solar farms (E+ base siting)

- Solar, existing and planned
- Solar, additional selected sites 2050 E+ base
- Wind, existing and planned
- Wind, additional selected sites 2050 E+ base
  (dots indicate approximate turbine footprint)

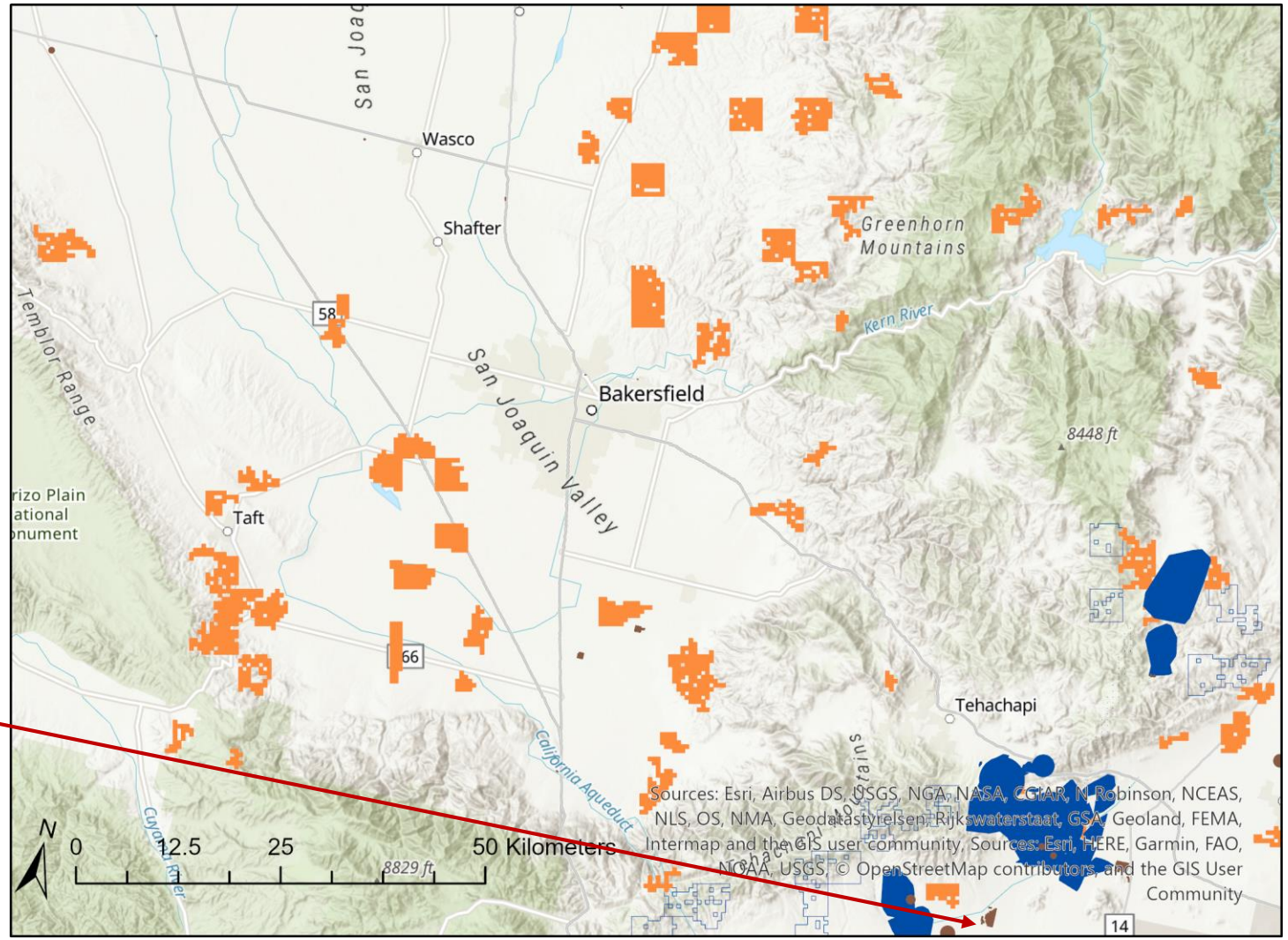
Keechi Wind
110 MW existing facility
Online date = 2015
Population density = 0 people / km²

[Town of Jacksboro (7 km away) has population density > 100 p/km²]



Example area detail: Bakersfield, CA
2050 wind and solar farms (E+ base siting)

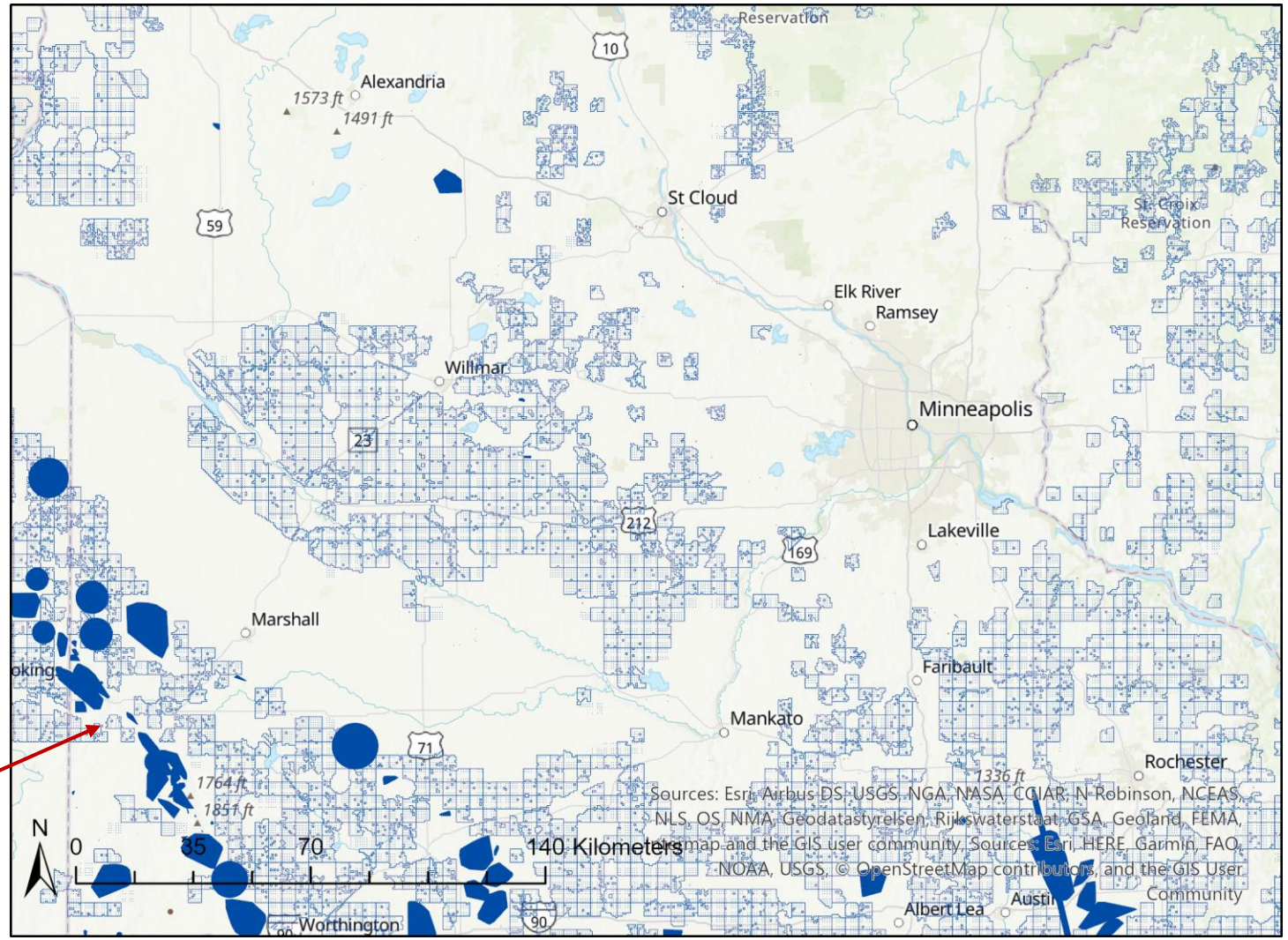
- Solar, existing and planned
- Solar, additional selected sites 2050 E+ base
- Wind, existing and planned
- Wind, additional selected sites 2050 E+ base
  (dots indicate approximate turbine footprint)



Catalina Solar
110 MW existing facility
Online date = 2014
Population density = 4 people / km²

Example area detail: Minneapolis, MN
2050 wind and solar farms (E+ base siting)

- Solar, existing and planned
- Solar, additional selected sites 2050 E+ base
- Wind, existing and planned
- Wind, additional selected sites 2050 E+ base
  (dots indicate approximate turbine footprint)



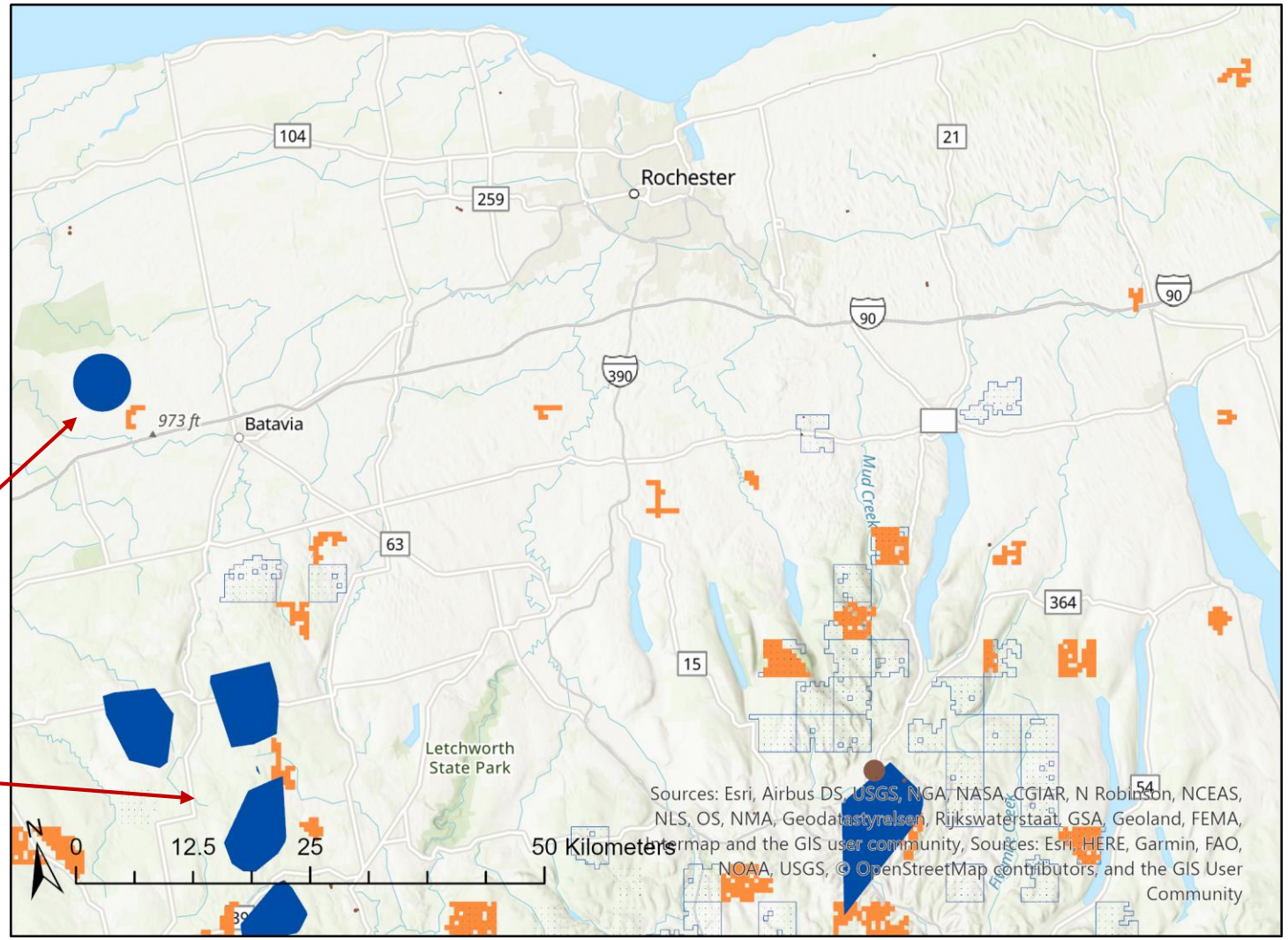
Note siting of new wind farm adjacent existing facilities

Example area detail: Rochester, NY
2050 wind and solar farms (E+ base siting)

- Solar, existing and planned
- Solar, additional selected sites 2050 E+ base
- Wind, existing and planned
- Wind, additional selected sites 2050 E+ base
  (dots indicate approximate turbine footprint)

Alabama Ledge Wind
80 MW proposed facility
Scheduled online date = 2021

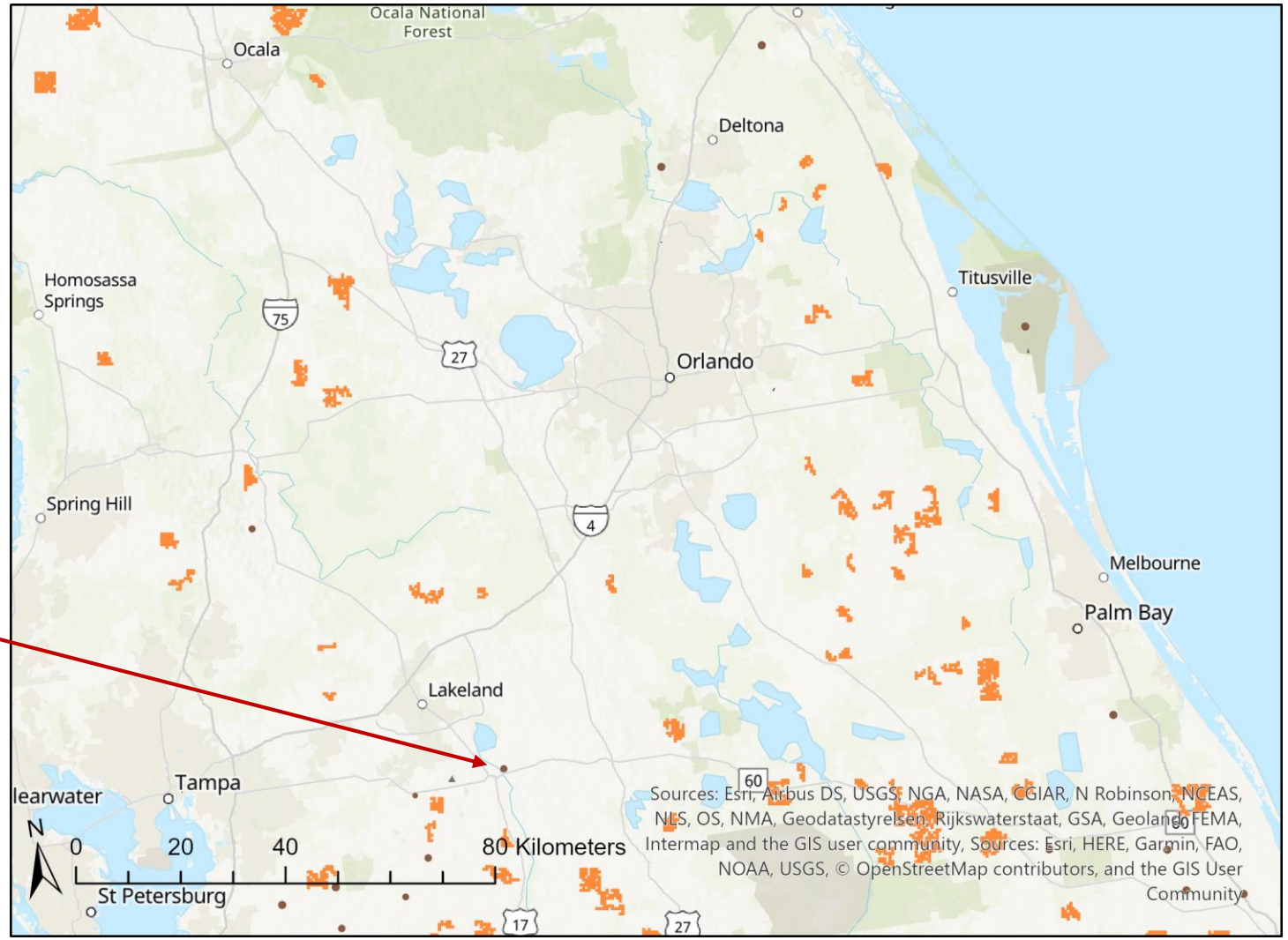
Existing wind facilities



Example area detail: Orlando, FL
2050 wind and solar farms (E+ base siting)

- Solar, existing and planned
- Solar, additional selected sites 2050 E+ base
- Wind, existing and planned
- Wind, additional selected sites 2050 E+ base
  (dots indicate approximate turbine footprint)

Peace Creek Solar
57 MW proposed facility
Scheduled online date = 2020



Siting of solar and wind generators and transmission for the E+ pathway with constrained land availability

Summary of this section

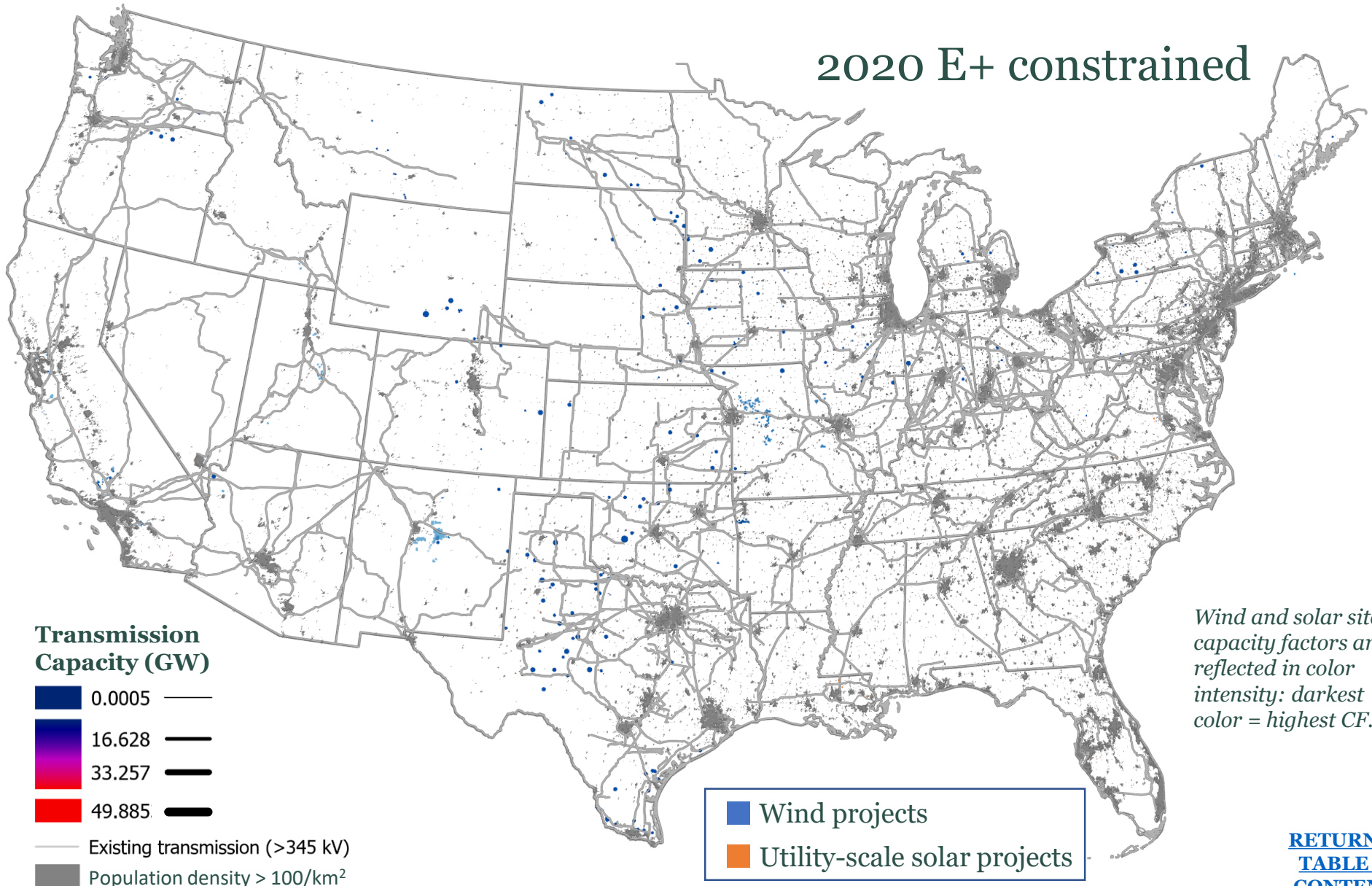
- The constrained site availability case was run to reflect more restrictive permitting and/or other factors that might constrain where solar and wind resource can be deployed.
- In the Constrained land availability scenario, wind farms cannot be deployed on prime farmlands and neither wind nor solar can be sited in relatively intact landscapes (in addition to all land use screens applied in the Base scenario).
- These additional constraints, particularly the prime farmlands exclusion for wind power, requires a more dispersed deployment of wind across the Great Plains states, shifting capacity from Iowa, Minnesota and Oklahoma to North Dakota, South Dakota and Texas.
- The ranking of top 10 solar states in 2050 is nearly unaffected from the Base land availability case.
- About $3.3 trillion is invested in ~3.0 TW of wind and solar capacity by 2050.
- By 2050 total onshore wind and solar farm area is 543,000 km^2 and directly impacted land area is ~40,000 km^2 (an area roughly twice the size of New Jersey).
- Constrained land availability requires greater transmission expansion than Base availability, as wind farms push into more remote areas of the Great Plains states. Transmission capacity expands by ~75% by 2030 and 230% by 2050.
- Total capital invested in transmission is ~$390b through 2030 and $2.5 trillion by 2050.

Modeled 2020 wind and utility-scale solar capacity; Existing transmission lines (≥ 345 kV).

2020 (modeled)	Wind	Solar
Capacity installed (TW)		
	0.14	0.06
Land used (1000 km²)		
Total	55	0.94
Direct	0.55	0.85
Capital invested (Billion $$_{2018}$$)*		
Solar	-	42
Onshore wind	75	-
Offshore wind	-	-
Existing transmission		
Capacity (GW-km)**	320,000	
Increase over 2020	-	

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Homeland Infrastructure Foundation-Level Data (HIFLD), 2008, as cited in National Renewable Energy Laboratory, Renewable Electricity Futures Study, 2012.



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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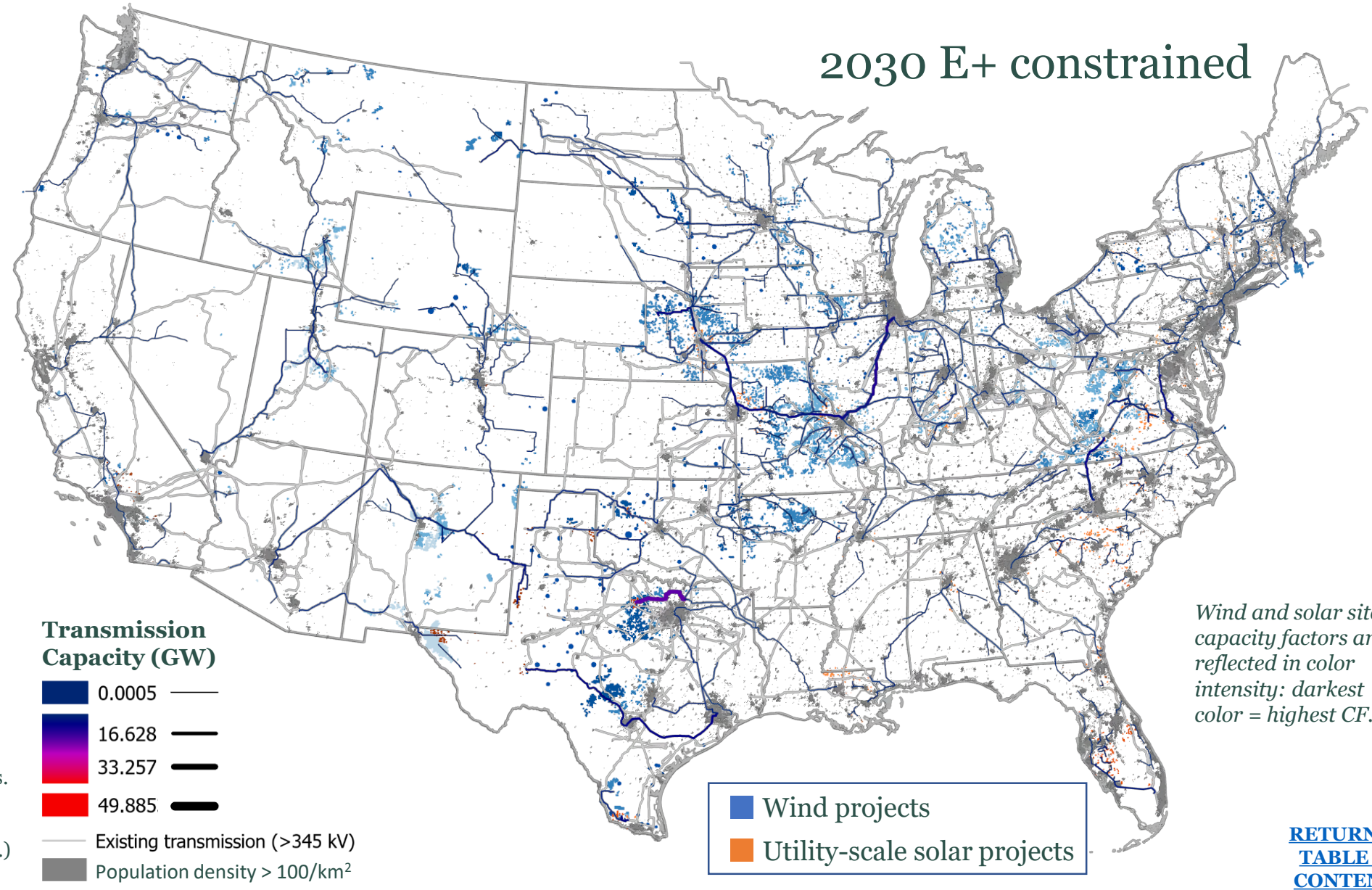
765 GW of wind and solar capacity operating in 2030; transmission capacity grows by 73%.

2030	Wind	Solar
Capacity installed (TW)		
	0.43	0.34
Land used (1000 km²)		
Total	158	8.02
Direct	1.58	7.30
Capital invested (Billion $_{2018}$)*		
Solar	-	367
Onshore wind	448	-
Offshore wind	15	-
Transmission added vs. 2020**		
Capacity (GW-km)		234,000
Increase over 2020		73%
Capital in serv (B$_{2018}$)		385

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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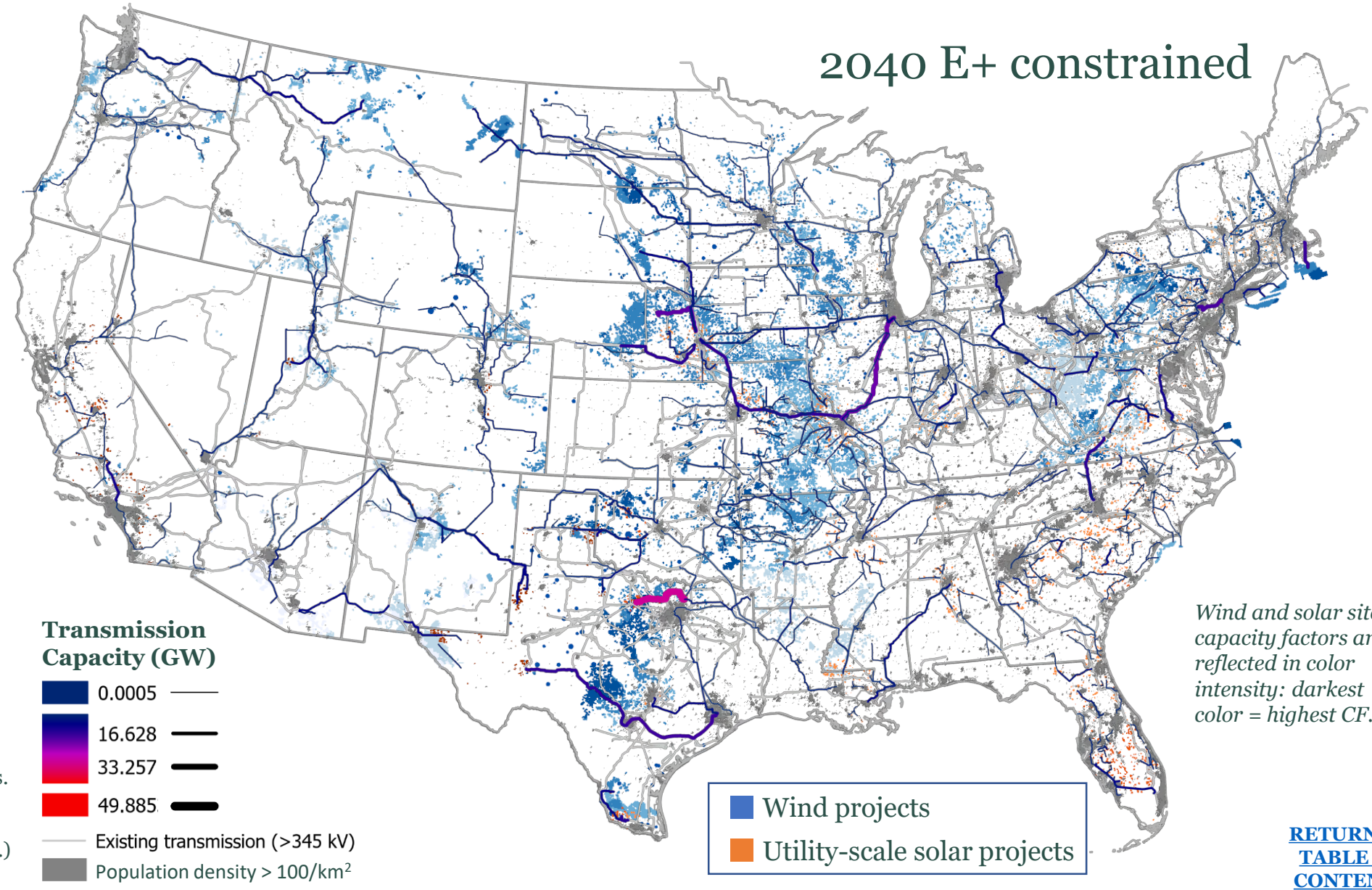
1.9 TW of wind and solar capacity operating in 2040; transmission capacity grows to 1.6x the 2020 level.

2040		
	Wind	**Solar**
Capacity installed (TW)		
	1.01	0.85
Land used (1000 km²)		
Total	362	21.3
Direct	3.63	19.4
Capital invested (Billion $_{2018}$)*		
Solar	-	891
Onshore wind	1,141	-
Offshore wind	87	-
Transmission added vs. 2020**		
Capacity (GW-km)		524,000
Increase over 2020		164%
Capital in serv (B$_{2018}$)		1,110

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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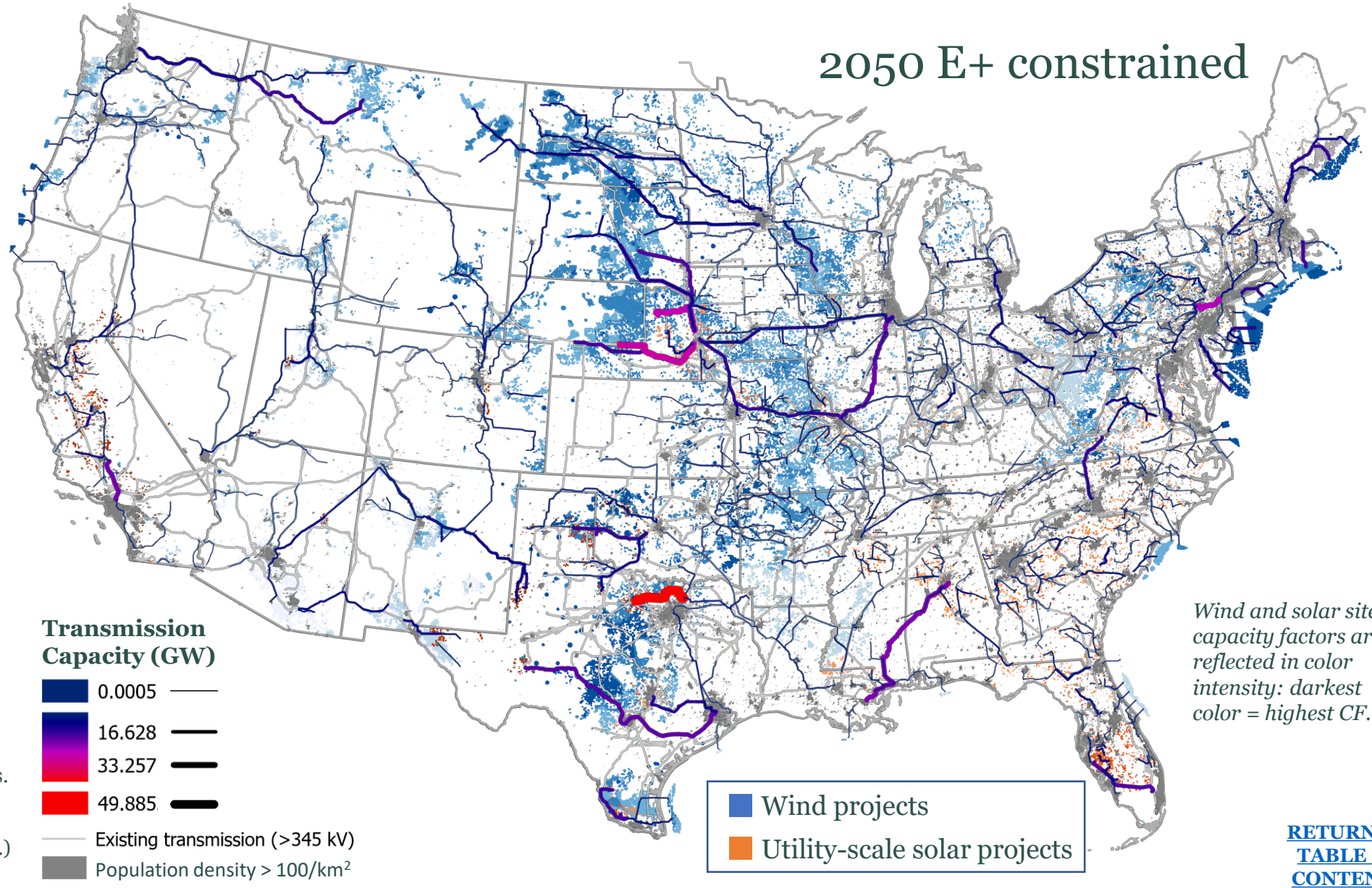
3 TW of wind and solar capacity operating in 2050. Constraining site availability results in more dispersed development.

2050		
	Wind	**Solar**
Capacity installed (TW)		
	1.55	1.48
Land used (1000 km²)		
Total	505	37.8
Direct	5.05	34.4
Capital invested (Billion $_{2018}$)*		
Solar	-	1,473
Onshore wind	1,548	-
Offshore wind	297	-
Transmission added vs. 2020**		
Capacity (GW-km)		749,000
Increase over 2020		234%
Capital in serv (B$_{2018}$)		2,460

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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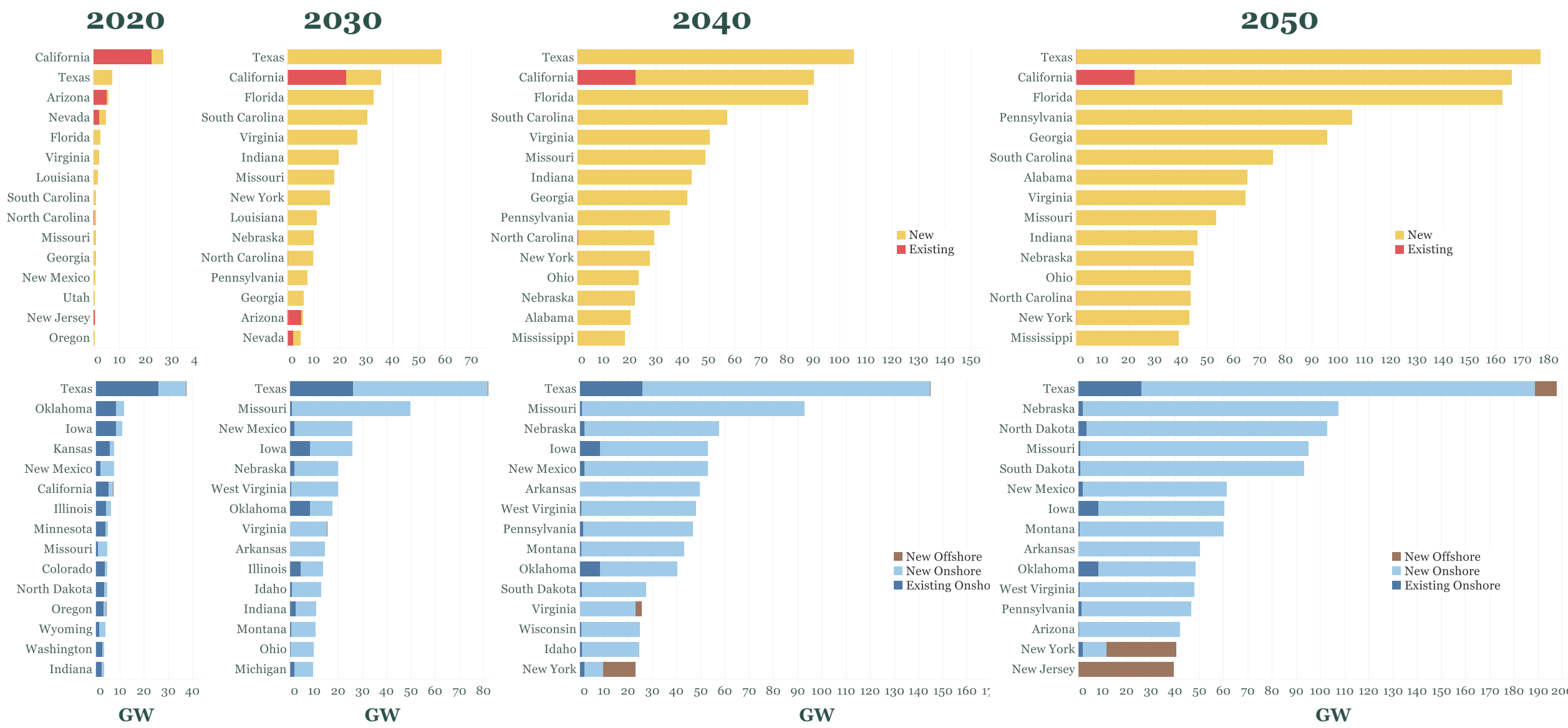
Top 15 states for installed wind and utility-scale solar capacity each decade, E+ (constrained siting)



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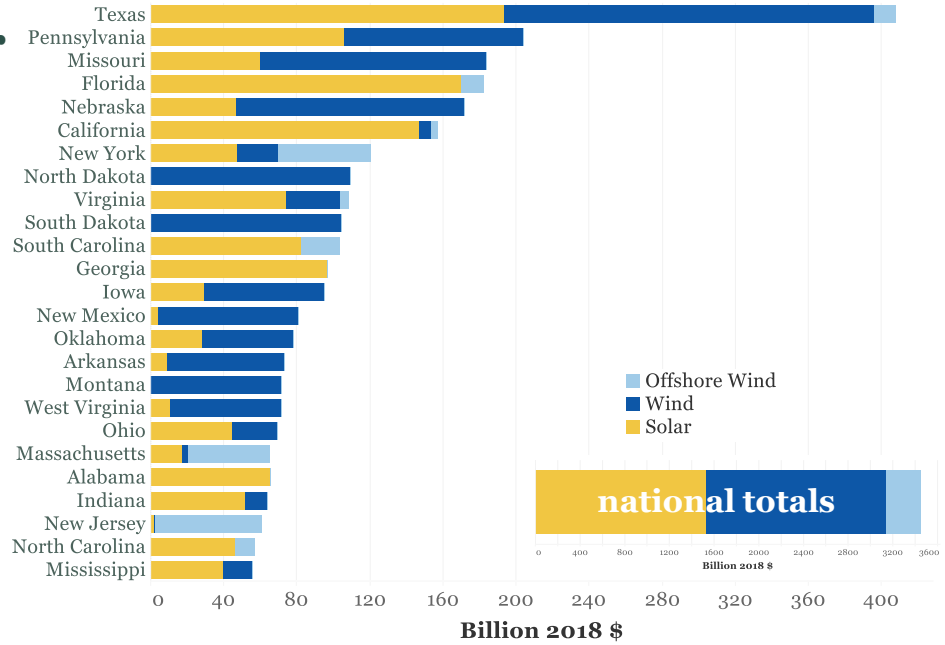
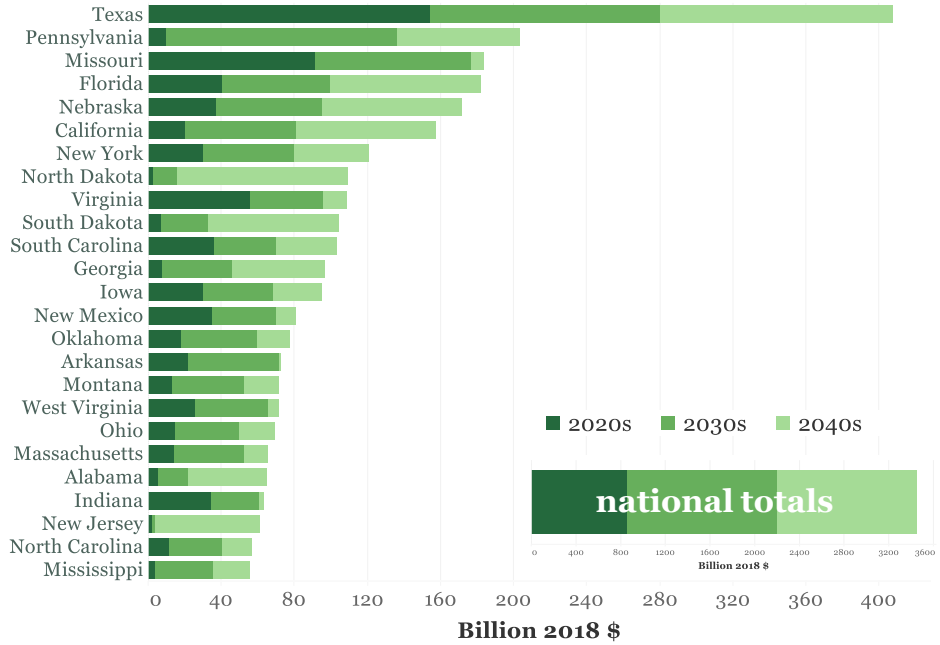
Capital investments by state in wind, utility-scale solar, and associated transmission capacities, E+ (constrained siting)

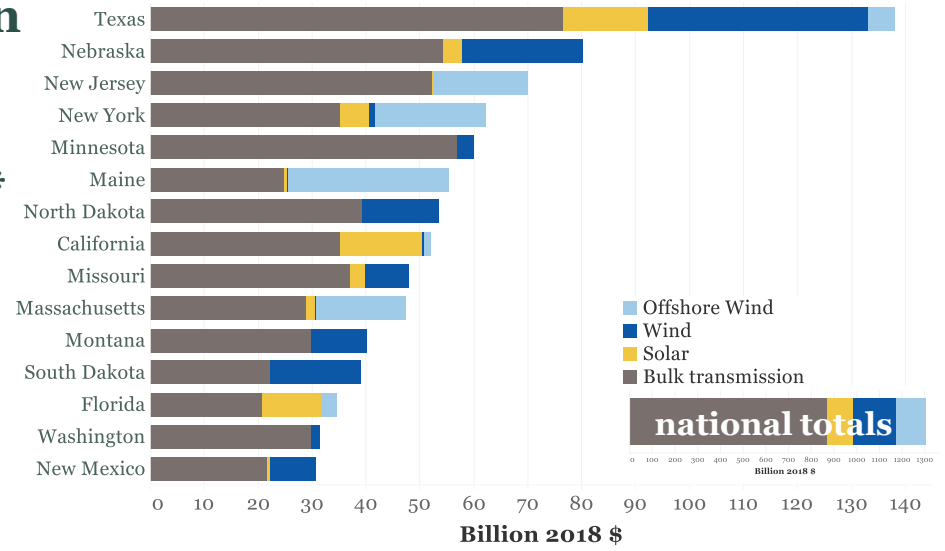
Wind & solar capacity investments, top 25 states

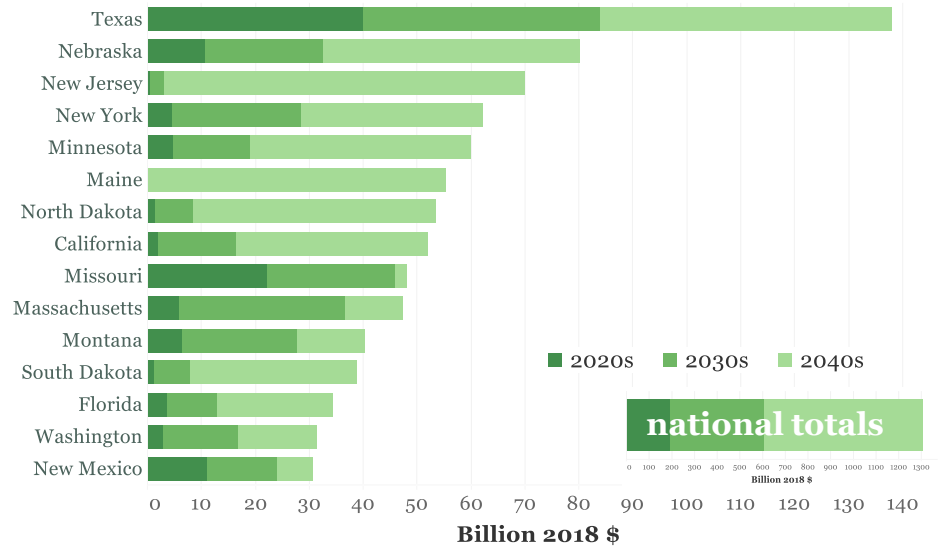




Transmission capacity investments, top 15 states*

* Includes investments in new capacity only. (End-of-life replacement costs, i.e., sustaining capital, is not included in this estimate.) Blue and yellow are investments in spur lines from wind and solar projects to nearest substation.





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Siting of solar and wind generators and transmission for the E+ RE+ pathway with base land availability

Summary of this section

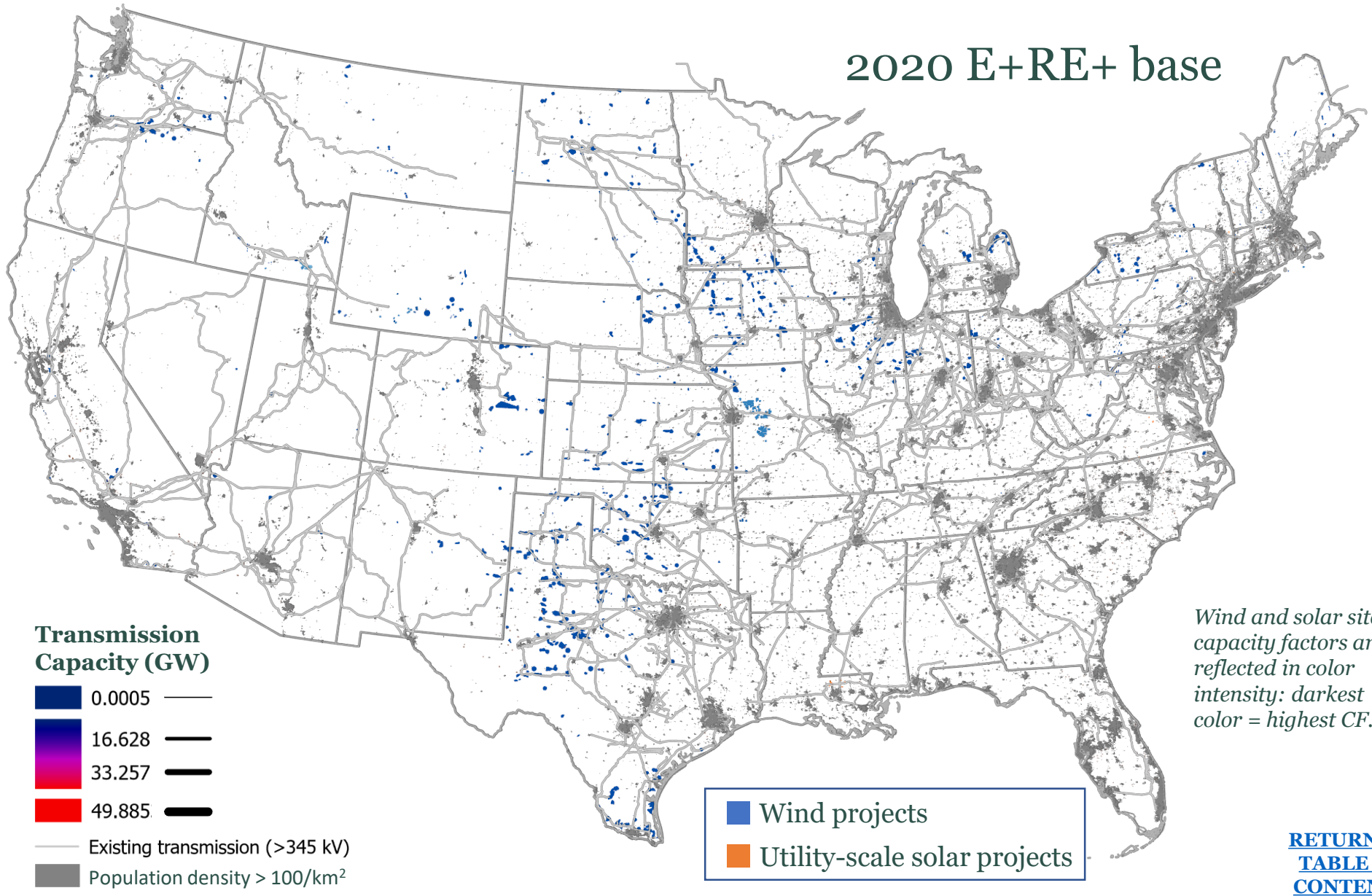
- The E+ RE+ case relies exclusively on renewable energy by 2050, and requires 5.8 TW of wind and solar capacity to meet economy-wide demands (nearly double the capacity in the E+ case). This represents $6.3 trillion of investment.
- The ranking of top 10 states for solar and for wind capacity installed in 2050 are both similar to those in the E+ case.
- By 2050, wind and solar farms span a total area of more than 1 million km², with wind farms accounting for 94% of this.
- Offshore wind farms span another 64,000 km² and are built extensively along the entire Atlantic Coast, as well as some areas in the Gulf of Mexico and floating turbines on the Pacific coast.
- Lands directly impacted by onshore wind and solar farms (e.g. with roads, turbine pads, solar arrays, inverters, and substations) totals 66,000 km² (an area larger than West Virginia).
- Transmission capacity expands ~75% by 2030 and ~400% by 2050 (to over 1.6 million GW-km installed). The needed expansion from 2020 to 2050 is about double that of the E+ case.
- Total capital invested in transmission is ~$320 billion through 2030 and $3.6 trillion by 2050.

Modeled 2020 wind and utility-scale solar capacity; Existing transmission lines (≥ 345 kV).

2020 (modeled)		
	Wind	**Solar**
Capacity installed (TW)		
	0.14	0.07
Land used (1000 km²)		
Total	57	1.12
Direct	5.8	1.02
Capital invested (Billion $$_{2018}$$)*		
Solar	-	47
Onshore wind	69	-
Offshore wind	-	-
Existing transmission		
Capacity (GW-km)**		320,000
Increase over 2020		-

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Homeland Infrastructure Foundation-Level Data (HIFLD), 2008, as cited in National Renewable Energy Laboratory, Renewable Electricity Futures Study, 2012.



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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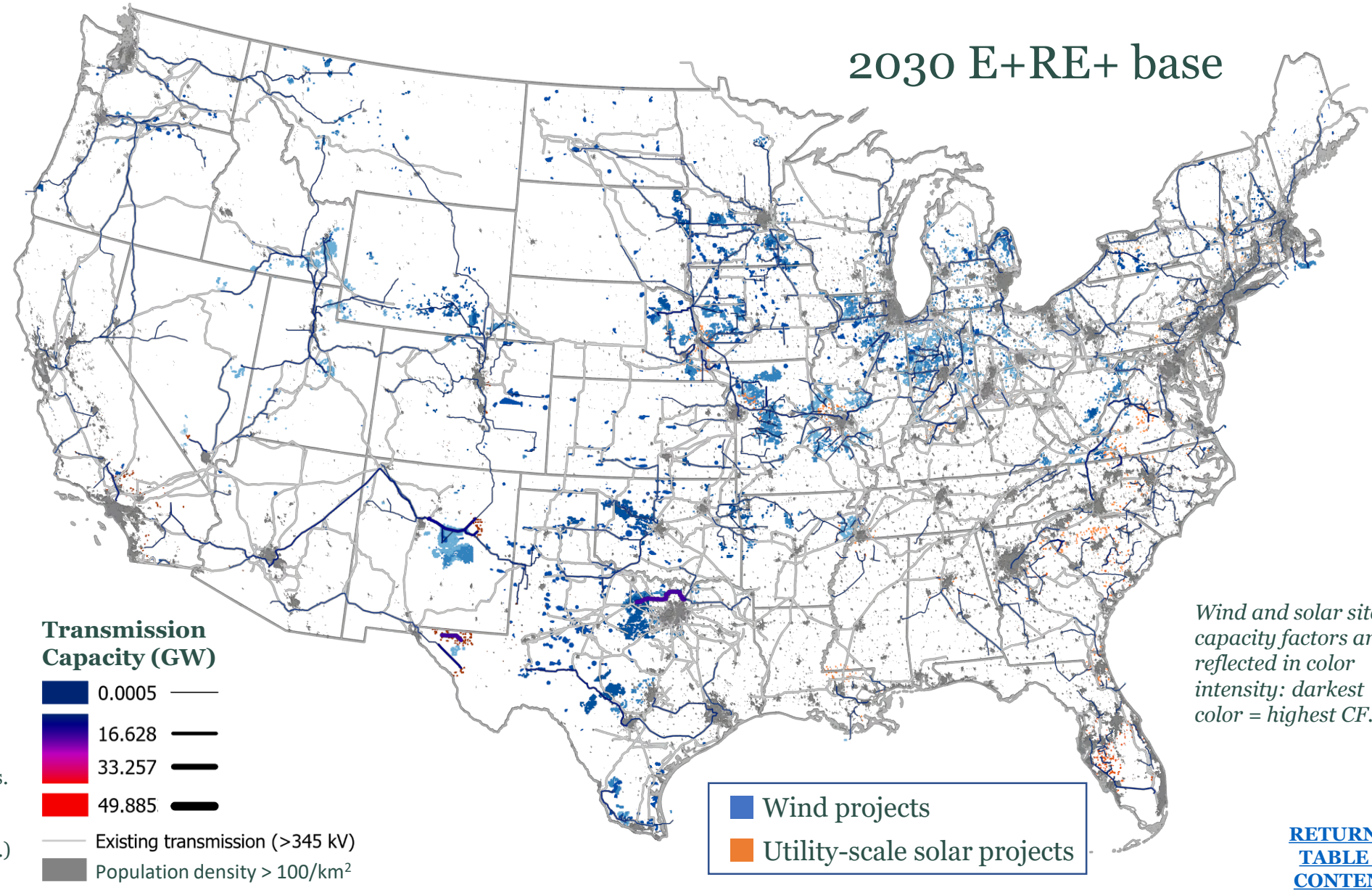
866 GW of wind and solar capacity operating in 2030; transmission capacity grows by 74%.

2030	Wind	Solar
Capacity installed (TW)		
	0.46	0.40
Land used (1000 km²)		
Total	174	8.7
Direct	1.74	7.9
Capital invested (Billion $_{2018}$)*		
Solar	-	450
Onshore wind	490	-
Offshore wind	15	-
Transmission added vs. 2020**		
Capacity (GW-km)		235,000
Increase over 2020		74%
Capital in serv (B$_{2018}$)		320

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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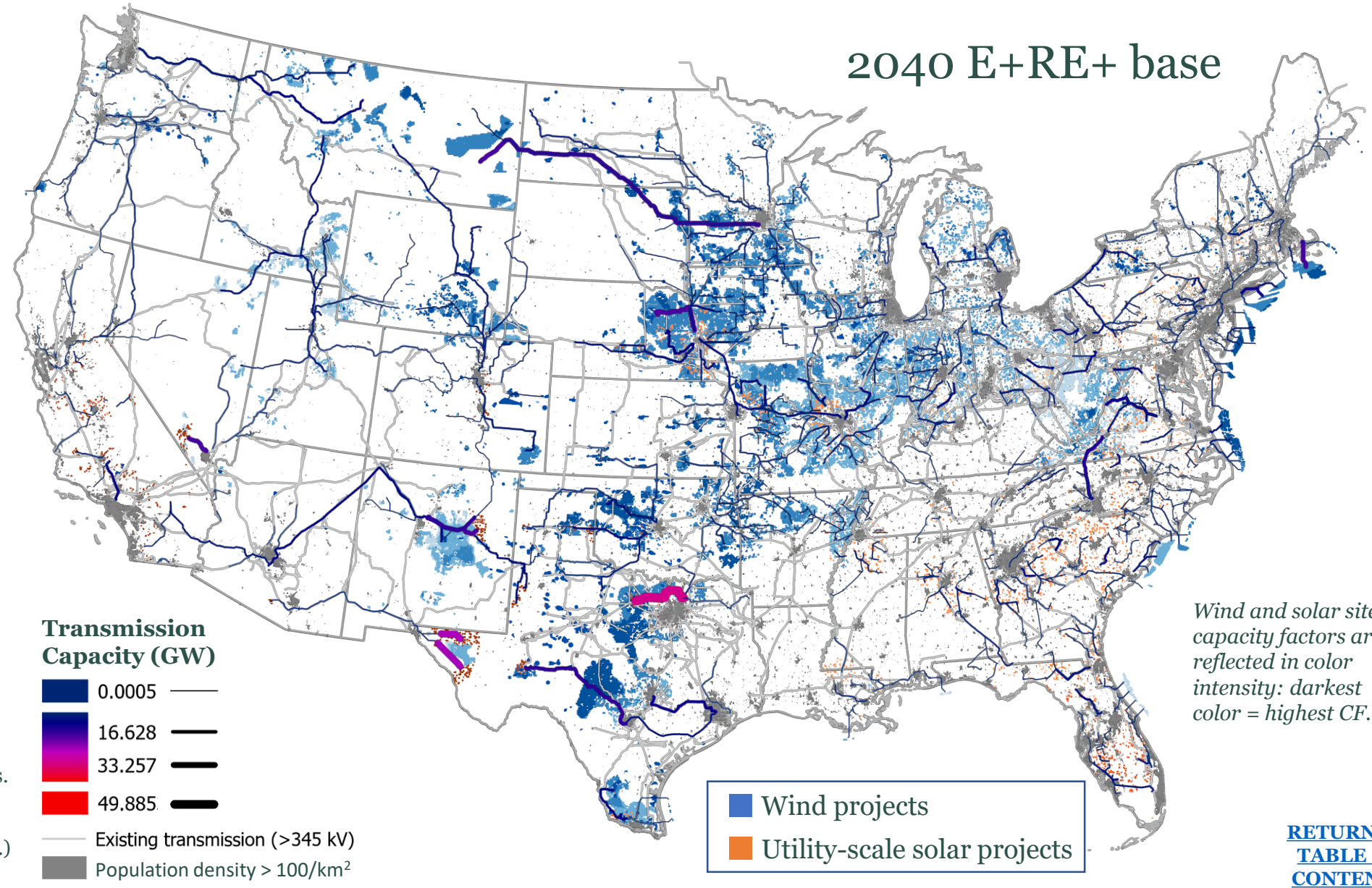
2.7 TW of wind and solar capacity operating in 2040; transmission capacity grows to 2.4x the 2020 level.

2040		
	Wind	**Solar**
Capacity installed (TW)		
	1.42	1.23
Land used (1000 km²)		
Total	493	26.9
Direct	4.9	24.5
Capital invested (Billion $_{2018}$)*		
Solar	-	1,305
Onshore wind	1,497	-
Offshore wind	223	-
Transmission added vs. 2020**		
Capacity (GW-km)		760,000
Increase over 2020		237%
Capital in serv (B$_{2018}$)		1,320

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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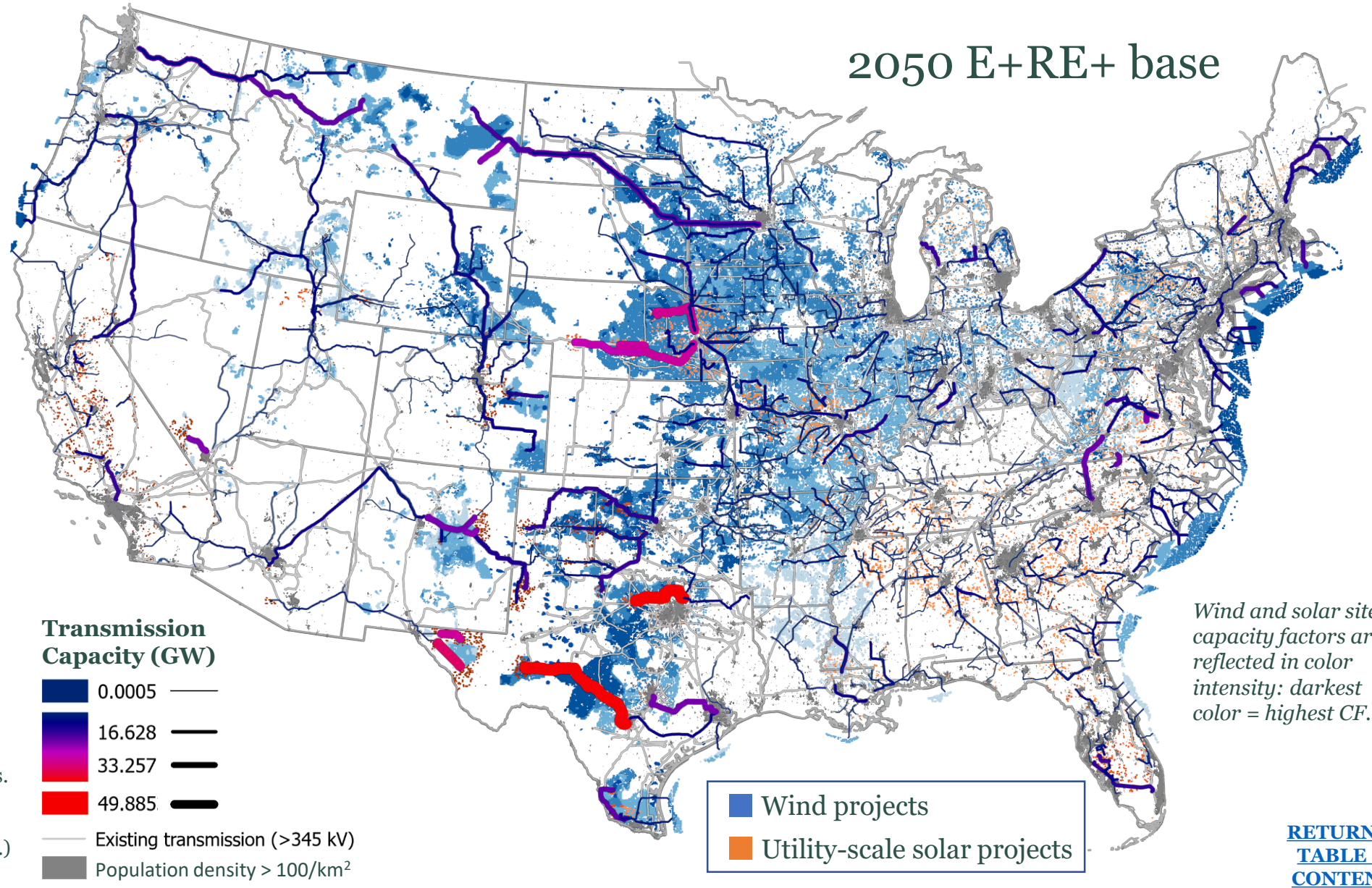
5.9 TW of wind and solar capacity operating in 2050; transmission capacity grows to 5.1x the 2020 level.

2050		
	Wind	**Solar**
Capacity installed (TW)		
	3.07	2.75
Land used (1000 km²)		
Total	1,003	61.2
Direct	10.0	55.7
Capital invested (Billion $_{2018}$)*		
Solar	-	2,684
Onshore wind	3,010	-
Offshore wind	594	-
Transmission added vs. 2020**		
Capacity (GW-km)		1,309,000
Increase over 2020		409%
Capital in serv (B$_{2018}$)		3,560

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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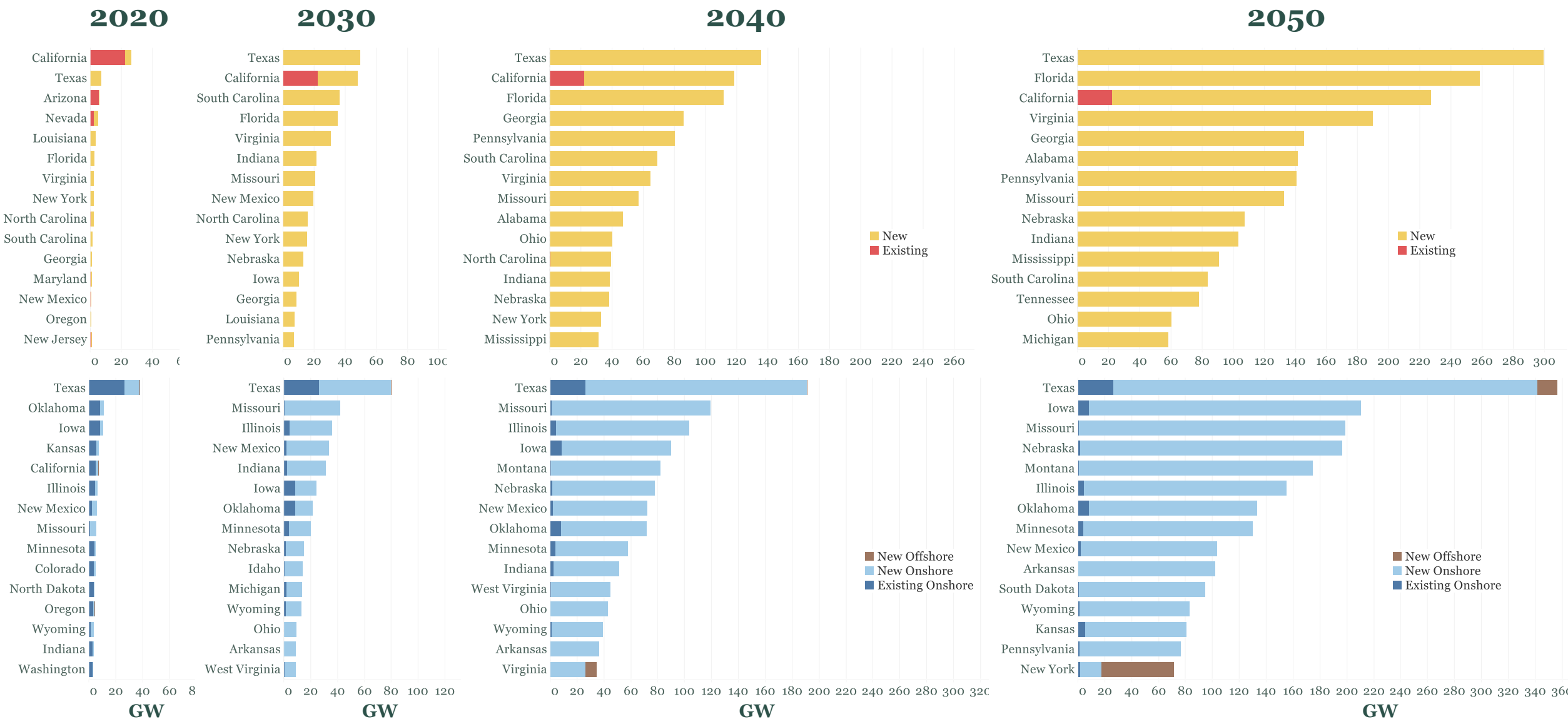
Top 15 states for installed wind and utility-scale solar capacity each decade, E+RE+ (base siting)



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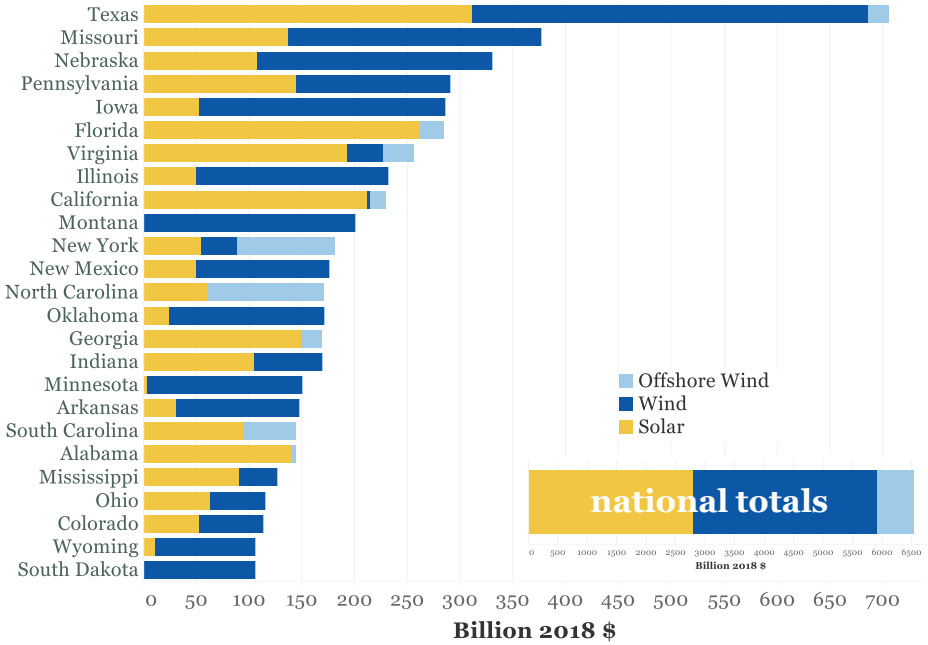
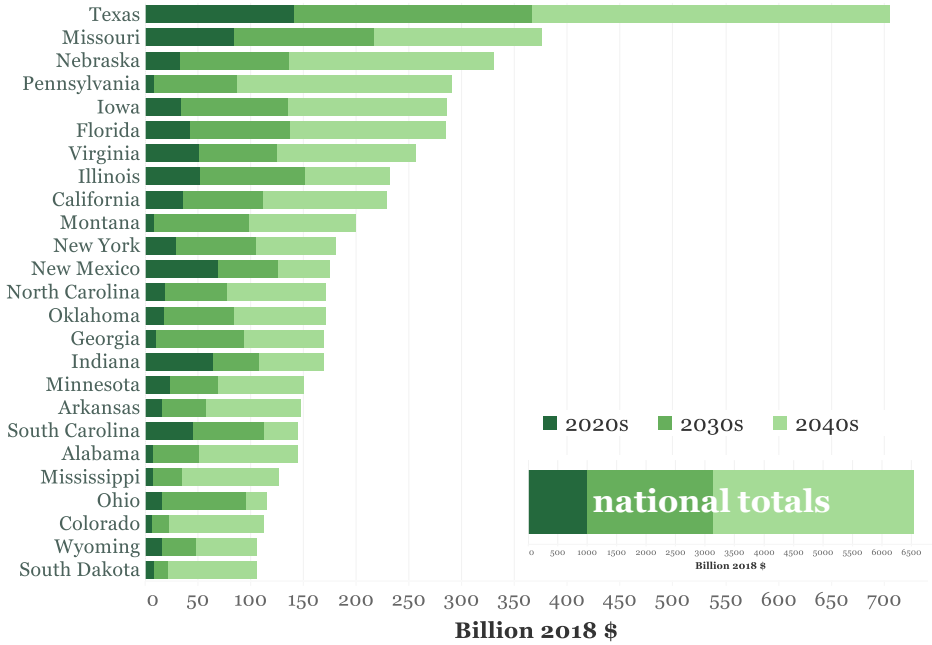
Capital investments by state in wind, utility-scale solar, and associated transmission capacities, E+RE+ (base siting)

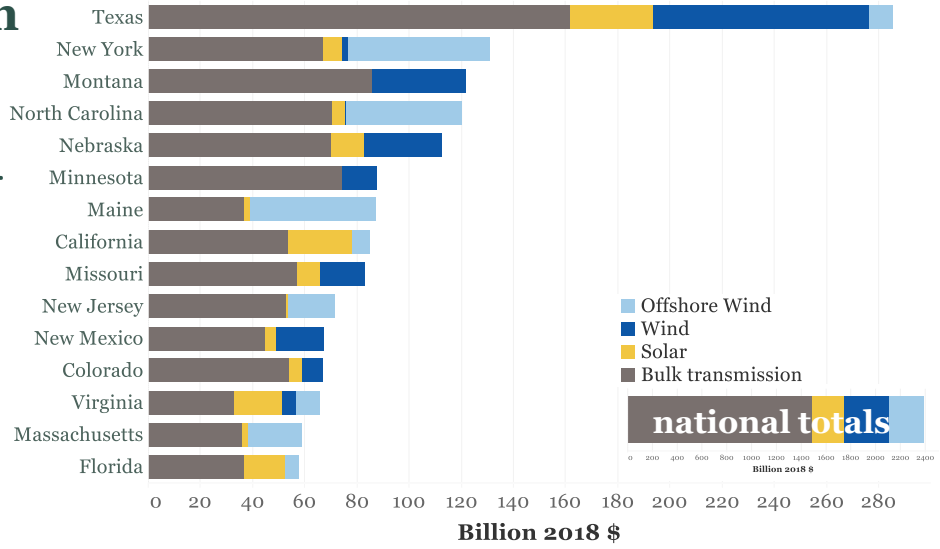
Wind & solar capacity investments, top 25 states

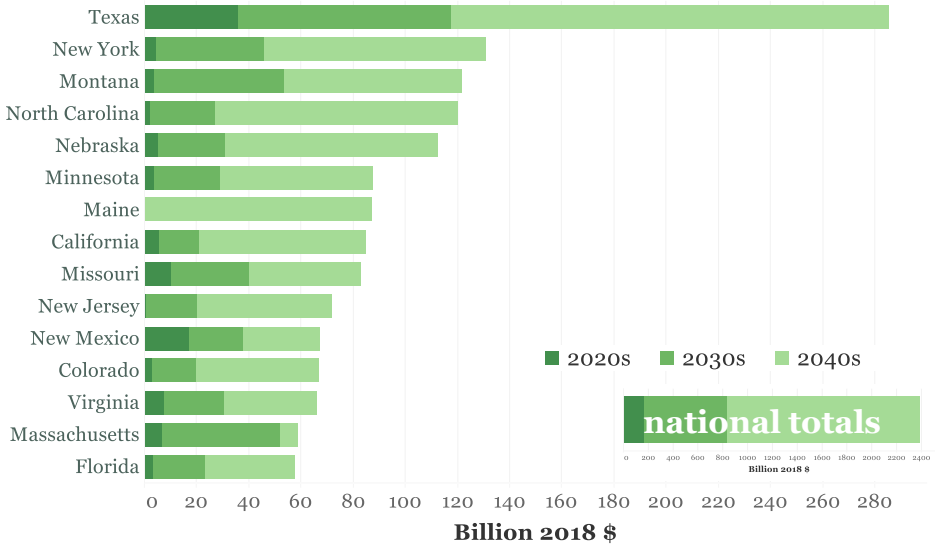




Transmission capacity investments, top 15 states*

* Includes investments in new capacity only. (End-of-life replacement costs, i.e., sustaining capital, is not included in this estimate.) Blue and yellow are investments in spur lines from wind and solar projects to nearest substation.





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Siting of solar and wind generators and transmission for the E+ RE- pathway with base land availability

Summary of this section

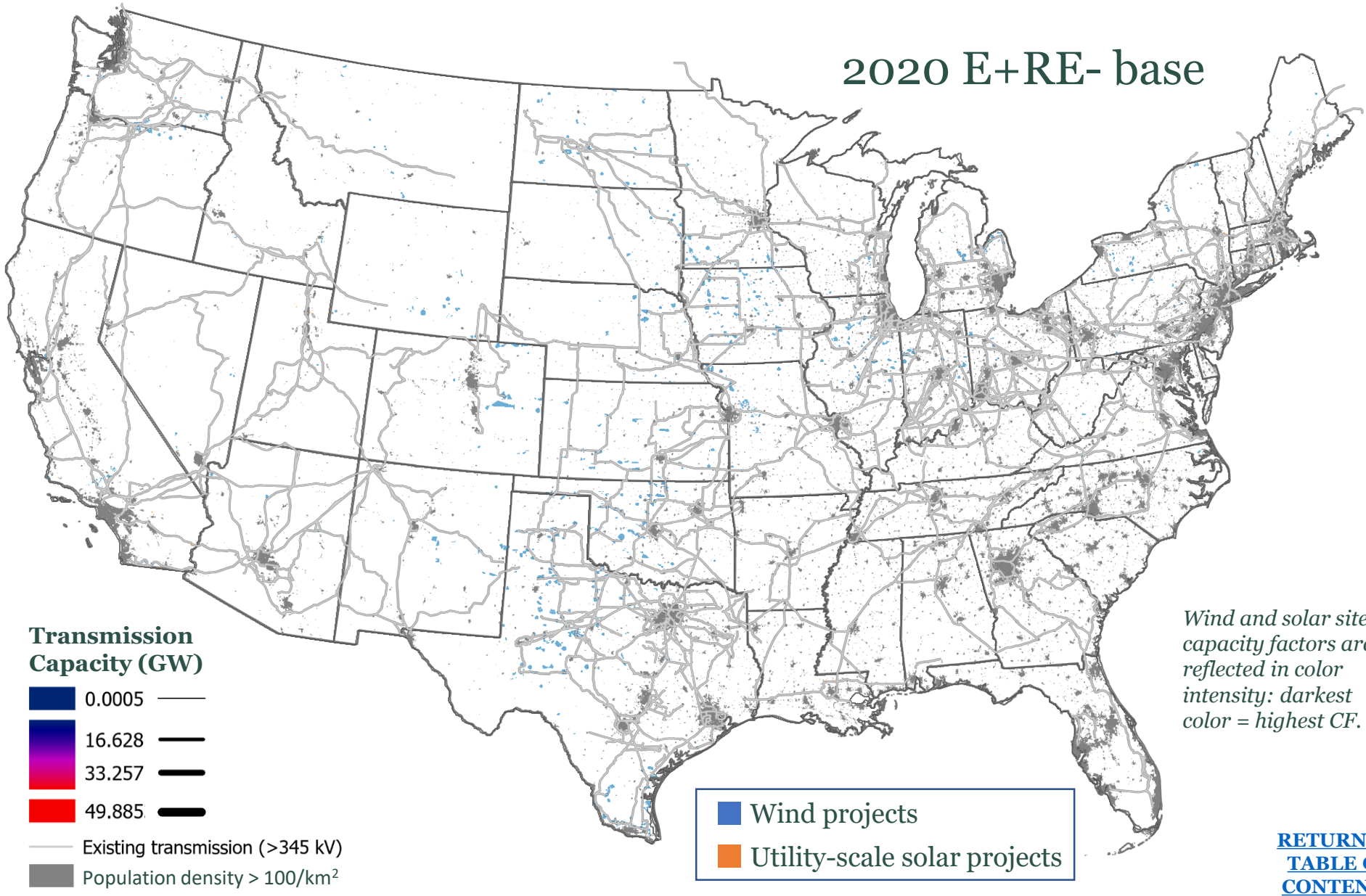
- The E+RE- case limits the allowed annual rate of solar and wind capacity expansion to 35 GW, resulting in 270 GW each of solar and onshore wind installed by 2030 and about 650 GW of each in 2050. Cumulative capital invested by 2050 is $1.4 trillion.
- The ranking of top 10 states for solar and for wind capacity installed in 2050 are both similar to those in the E+ case, but with significantly lower installed capacities.
- By 2050 wind and solar farms span a total area of about 260,000 km², with wind farms accounting for 95% of this.
- The direct land impact of onshore wind and solar farms (e.g. with roads, turbine pads, solar arrays, inverters, and substations) totals about 16,000 km² (an area larger than Connecticut).
- Offshore wind farms span an area of 5,700 km² (57 km² of directly-impacted area), primarily off the U.S. Northeast coast.
- Transmission capacity expands ~40% by 2030 and ~100% by 2050. The needed expansion from 2020 to 2050 is about half of that in the E+ case.
- Total capital invested in transmission is ~$290 billion through 2030 and $1.3 trillion by 2050.

Modeled 2020 wind and utility-scale solar capacity; Existing transmission lines (≥ 345 kV).

2020 (modeled)	Wind	Solar
Capacity installed (TW)		
	0.14	0.08
Land used (1000 km²)		
Total	56	1.39
Direct	0.56	1.26
Capital invested (Billion $$_{2018}$$)*		
Solar	-	60
Onshore wind	72	-
Offshore wind	-	-
Existing transmission		
Capacity (GW-km)**	320,000	
Increase over 2020	-	

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Homeland Infrastructure Foundation-Level Data (HIFLD), 2008, as cited in National Renewable Energy Laboratory, Renewable Electricity Futures Study, 2012.



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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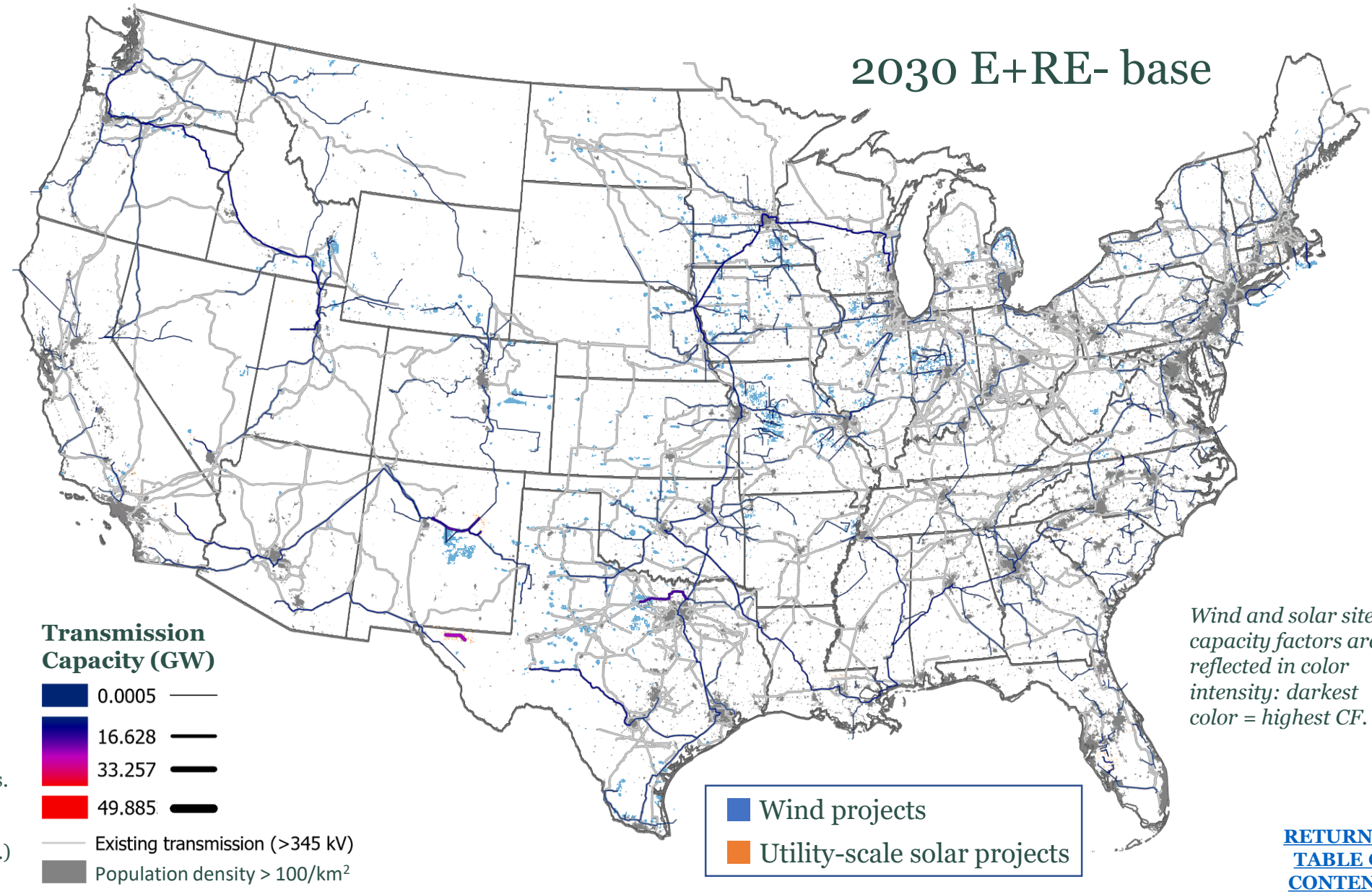
539 GW of wind and solar capacity operating in 2030; transmission capacity grows by 39%.

2030	Wind	Solar
Capacity installed (TW)		
	0.27	0.27
Land used (1000 km²)		
Total	102	5.8
Direct	1.03	5.3
Capital invested (Billion $_{2018}$)*		
Solar	-	292
Onshore wind	229	-
Offshore wind	33	-
Transmission added vs. 2020**		
Capacity (GW-km)		125,000
Increase over 2020		39%
Capital in serv (B$_{2018}$)		290

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



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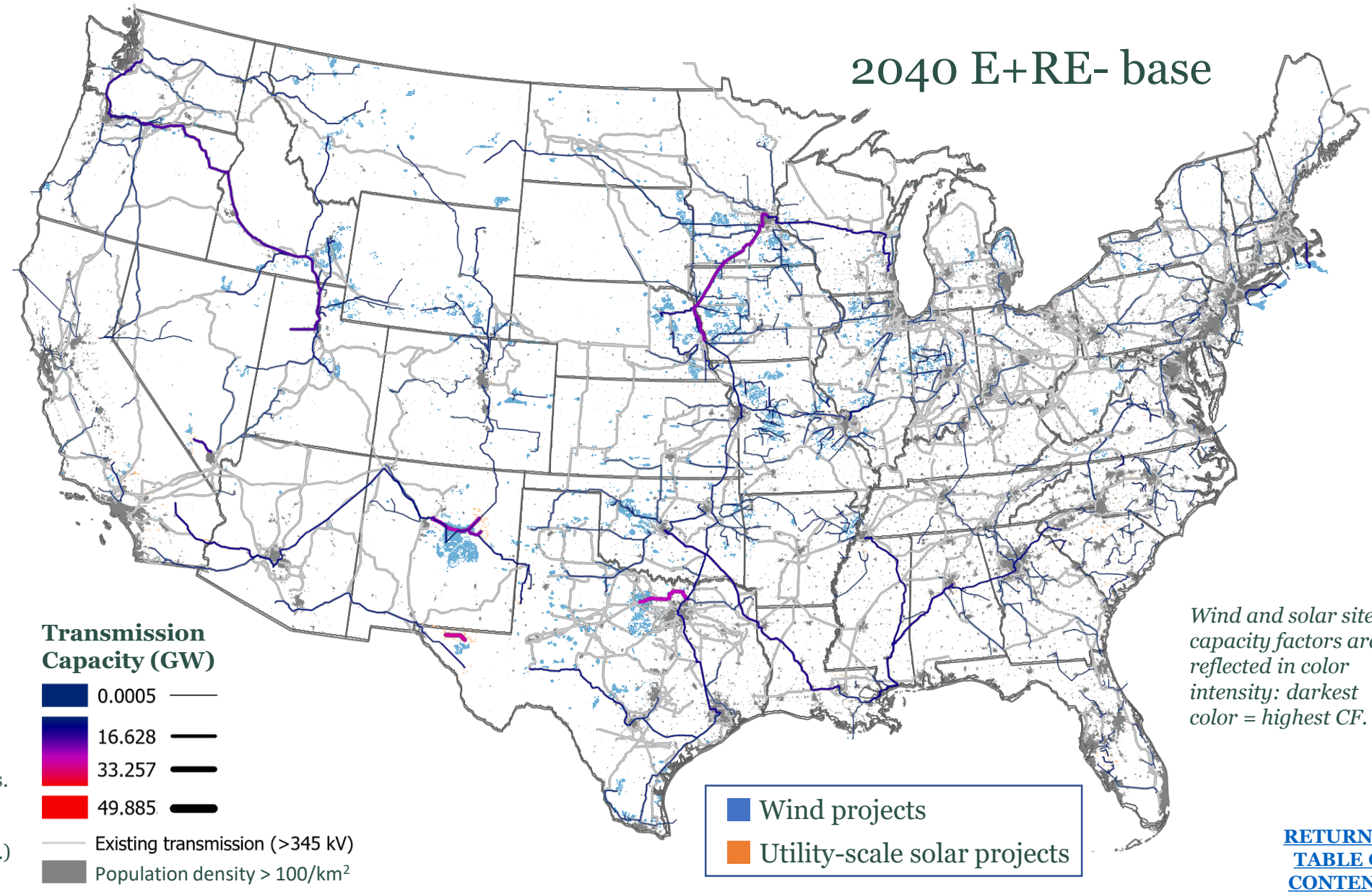
924 GW of wind and solar capacity operating in 2040; transmission capacity grows by 81% over 2020 level.

2040		
	Wind	**Solar**
Capacity installed (TW)		
	0.47	0.46
Land used (1000 km²)		
Total	170	10.1
Direct	1.7	9.19
Capital invested (Billion $_{2018}$)*		
Solar	-	489
Onshore wind	443	-
Offshore wind	57	-
Transmission added vs. 2020**		
Capacity (GW-km)		260,000
Increase over 2020		81%
Capital in serv (B$_{2018}$)		990

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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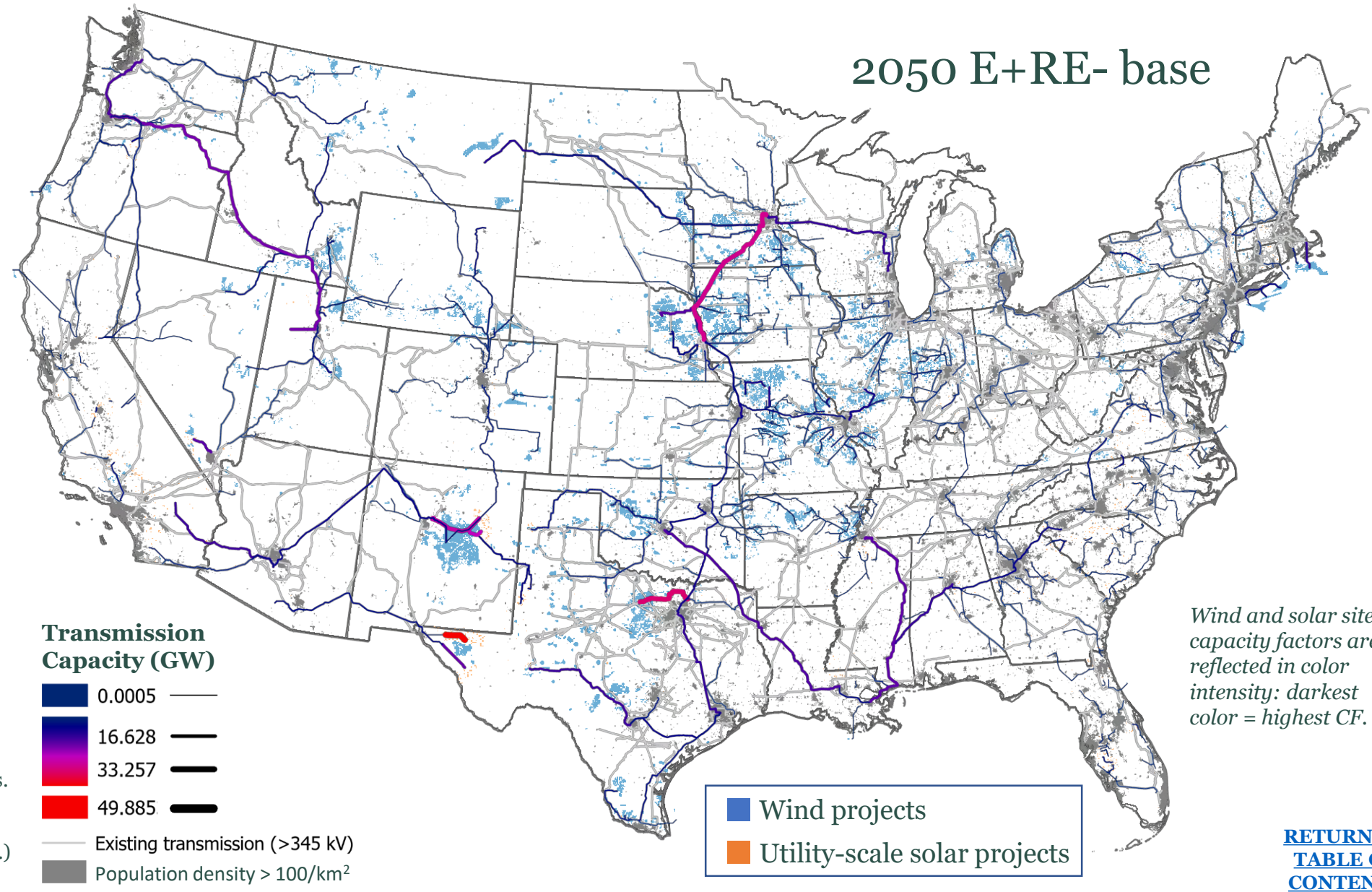
1.3 TW of solar and wind capacity operating in 2050; transmission capacity is 2x the 2020 level.

2050		
	Wind	**Solar**
Capacity installed (TW)		
	0.67	0.64
Land used (1000 km²)		
Total	244	14.2
Direct	2.44	13.0
Capital invested (Billion $_{2018}$)*		
Solar	-	655
Onshore wind	658	-
Offshore wind	71	-
Transmission added vs. 2020**		
Capacity (GW-km)		306,000
Increase over 2020		96%
Capital in serv (B$_{2018}$)		1,280

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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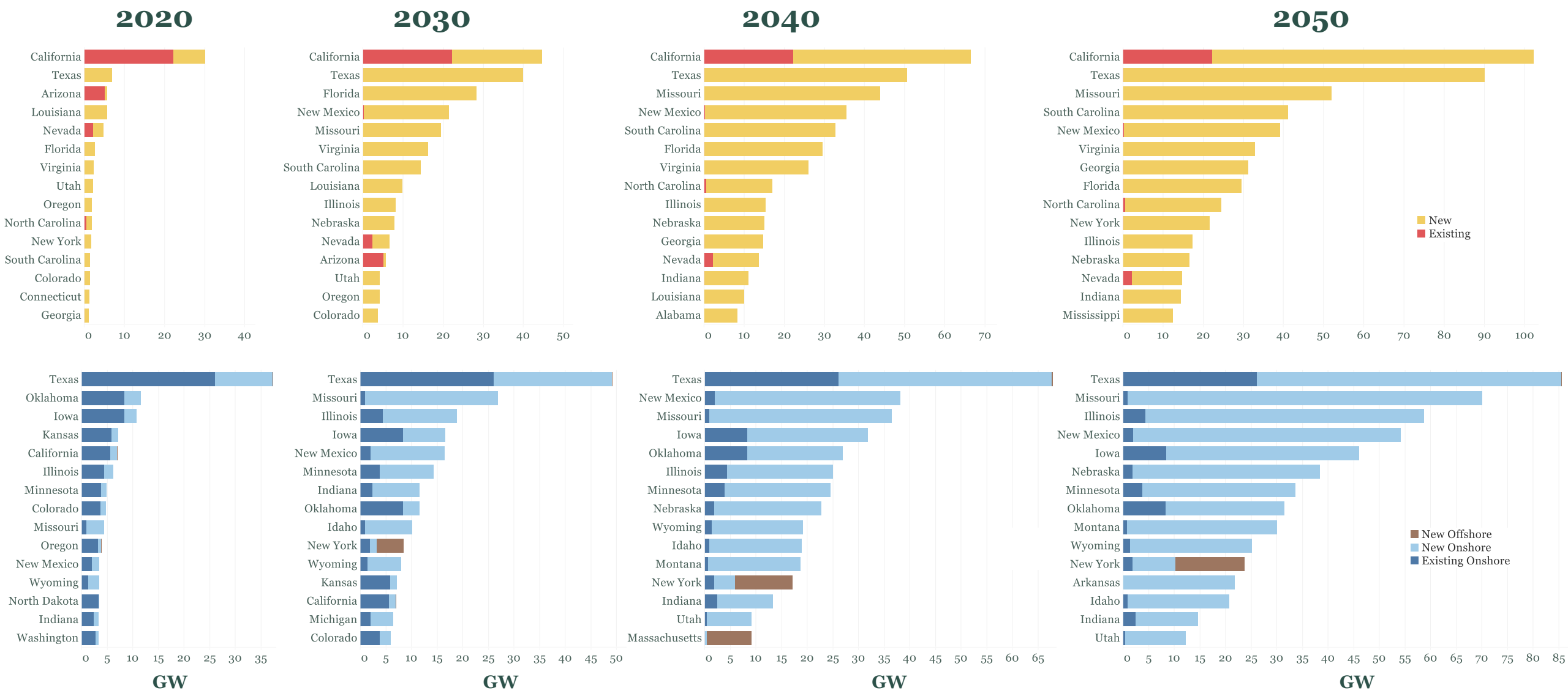
Top 15 states for installed wind and utility-scale solar capacity each decade, E+RE- (base siting)



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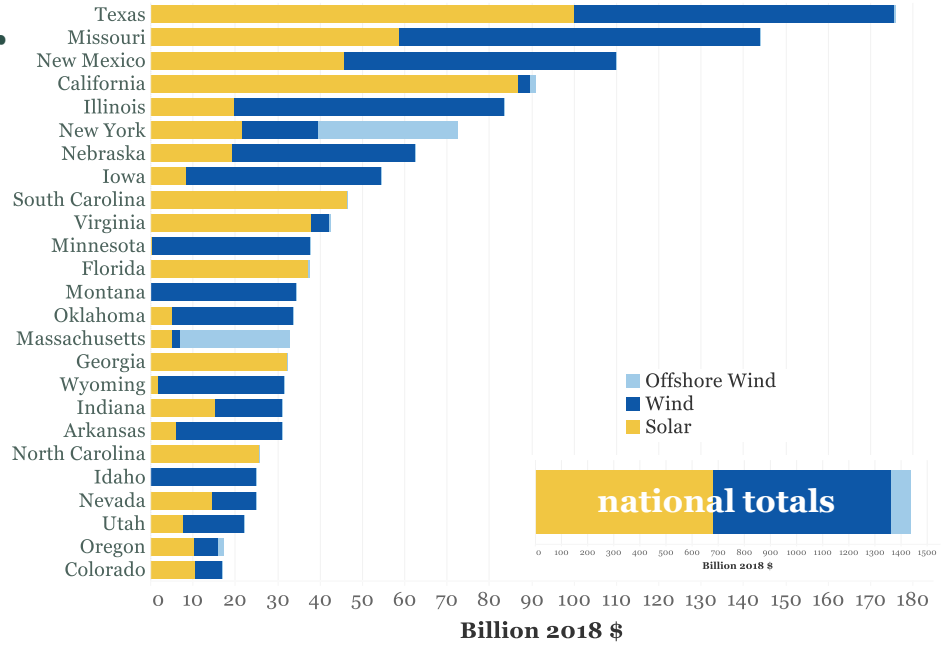
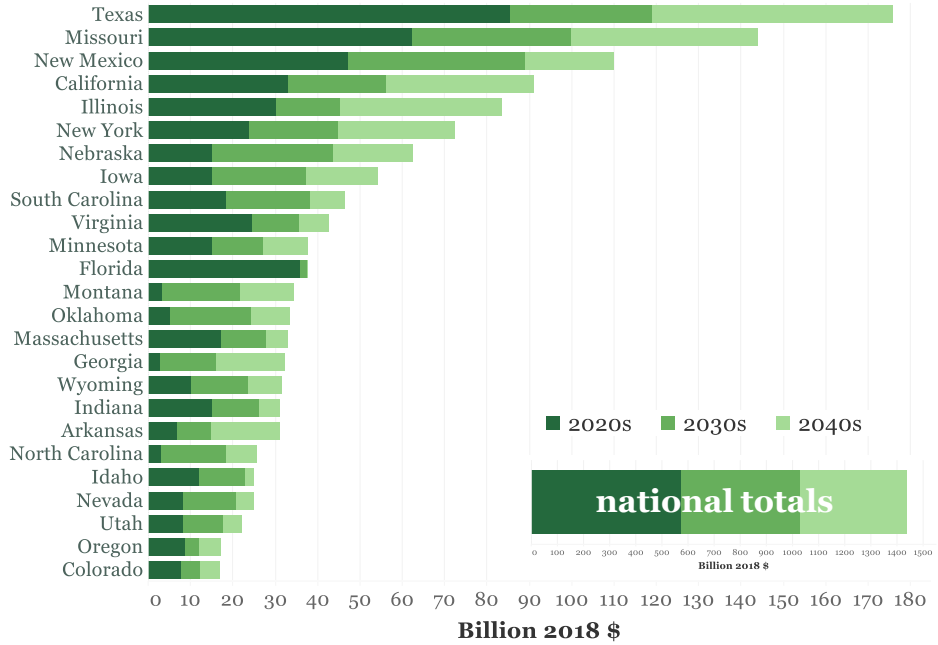
Capital investments by state in wind, utility-scale solar, and associated transmission capacities, E+RE- (base siting)

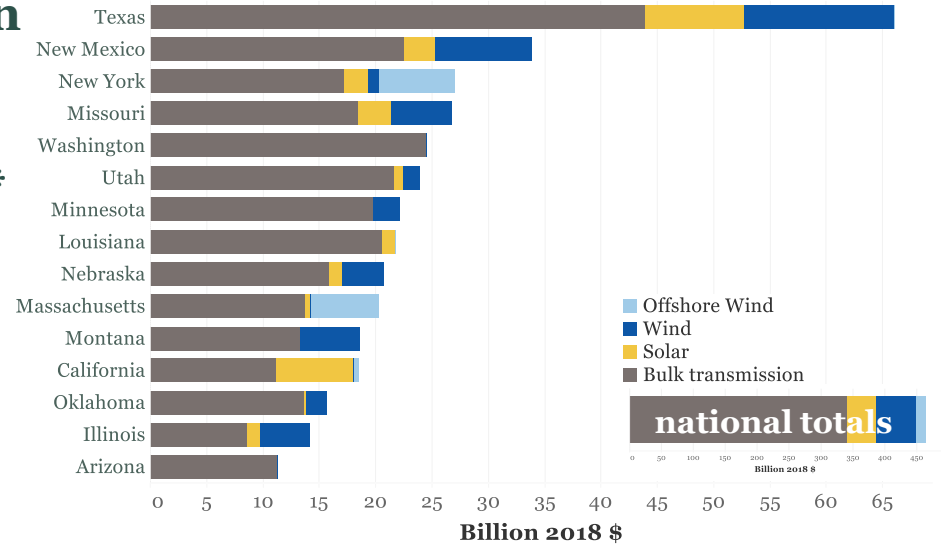
Wind & solar capacity investments, top 25 states

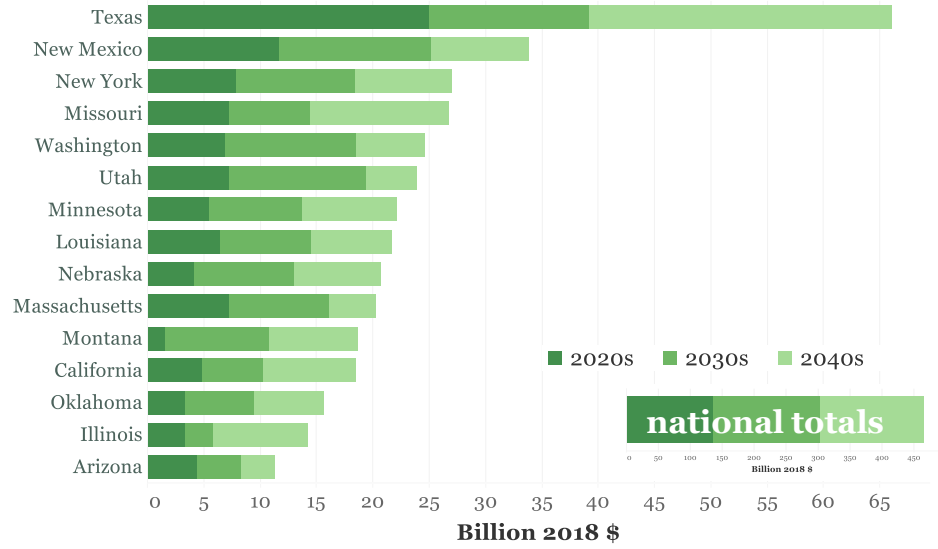




Transmission capacity investments, top 15 states*

* Includes investments in new capacity only. (End-of-life replacement costs, i.e., sustaining capital, is not included in this estimate.) Blue and yellow are investments in spur lines from wind and solar projects to nearest substation.





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Siting of solar and wind generators and transmission for the REF pathway with base land availability.

Summary of this section

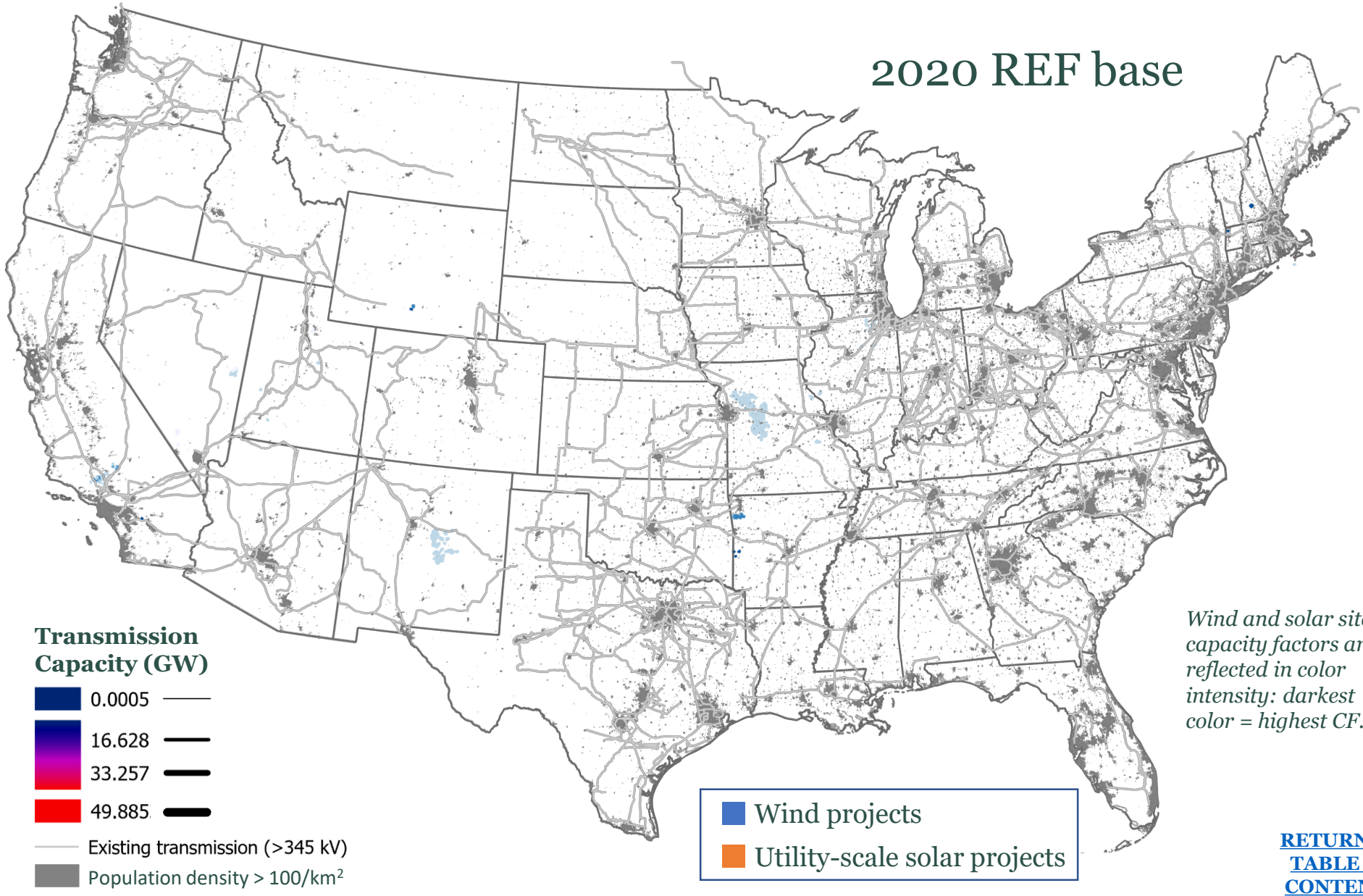
- REF is a "no new policy" case, with no greenhouse gas emissions reduction goals. Solar and wind capacity expand much more slowly than in the modeled decarbonization cases. Less than 250 GW of combined solar and wind capacity are installed in by 2030 and less than 600 GW by 2050. Cumulative capital invested by 2050 is about $520 billion.
- The ranking of top 10 states for solar and for wind installed in 2050 varies considerably from those in the E+ case.
- By 2050 wind and solar farms span a total area of less than 150,000 km², with wind farms accounting for most of this.
- The direct land impact of onshore wind and solar farms (e.g. with roads, turbine pads, solar arrays, inverters, and substations) totals about 4,200 km² (slightly larger than Rhode Island).
- Transmission capacity expands ~18% by 2030 and ~47% by 2050. The needed expansion from 2020 to 2050 is about a quarter of that in the E+ case and half that in the E+ RE- case.
- Total capital invested in transmission is ~$210 billion through 2030 and $0.95 trillion by 2050.

Modeled 2020 wind and utility-scale solar capacity; Existing transmission lines (≥ 345 kV).

2020 (modeled)	Wind	Solar
Capacity installed (TW)		
	0.15	0.06
Land used (1000 km²)		
Total	61.5	0.95
Direct	0.62	0.86
Capital invested (Billion $$_{2018}$$)*		
Solar	-	36
Onshore wind	84	-
Offshore wind	-	-
Existing transmission		
Capacity (GW-km)**	320,000	
Increase over 2020	-	

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Homeland Infrastructure Foundation-Level Data (HIFLD), 2008, as cited in National Renewable Energy Laboratory, Renewable Electricity Futures Study, 2012.



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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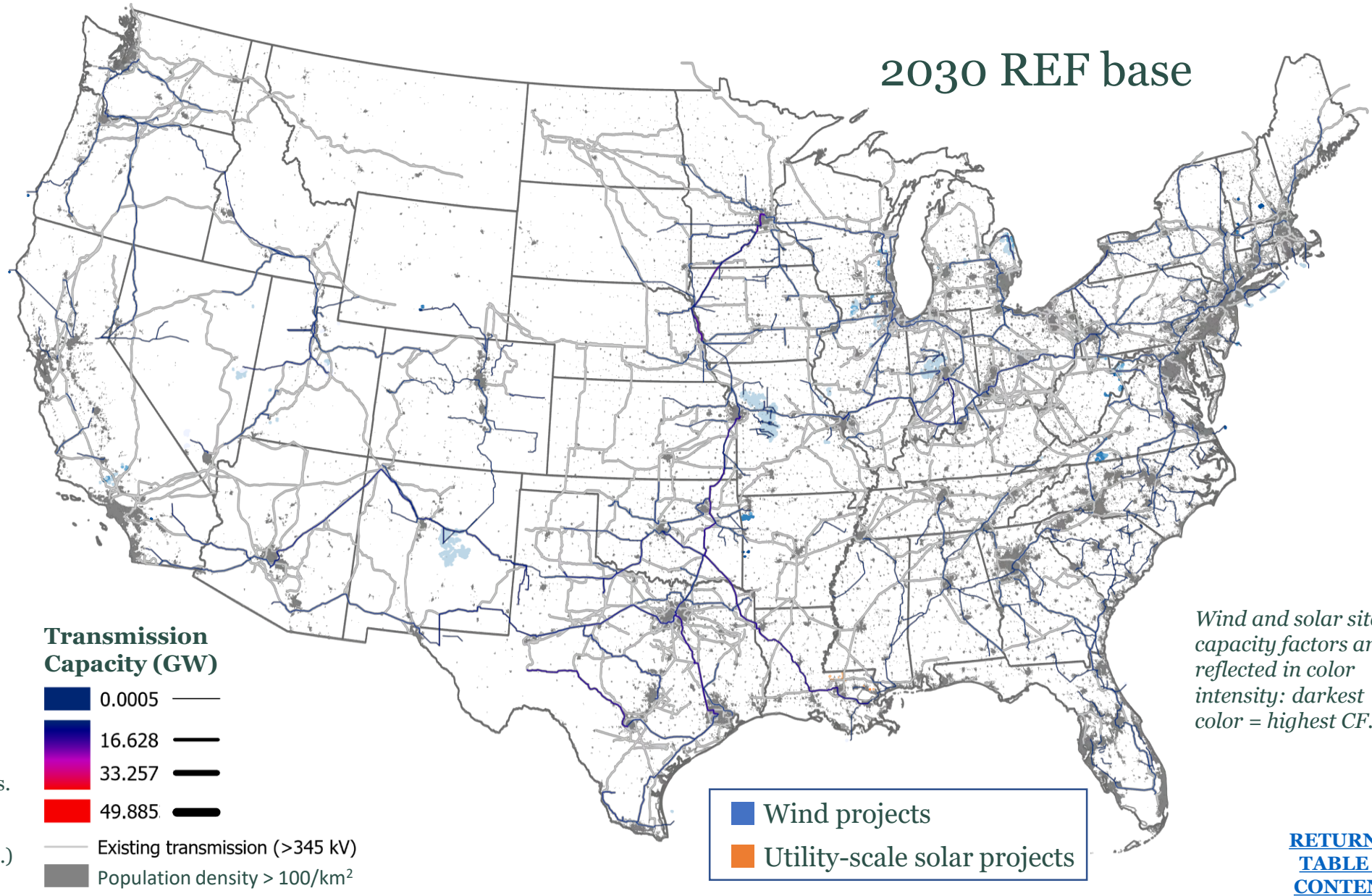
239 GW of wind and solar capacity operating in 2030; transmission capacity grows by 18%.

2030	Wind	Solar
Capacity installed (TW)		
	0.17	0.06
Land used (1000 km²)		
Total	69.1	1.02
Direct	0.69	0.92
Capital invested (Billion $_{2018}$)*		
Solar	-	41
Onshore wind	110	-
Offshore wind	9	-
Transmission added vs. 2020**		
Capacity (GW-km)		60,000
Increase over 2020		18%
Capital in serv (B$_{2018}$)		210

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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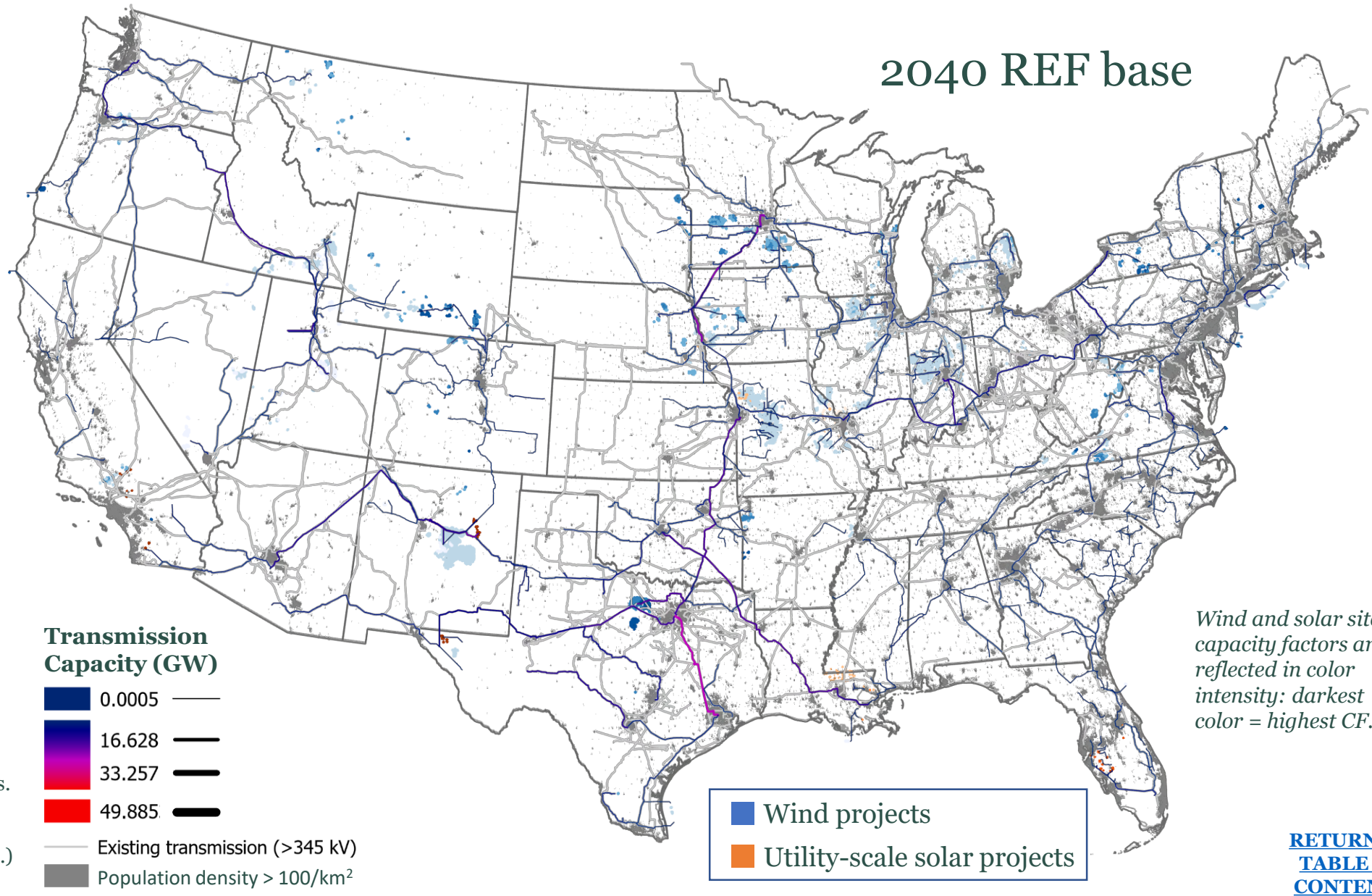
373 GW of wind and solar capacity operating in 2040; transmission capacity grows by 38% over 2020 level.

2040		
	Wind	**Solar**
Capacity installed (TW)		
	0.27	0.11
Land used (1000 km²)		
Total	102	1.87
Direct	1.02	1.70
Capital invested (Billion $_{2018}$)*		
Solar	-	83
Onshore wind	213	-
Offshore wind	19	-
Transmission added vs. 2020**		
Capacity (GW-km)		122,000
Increase over 2020		38%
Capital in serv (B$_{2018}$)		510

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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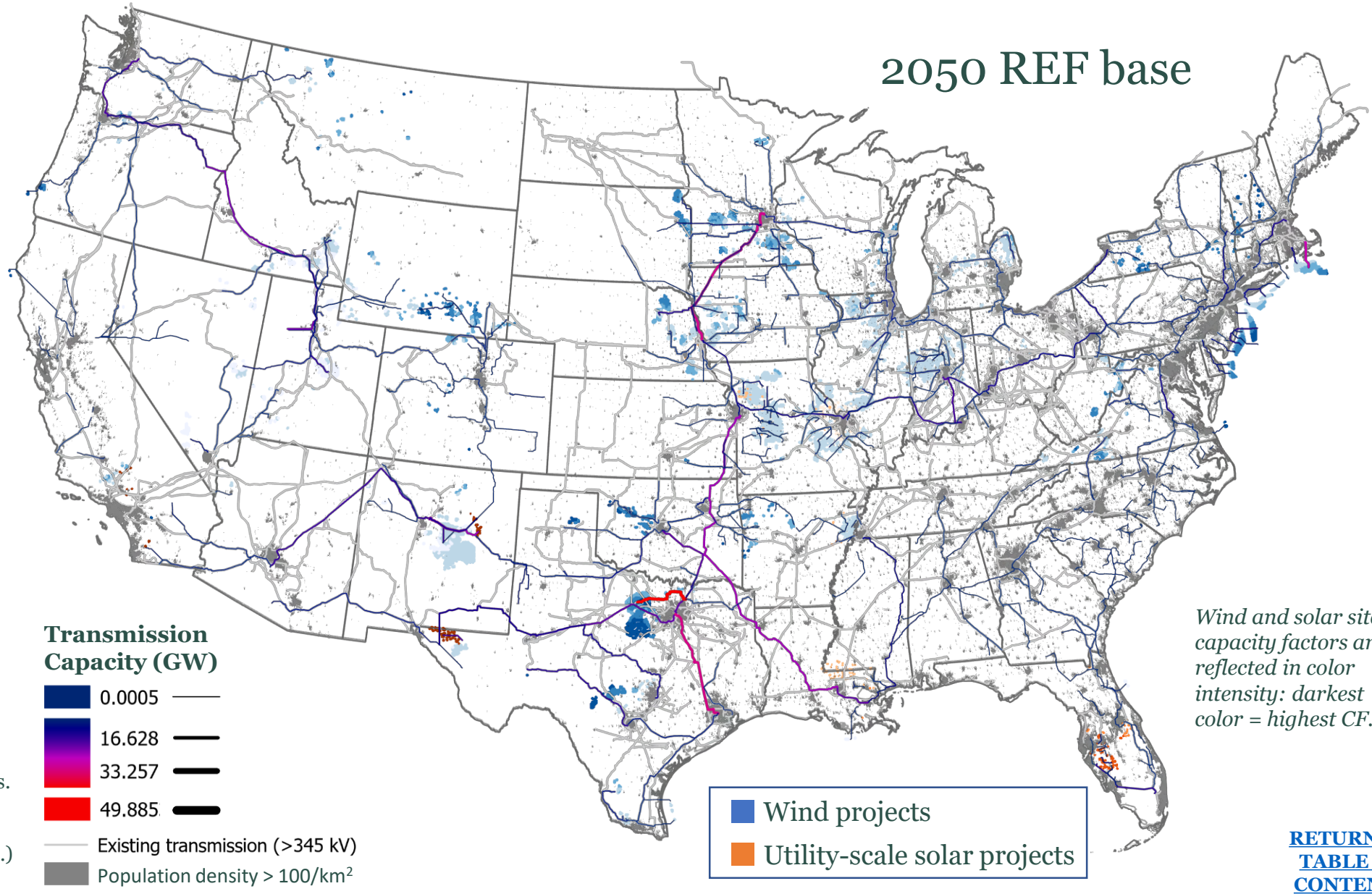
562 GW of wind and solar capacity operating in 2050; transmission capacity is 1.5x the 2020 level.

2050		
	Wind	**Solar**
Capacity installed (TW)		
	0.41	0.16
Land used (1000 km²)		
Total	142	3.05
Direct	1.42	2.77
Capital invested (Billion $_{2018}$)*		
Solar	-	128
Onshore wind	327	-
Offshore wind	62	-
Transmission added vs. 2020**		
Capacity (GW-km)		152,000
Increase over 2020		47%
Capital in serv (B$_{2018}$)		945

* Excludes investments associated with 2020 pre-existing capacity. Capital is for additional capacity required to meet total modeled wind & solar generation levels.

** Transmission expansion is mapped to follow existing rights of way (>160 kV); paths are indicative not definitive. Spur lines from solar and wind projects to substations are not shown, but are included in GW-km and investment totals. Capital in service includes capital for transmission expansions and "sustaining capital" (for end-of-life line replacements.)



Wind and solar site capacity factors are reflected in color intensity: darkest color = highest CF.

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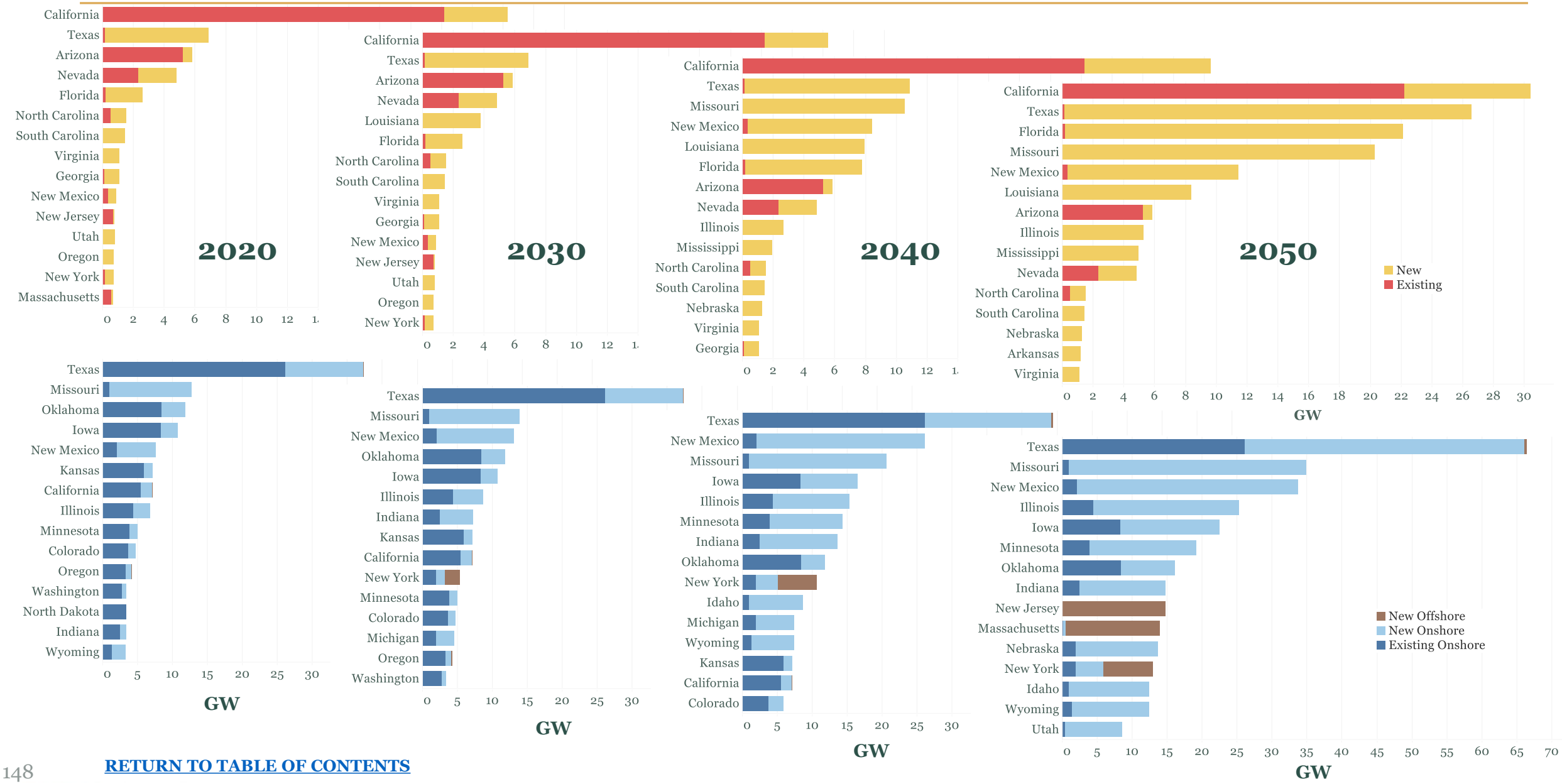
Top 15 states for installed wind and utility-scale solar capacity each decade, REF (base siting)



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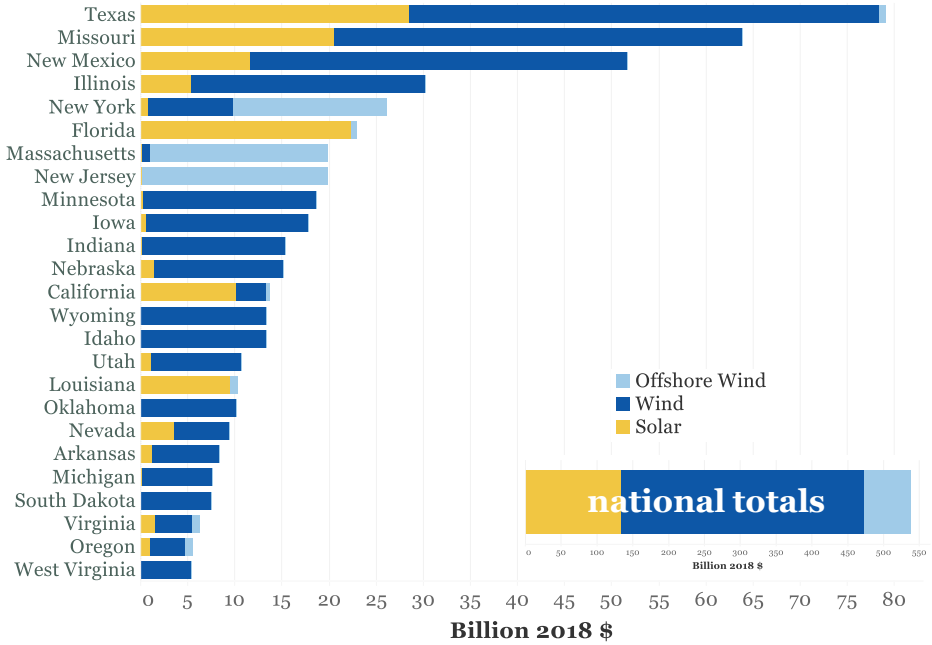
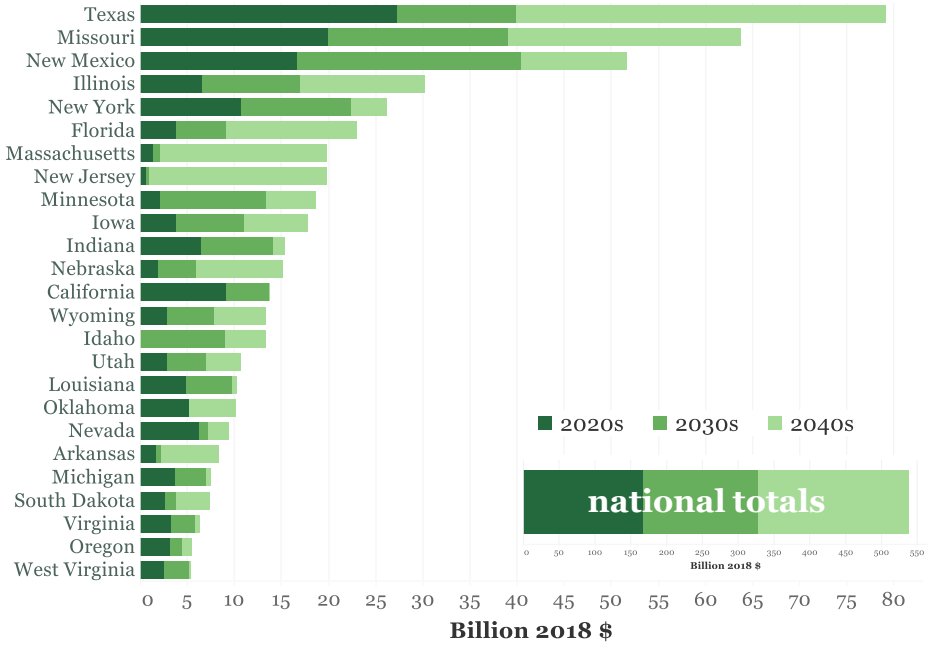
Capital investments by state in wind, utility-scale solar, and associated transmission capacities, REF (base siting)

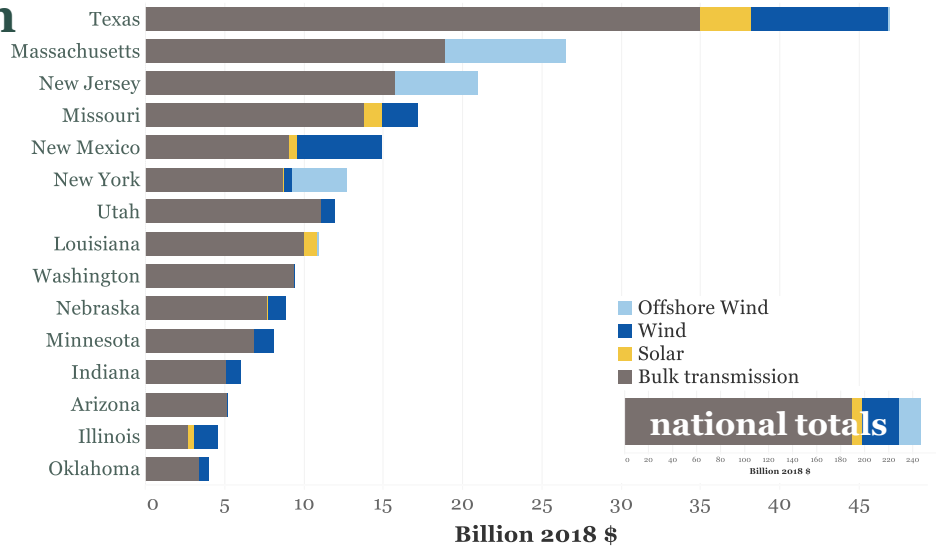
Wind & solar capacity investments, top 25 states

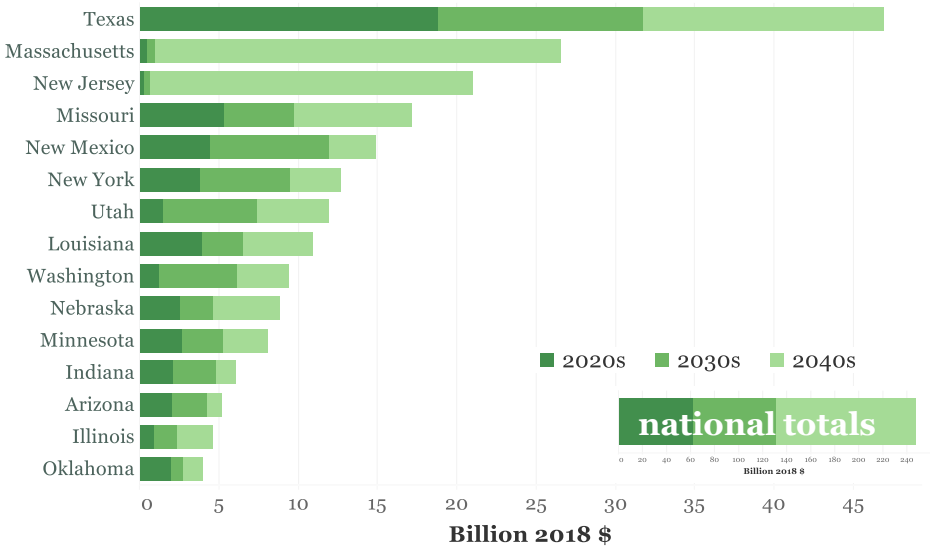




Transmission capacity investments, top 15 states*

* Includes investments in new capacity only. (End-of-life replacement costs, i.e., sustaining capital, is not included in this estimate.) Blue and yellow are investments in spur lines from wind and solar projects to nearest substation.





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Clean firm resources and thermal plant retirements

Summary of this section

- Installed capacity of "firm" generation sources — technologies that can produce power on demand, any time of year, for as long as required — remains similar to current levels in all scenarios, with ~500-1,000 GW (vs. 875 GW today).
- Coal fired capacity is completely retired by 2030 across all NZA scenarios with decline rates similar across all regions at higher than the historical peak of 21 GW/y in 2015. No new coal fired capacity is added in any scenario.
- About 50% of existing nuclear capacity retires by 2050 in all NZA scenarios (by assumption to reflect age-based retirements); the E+RE+ scenario phases out all nuclear by 2050 with 15 GW retired by 2030.
- New advanced nuclear generation capacity is added in all scenarios except E+RE+; expansion is modest in E+, E- and E+B+ with ~10-20 GW deployed in the 2030s and 2040s. The E+RE- scenario expands new nuclear capacity rapidly from 2025-2050, deploying ~260 GW by 2050, requiring historically unprecedented build rates in the 2040s.
- Natural gas retirements vary across NZA scenarios, with the E+RE+ scenario seeing the most (224 GW) and the E+RE- scenario seeing the least capacity retired (175 GW). By 2050, cumulative retirements are consistent across most NZA scenarios (450 GW) except for the E+RE- scenario (506 GW).
- New natural gas fired capacity is added in all scenarios except E+RE+. The most new capacity is added in E+RE- which sees ~580 GW of new gas capacity (around 230 GW of which includes CO_2 capture) by 2050.
- To meet firm capacity needs in the 100% renewable E+RE+ scenario, ~590 GW of new combustion turbine and combined cycle power plants are deployed and by 2050 and are fired entirely with zero-carbon synthetic gas.
- Siting studies indicated that most of the new thermal generation capacity can be sited at existing coal, natural gas and nuclear plant sites with few new sites to be developed, but many existing sites would fail on at least one safety or environmental criteria currently applicable to new greenfield projects.

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