Appendix: Baseload power potential from optimally-configured wind, solar and storage power plants across the United States

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Ratios of Wind and Solar

Figure 4 shows the optimal solar to wind ratios for 2020 and 2050.

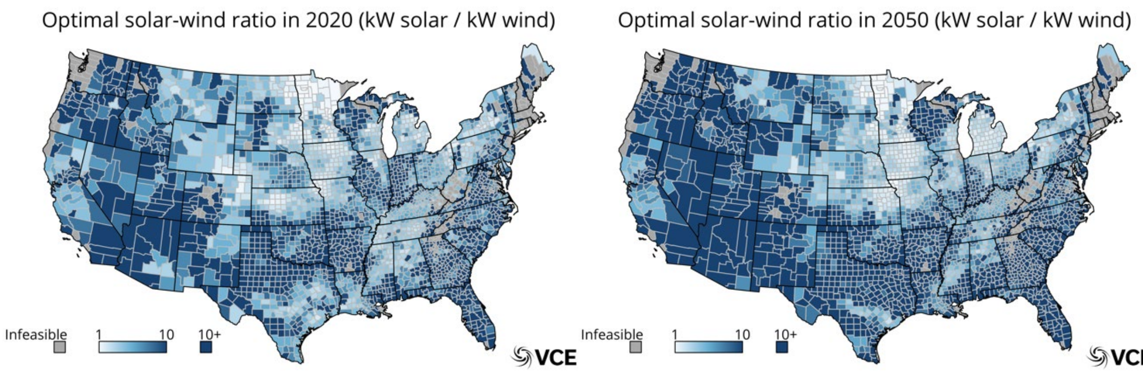


Figure 1: Optimal solar to wind ratio for renewable baseload in every feasible US county in 2020 (left) and 2050 (right).

The average solar to wind ratio in 2020 was about 11.4, which means that, on average, for every 1 kW of wind installed at a renewable baseload power plant, about 11.4 kW of solar was installed. In 2050, the average ratio increased to about 15. The median ratios were 6.5 and 7.7 for 2020 and 2050, respectively. Thus, given our forward technology cost assumptions, solar becomes more valuable relative to wind in the future. Note that these values do not include locations where the model did not deploy any wind (523 locations in 2020 and 612 locations in 2050). Every feasible location deployed some amount of solar.

Interestingly, we can also see the spatial changes of solar to wind ratios between 2020 and 2050. When energy storage is more expensive (2020 vs. 2050), the model puts more of an emphasis on deploying complimentary generation technology mixes in each location, i.e. wind for the night and solar for the day (roughly), with enough energy storage to fill in the gaps – there is no location where is it optimal to deploy just generation and thus every location installed some storage even during the more expensive early years. However, as the cost of energy storage falls, less emphasis is placed on complimentary generation as it becomes cheaper to store energy for times when the wind or solar are not producing energy.

Thus, as a general rule, as the cost of energy storage declines, the optimal solar-wind mix, for a given location, will tend toward the resource that has the lowest production cost (or levelized cost of electricity) in that location. We see this phenomenon in Figure 4. As the cost of energy storage declines in 2050, the optimal solar-wind ratios have increased (more solar relative to wind) in locations with better solar than wind resources (across the south and west) and decreased (more favored wind than solar) in locations with better wind than solar resources such as the Upper Midwest.

Available reserves

As part of the analysis, the model was limited in its ability to discharge the energy storage units and was required to keep the systems at least 5% full, thus there are always reserves available in case of an unexpected shortfall in generation or some other interruption. Figure 6 shows the minimum hours of available reserves (based on the 5% energy storage lower limit) in 2020 and 2050.

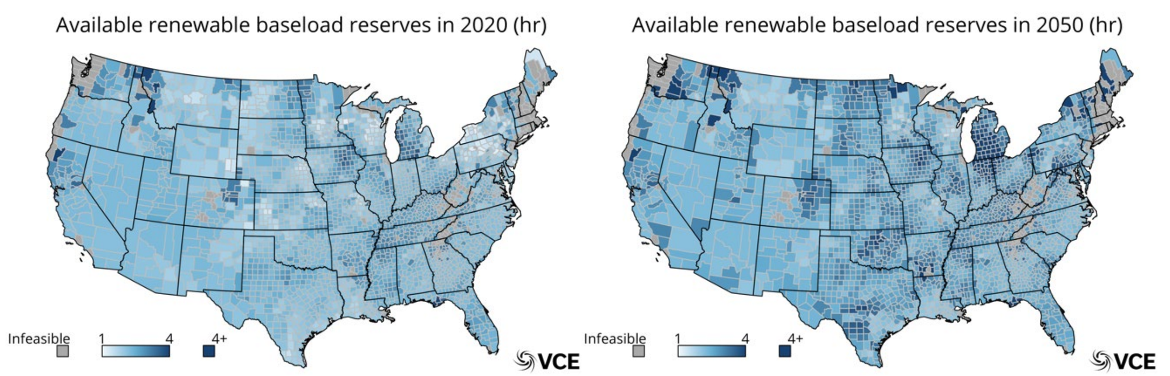


Figure 2: Hours of available renewable baseload output from energy storage reserves in 2020 (left) and 2050 (right).

The average duration of renewable baseload reserves in 2020 is about 2.1 hours (median 2.2 hours) and in 2050, it is about 2.5 hours (median 2.6 hours). Thus, not only does the cost of renewable baseload get cheaper over time, it gets more secure because more energy storage capacity is deployed relative to renewable generation capacity. These values are inherently conservative as energy storage systems are likely to have more than their minimum level of energy at any given time should there be a need to deploy said reserves.

Multiple versus single year results

Because wind and solar are dependent on meteorological conditions, the weather data chosen for the analysis can influence the results. The above results used multiple years' (2014, 2015, and 2016) worth of weather data and the model had to pick the optimal single deployment strategy (capacities of renewables and storage) to meet the demand in all years. Most analyses just use one year's worth of input data to make their work computationally tractable, and if we had chosen to do so as well, the results would be different. It is also true that more years would influence our results, but at some point, the results would likely converge and change little with more information.

In fact, each year alone (2014, 2015, or 2016 vs. all three together) would have overestimated the amount of renewable baseload capacity available by varying amounts in 2050. Using 2014 alone would have overestimated total available optimal renewable baseload capacity (in 2050) by about 80 GW, or about 1%, which is rather small, but using 2015 data alone would have overestimated the available capacity by close to 13%, or by almost 818 GW. Each of the weather years alone also underestimated the 2050 LCODE values by between 8 and 11% depending on the year.

Thus, as energy models continue to explore higher and higher levels of weather-dependent renewables, this result underscores the importance of running multiple highly-granular years of weather data to capture events such as the polar vortex[1] of 2014 and the wind draught of 2015[2].

Comparison to other technologies

These results provide crucial context in the current discussion around the potential for renewables to become a major supplier of energy in the US and abroad. Our initial results indicate that, by 2050, the potential for about 6.8 TW[1] of renewable baseload exists, with an average cost of about $51 / MWh, which is competitive with today's wholesale power prices.

These values should also be compared with other technologies that are able to supply baseload power to the grid. Table 3 shows the LCODE values for other baseload technologies given their assumed cost declines from 2020 to 2050.

[1] For reference, we have about 1.2 TW of installed power plant capacity (of all kinds) today.

Table 1: Estimated baseload LCODE values from other technologies between 2020 and 2050. All capacity factors assumed to be 100%, LCODE values in $/MWh. Technology cost and lifetime assumptions the 2019 NREL Annual Technology Baseline[3].

Technology	2020	2030	2040	2050
NGCC[2]	$41	$40	$37	$34
Coal	$49	$48	$46	$44
Nuclear	$46	$44	$43	$42

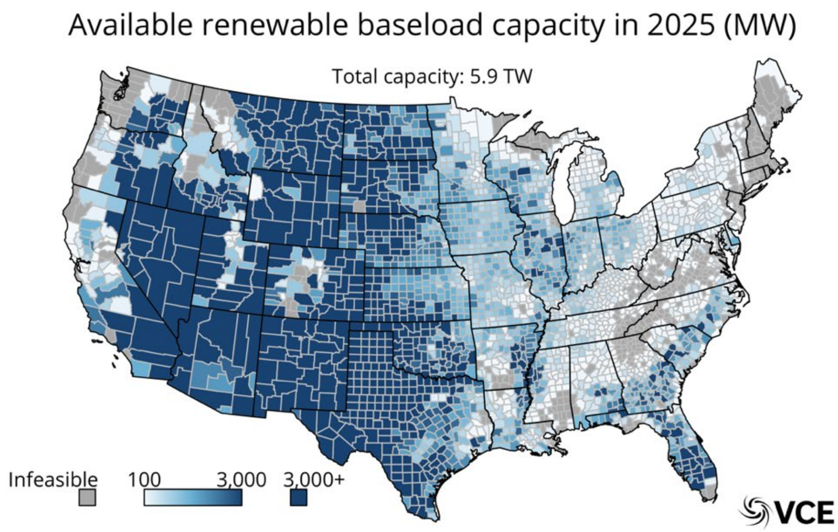
By 2050, average renewable baseload costs are comparable to other firm generation technologies, but still somewhat higher. Note that in some locations, the renewable baseload costs are lower than other firm generation technologies. Further, the renewable baseload technologies include reserves of 2-4 hours at all times. Additionally, the other baseload generators are exposed to market prices for their fuel source. Moreover, if the LCODEs in Table 3 included a modest $60 / metric ton cost of carbon, the LCODE of NGCC in 2050 increases to $55 / MWh, about the same level as the average renewable energy baseload (coal increases to $95 / MWh). Note, the technologies in Table 3 are assumed to be able to deploy all of their produced electricity to load (with 100% capacity factors), which will make them appear cheaper. This simple comparison also does not take into account any capacity market payments that such renewable energy baseload systems might qualify for that renewables alone currently do not[4].

[2] NGCC: natural gas combined cycle

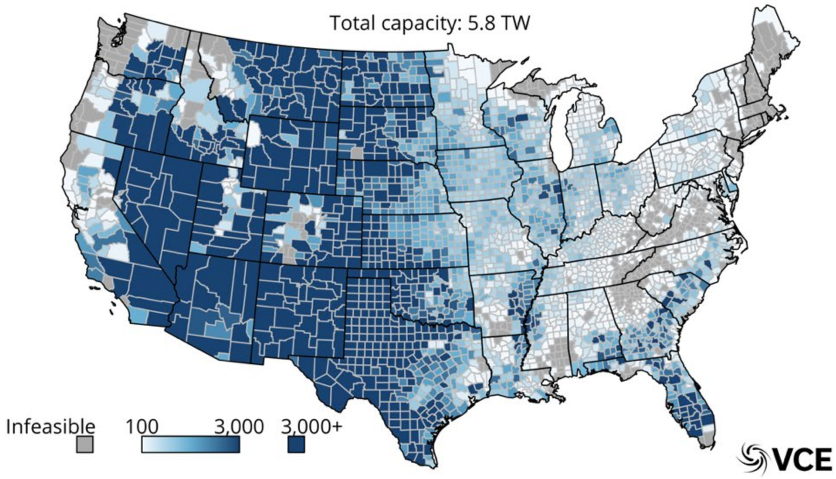
Further results

This section contains all the map results for the interim years not shown in the main paper.

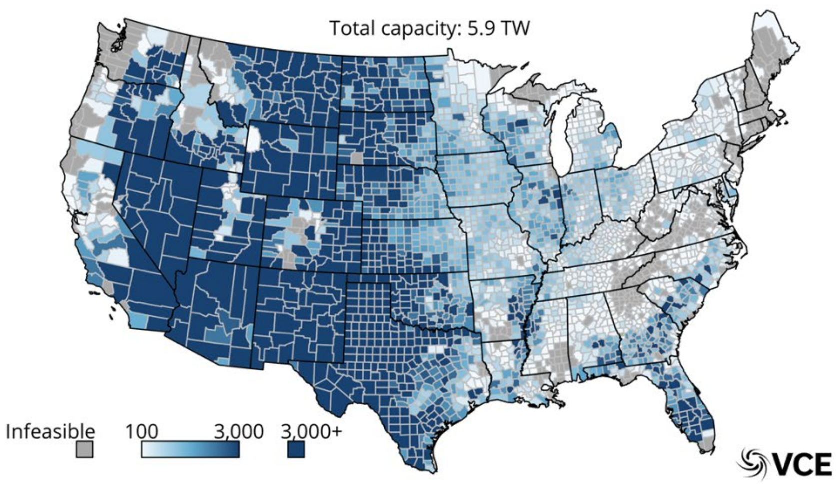
Baseload capacity maps



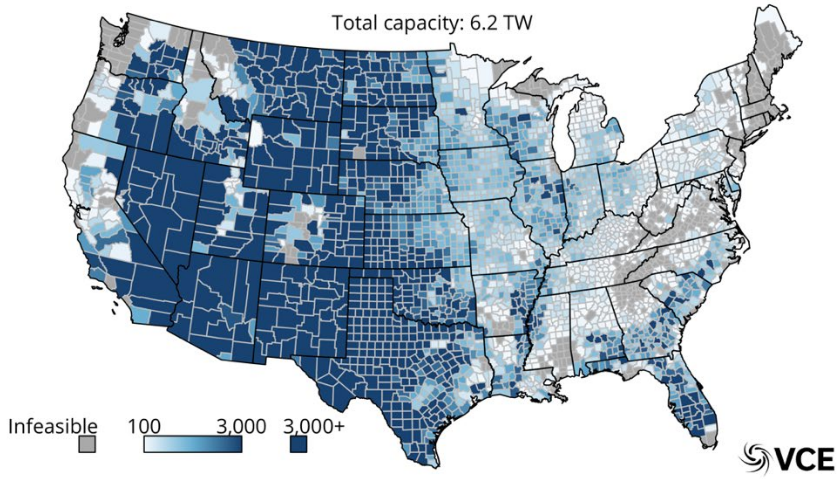
Available renewable baseload capacity in 2030 (MW)



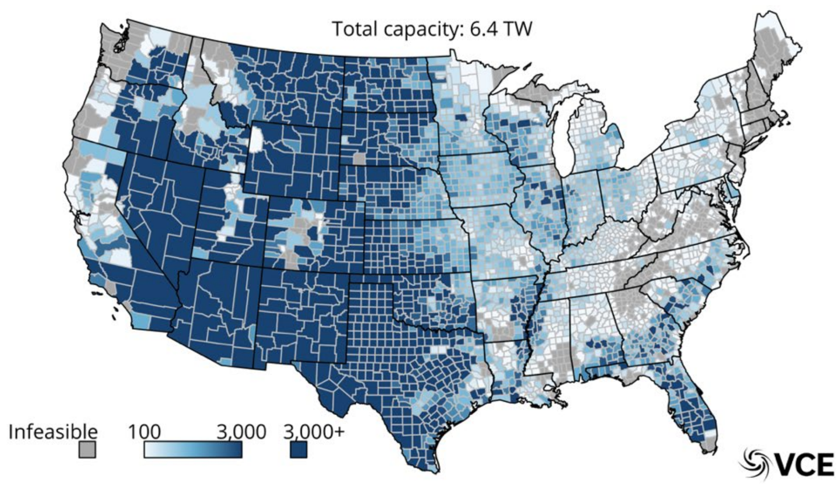
Available renewable baseload capacity in 2035 (MW)



Available renewable baseload capacity in 2040 (MW)

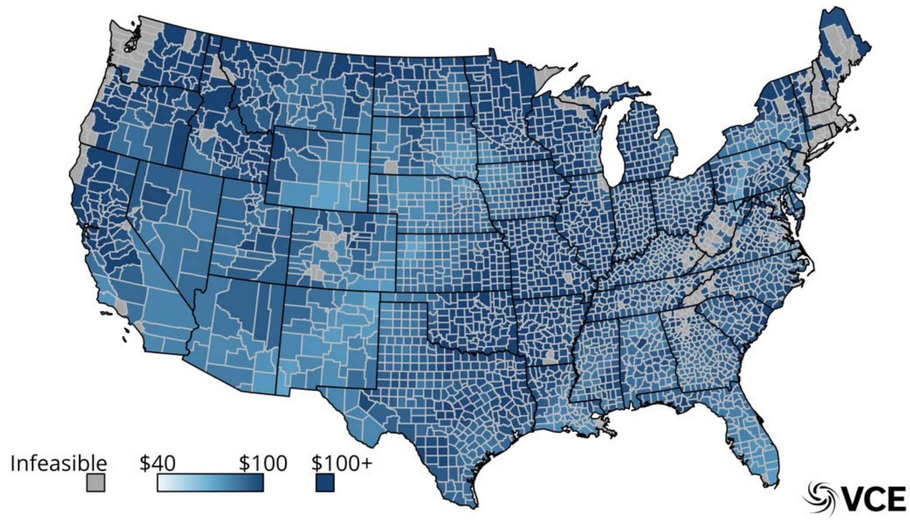


Available renewable baseload capacity in 2045 (MW)

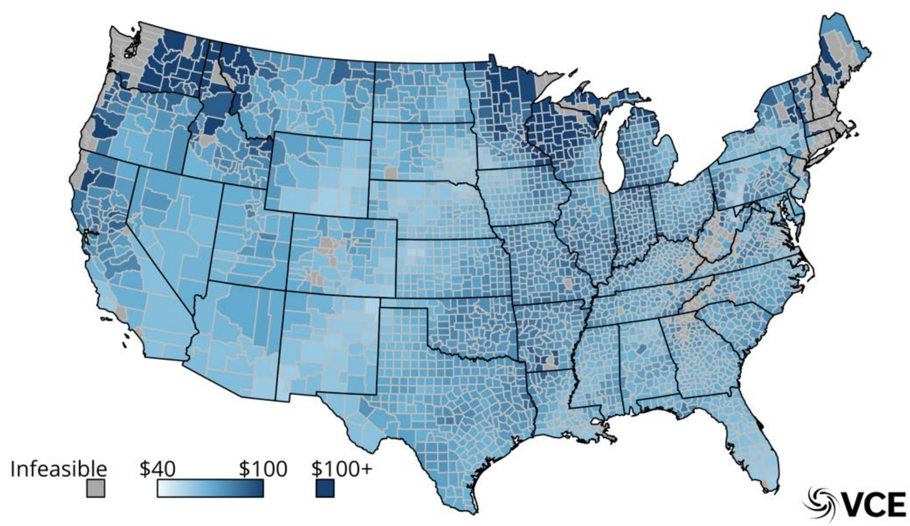


LCODE maps

Optimal renewable baseload LCODE in 2025 ($/MWh)



Optimal renewable baseload LCODE in 2030 ($/MWh)



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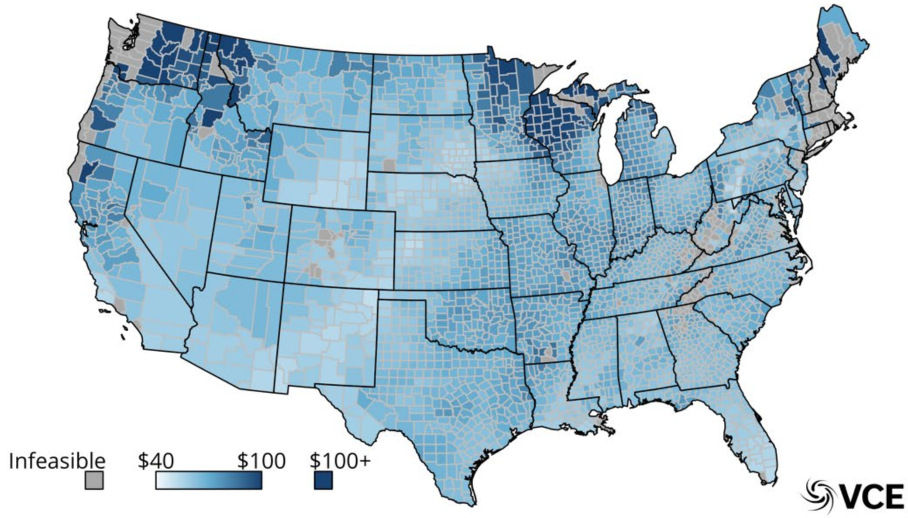

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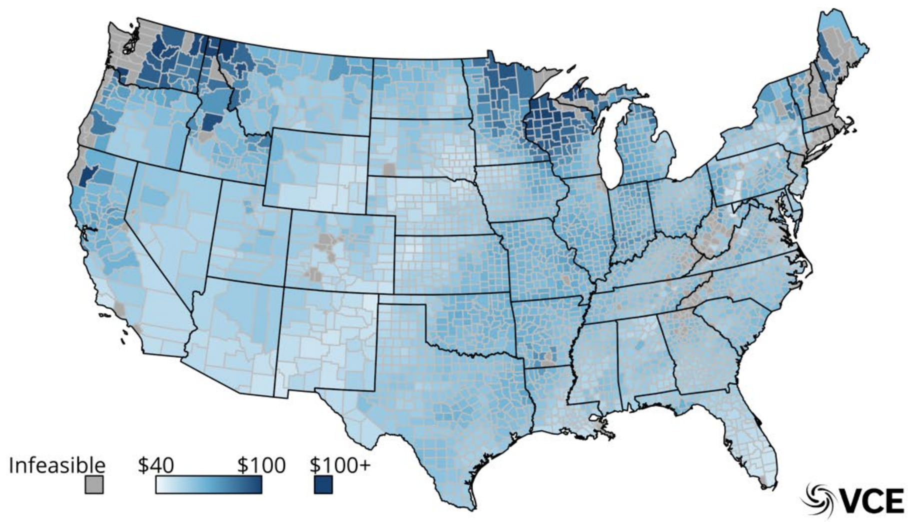
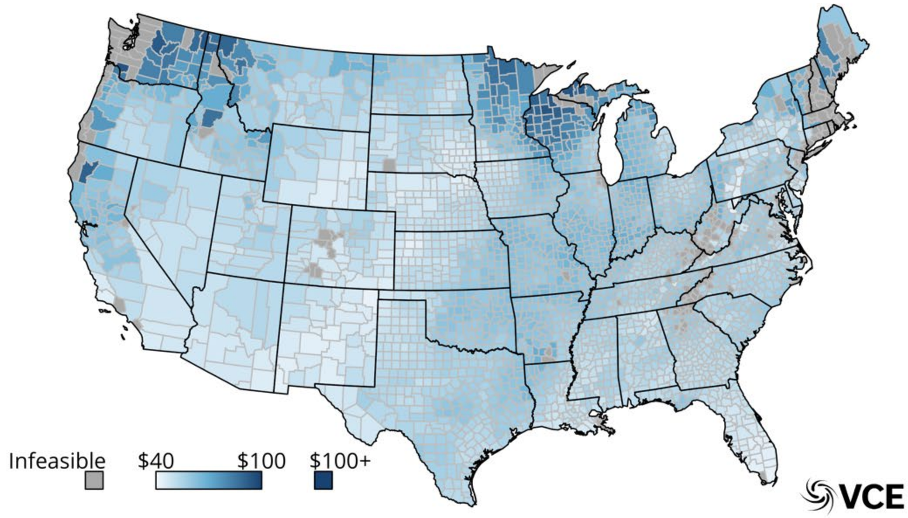
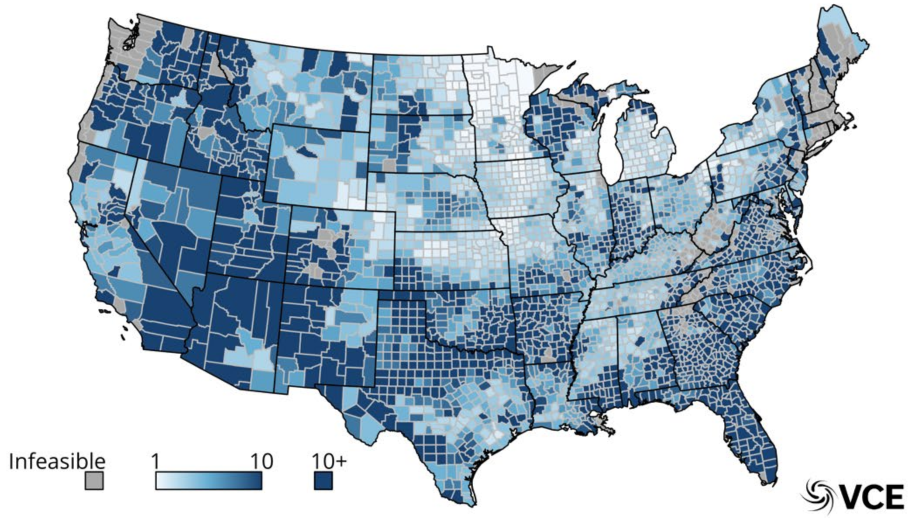


Optimal renewable baseload LCODE in 2045 ($/MWh)

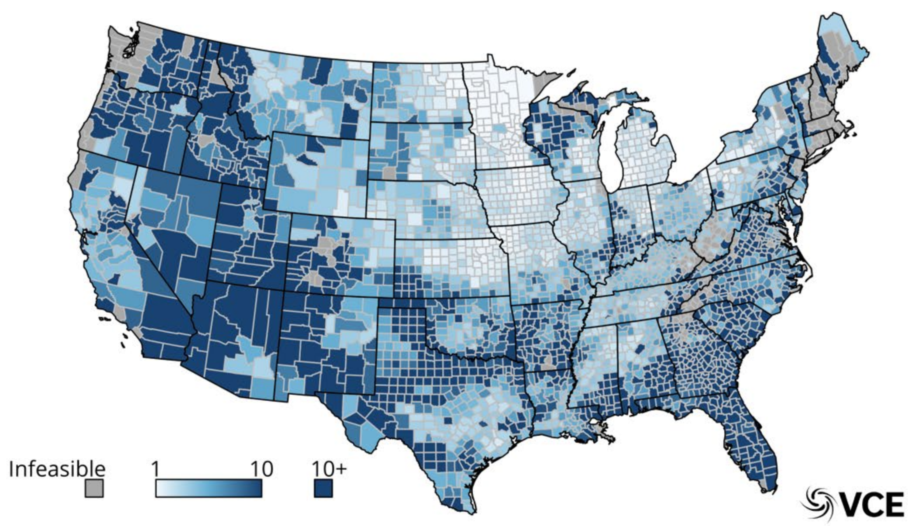


Solar-wind ratio maps

Optimal solar-wind ratio in 2025 (kW solar / kW wind)



Optimal solar-wind ratio in 2030 (kW solar / kW wind)



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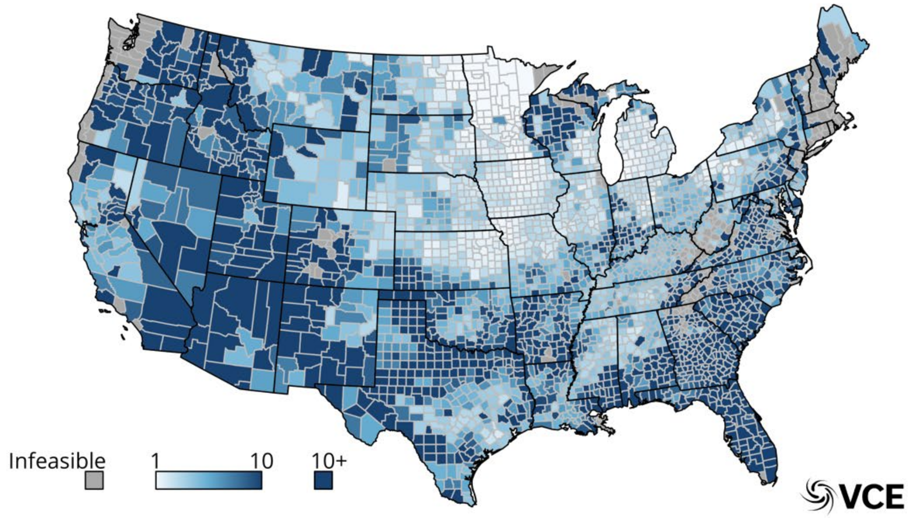

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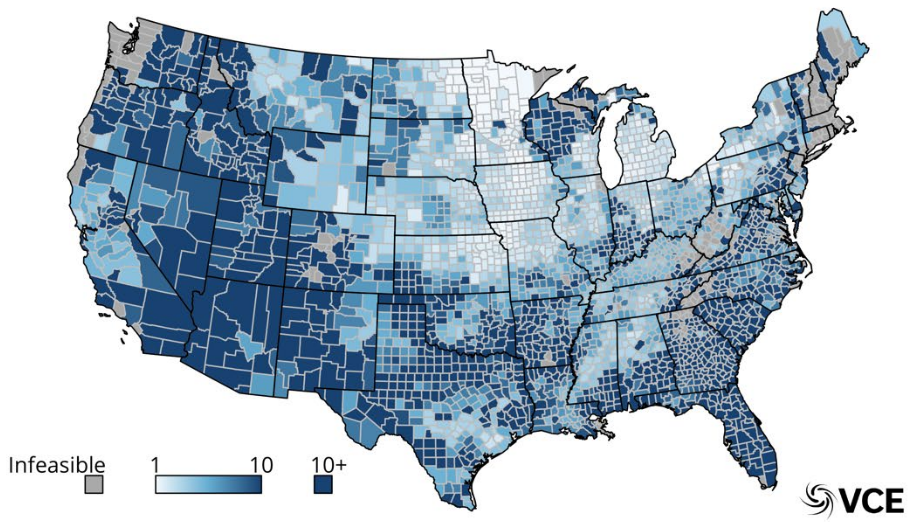

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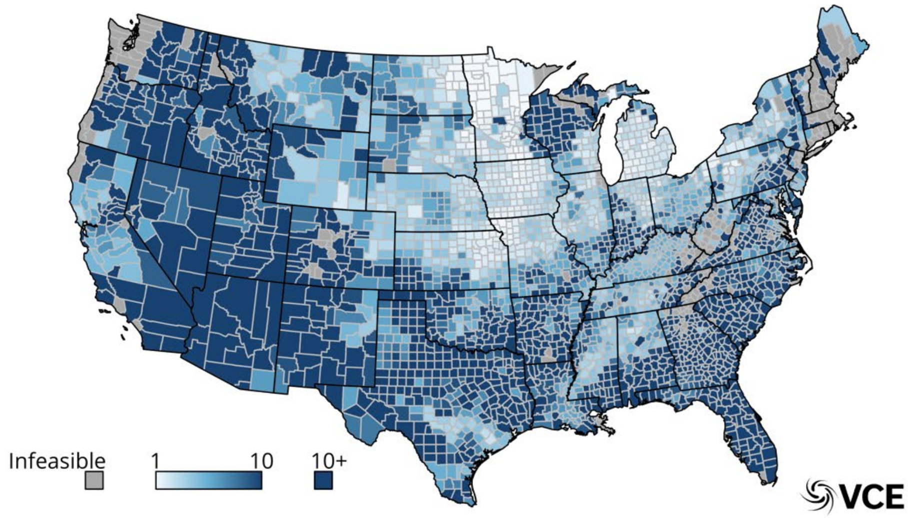
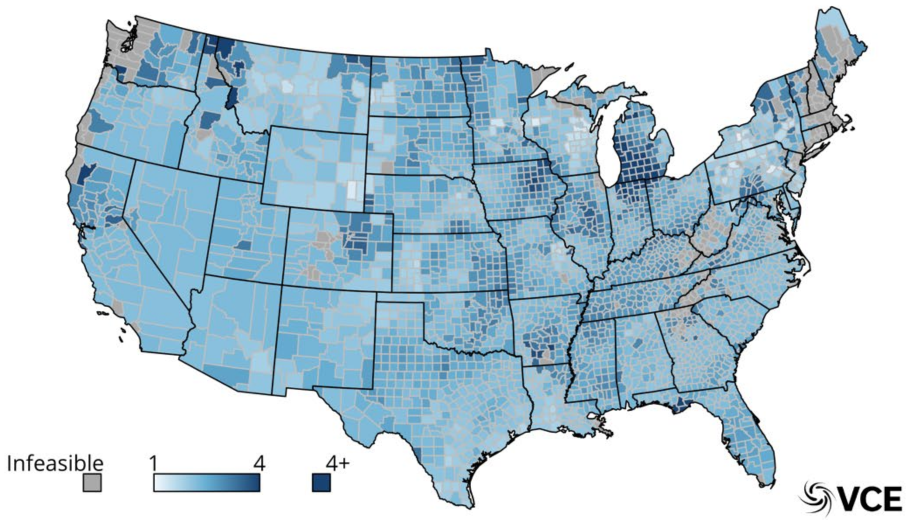
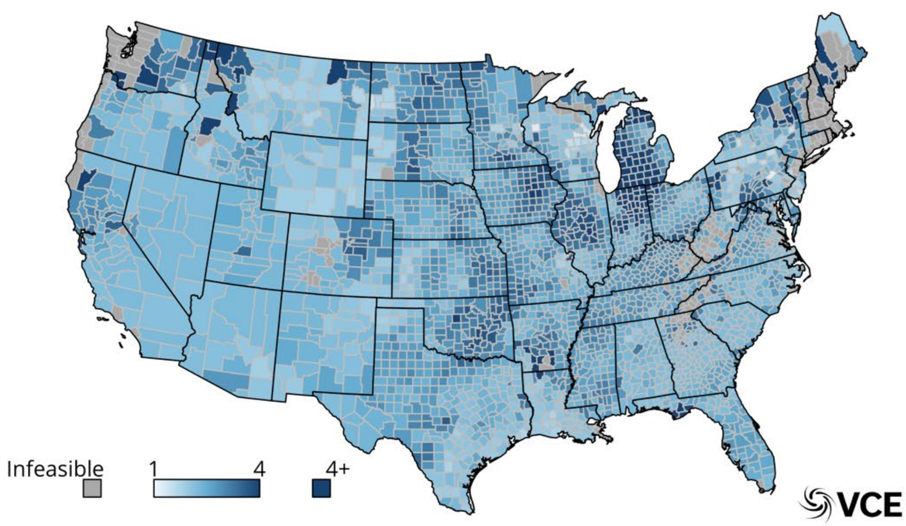


Reserves maps

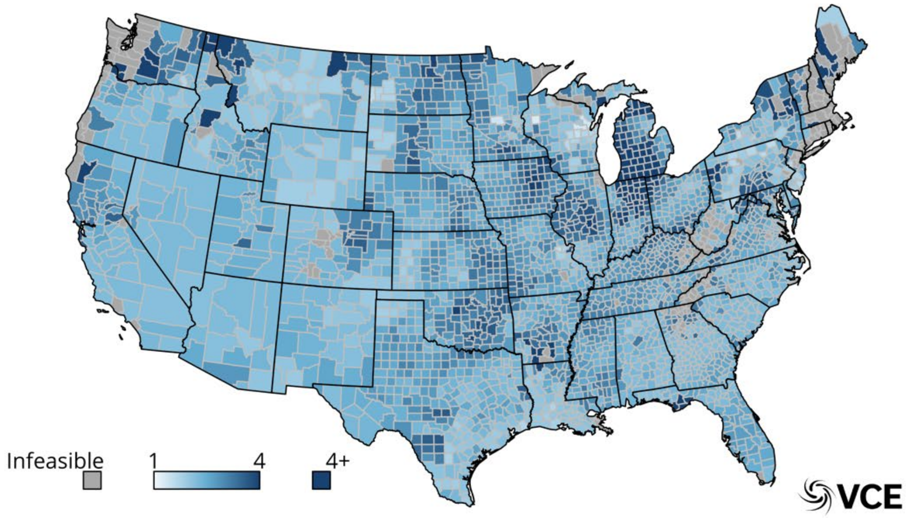
Available renewable baseload reserves in 2025 (hr)



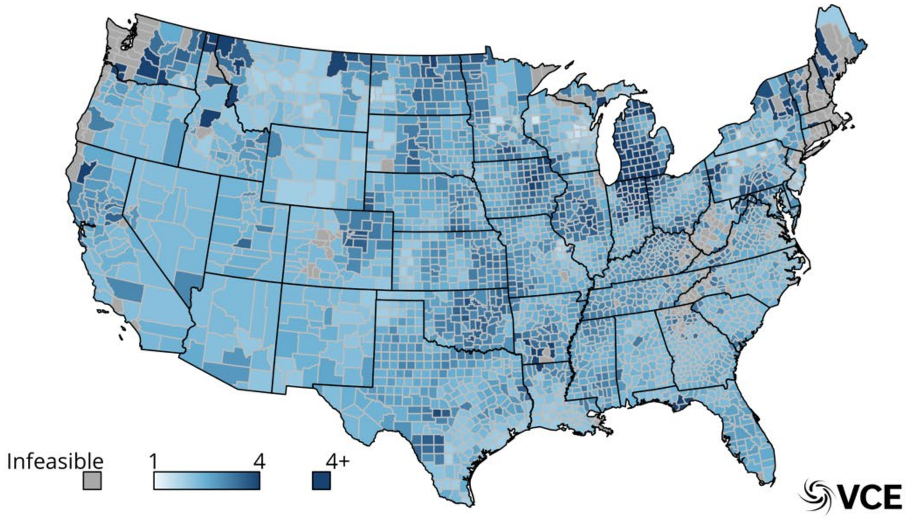
Available renewable baseload reserves in 2030 (hr)



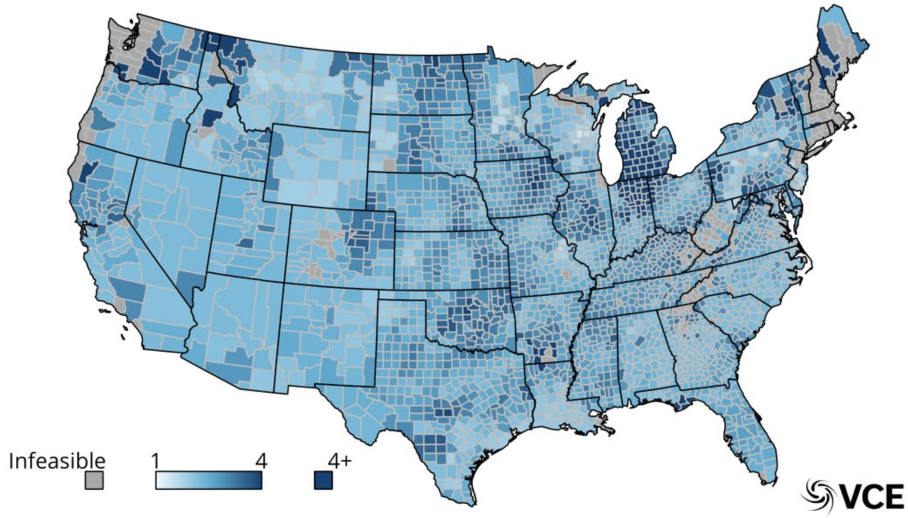
Available renewable baseload reserves in 2035 (hr)



Available renewable baseload reserves in 2040 (hr)



Available renewable baseload reserves in 2045 (hr)



1. Kim, B.-M. *et al*. Weakening of the stratospheric polar vortex by Arctic sea-ice loss. *Nat. Commun.* **5**, 4646 (2014).
2. Lledó, L., Bellprat, O., Doblas-Reyes, F. J. & Soret, A. Investigating the Effects of Pacific Sea Surface Temperatures on the Wind Drought of 2015 Over the United States. *J. Geophys. Res. Atmos.* **123**, 4837–4849 (2018).
3. National Renewable Energy Lab. Annual Technology Baseline: Electricity. *Annual Technology Baseline: Electricity* (2019).
4. Mays, J., Morton, D. P. & O'Neill, R. P. Asymmetric risk and fuel neutrality in electricity capacity markets. *Nat. Energy* **4**, 948–956 (2019).