October 2020

Consumer, Employment, and Environmental Benefits of Electricity Transmission Expansion in the Eastern U.S.

- Christopher T.M. Clack, Vibrant Clean Energy LLC
- Michael Goggin, Grid Strategies LLC
- Aditya Choukulkar, Brianna Cote, & Sarah McKee, Vibrant Clean Energy LLC

Americans for a Clean Energy Grid

About Us

Americans for a Clean Energy Grid (ACEG) is the only non-profit broad-based public interest advocacy coalition focused on the need to expand, integrate, and modernize the North American high voltage grid.

Expanded high voltage transmission will make America's electric grid more affordable, reliable, and sustainable and allow America to tap all economic energy resources, overcome system management challenges, and create thousands of well-compensated jobs. But an insular, outdated and often short-sighted regional transmission planning and permitting system stands in the way of achieving those goals.

ACEG brings together the diverse support for an expanded and modernized grid from business, labor, consumer and environmental groups, and other transmission supporters to educate policymakers and key opinion leaders to support policy which recognizes the benefits of a robust transmission grid.

Table of Contents

01

Executive Summary

Investing in electricity transmission is a win-win for American consumers, workers, and the environment. Most of America's world-class renewable resources are currently stranded in remote areas where the power grid is weak to nonexistent. Policy barriers in how we plan, pay for, and permit transmission are blocking private investment in modernizing our power grid. This study finds breaking that logjam will unleash up to $7.8 trillion in investment in rural America, create more than 6 million net new domestic jobs, save consumers more than $100 billion, and provide all Americans with cleaner air.

This study examines varying levels of renewable energy deployment and carbon dioxide (CO_2) emissions reductions in the Eastern Interconnect, the power grid that physically connects all of the Eastern United States and roughly ends at Montana, Wyoming, Colorado, and Texas, where the Western Interconnect and Electric Reliability Council Of Texas (ERCOT) power grids begin. Other studies have evaluated benefits of transmission between these Interconnections;[1,2] but this study does not.

This analysis shows how by investing in transmission, the Eastern U.S. can access low-cost renewable energy to:

- Cost-effectively reduce electric sector CO_2 emissions by 65% by 2035, and by more than 95% by 2050 and reduce other air pollutants across the region.

- Reliably obtain more than 80% of its electricity from wind and solar by 2050.

- Decrease the average electric bill rate by more than one-third, from more than 9 cents/kWh today to approximately 6 cents/kWh by 2050, saving a typical household more than $300 per year. These savings are broadly shared by all consumers across the region. The cost of transmission accounted for only 3.6% of total electricity costs on average in the strong carbon reduction cases. Transmission yielded savings many times greater than that by providing access to low-cost renewable resources and increasing the overall efficiency of the power system.

- Create more than 6 million net new jobs, increasing electric sector employment more than 5-fold from approximately 1.3 million to more than 7.5 million jobs by 2050. The new jobs are broadly spread across the Eastern U.S. Transmission investment alone drives more than 1.5 million new jobs.

- Deliver reliable power by meeting electricity demand in every 5-minute period of the year, even with wind and solar providing 82% of electricity in 2050 in the strong carbon policy cases.

1 National Renewable Energy Laboratory. "Interconnections Seam Study." July 2018. https://www.terrawatts.com/seams-transgridx-2018.pdf

2 Nature Climate Change. "Future Cost-Competitive Electricity Systems and their Impact on U.S. CO_2 Emissions." January 25, 2016. https://www.nature.com/articles/nclimate2921

Table 1: Benefits of Reducing CO_2 Emissions by 95% Instead of 70% (In High Solar Deployment Case)	
Emissions reductions through 2050	7.6 billion metric tons of CO_2
Consumer savings through 2050	$105 billion
Jobs	6 million additional jobs

The study also found that scenarios with greater emissions reductions were more cost-effective and created more jobs than scenarios which achieved fewer emissions reductions, as indicated in Table 1. The scenario with 95% CO_2 emissions reductions and high solar deployment was also more cost-effective than the comparable scenario with around 70% emissions reductions, with cumulative savings of more than $105 billion through 2050. Moreover, 2.6 million more jobs were created in the scenarios with larger emissions reductions.

The study is one of the first to evaluate how wind, solar, storage, and transmission each play essential, unique, and complementary roles in providing consumers with reliable and affordable electricity. Wind and solar tend to produce at opposite times, so they complement each other. However, the best wind and solar resources are generally in different locations, so transmission is needed to aggregate them and deliver a reliable mix of power to customers at all times. Transmission also allows local weather-driven variation in wind and solar output to be canceled out by opposite variations in other regions, providing a more constant supply of power. Energy storage helps meet reliability needs and increases the utilization of transmission capacity by absorbing excess generation and filling in when wind and solar output is low. Together, along with some flexible capacity resources that fill in when needed, these resources provide a reliable, efficient, and clean portfolio.

This study evaluated four scenarios, with varying degrees of CO_2 emissions reductions and relative shares of wind and solar deployment:

- Weak Carbon policy High Solar deployment (WCHS)
- Weak Carbon policy High Wind deployment (WCHW)
- Strong Carbon policy High Solar deployment (SCHS)
- Strong Carbon policy High Wind deployment (SCHW)

The weak carbon policy cases were developed by extrapolating forward the "business as usual" rate of CO_2 emissions reductions from 2005-2017, while the strong carbon policy cases were benchmarked to meeting the Paris Agreement requirements, as explained in more detail in Appendix A.

Many of the same transmission upgrades were built across all four scenarios, indicating these investments will be needed regardless of future trends in renewable costs or carbon reductions. The model also used battery storage to increase the utilization of transmission lines, demonstrating that storage is a transmission complement, not a substitute. The analysis was conducted using Vibrant Clean Energy's WIS:dom®-P model, which has been extensively used by states, utilities, and grid operators for generation and transmission planning.

The Transition to Clean Energy

All scenarios saw continued rapid growth of wind and solar energy. As expected, the strong carbon policy cases resulted in greater deployment of renewable and storage resources, with wind and solar providing 62% of electricity by 2035 and 82% by 2050. The first chart shows the growth in renewable generation across the four scenarios through the year 2050, while the second chart shows the growth in renewable and storage capacity. In each year, the scenarios with stronger emissions reductions are shown as the two columns on the right, while the two columns on the left are the weaker emissions reduction cases. Utility-scale PV is shown in brighter red, while distributed PV is shown in darker red. Wind energy is shown in green.

Figure 1. Generation mix over time across scenarios

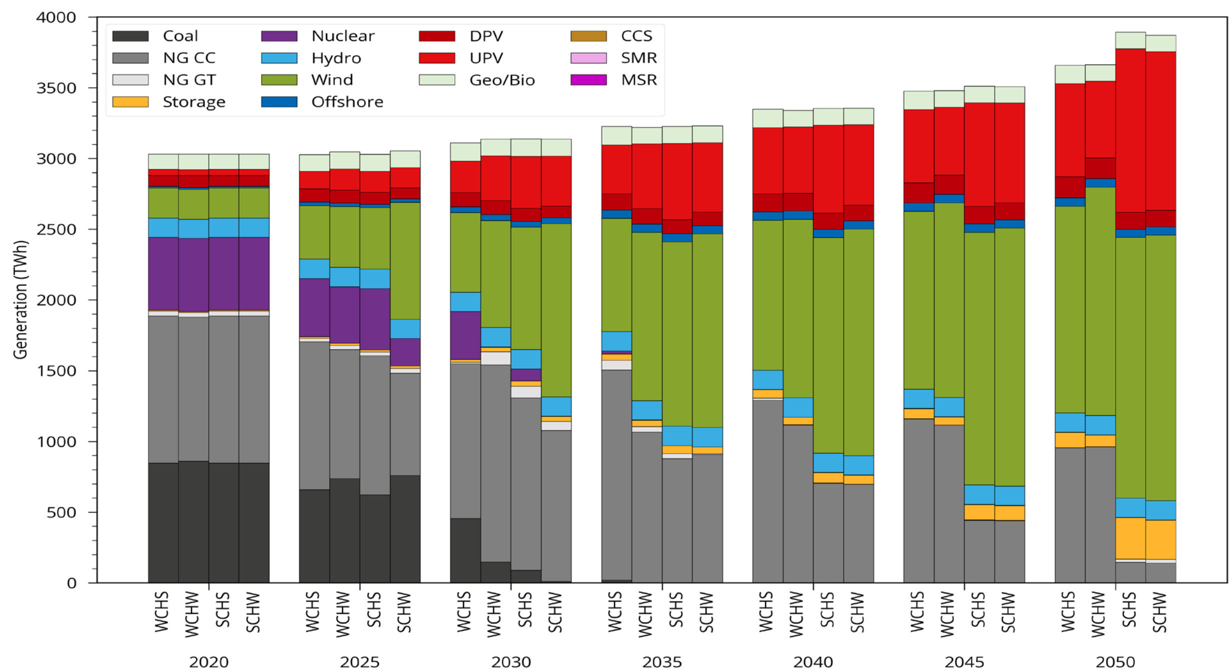
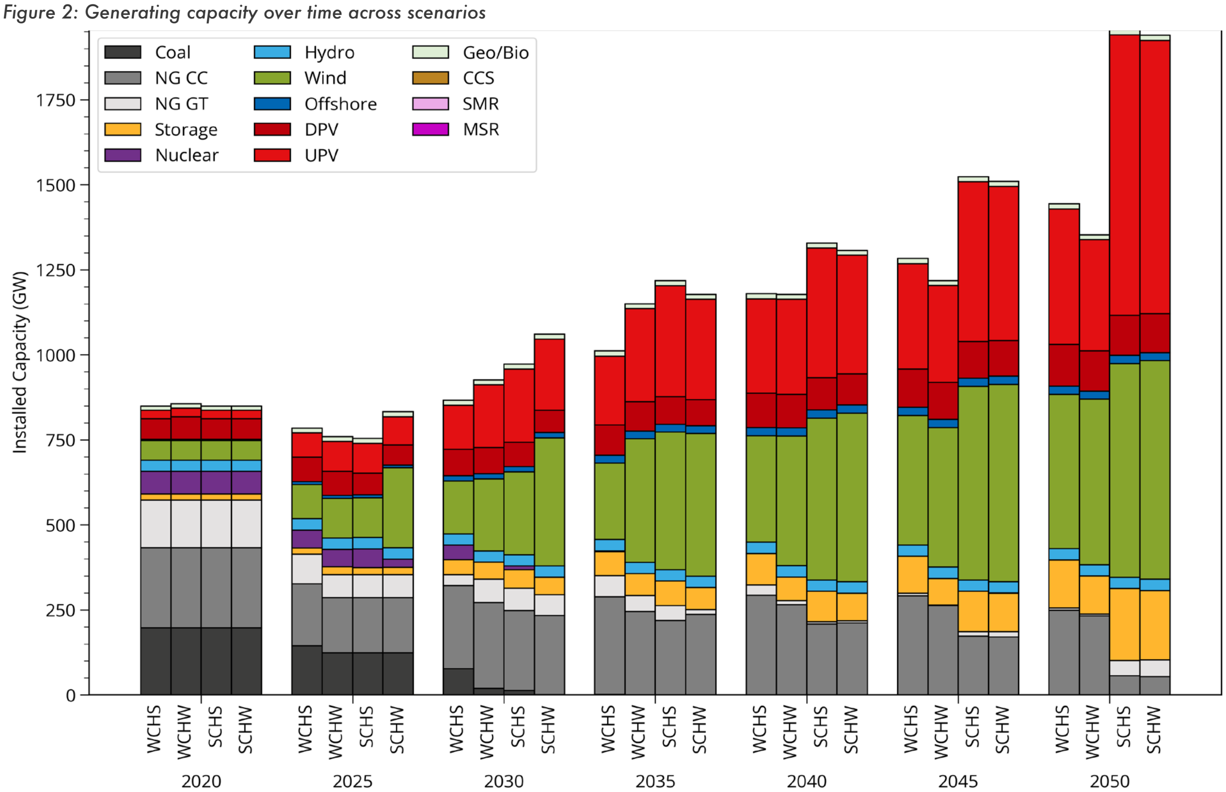
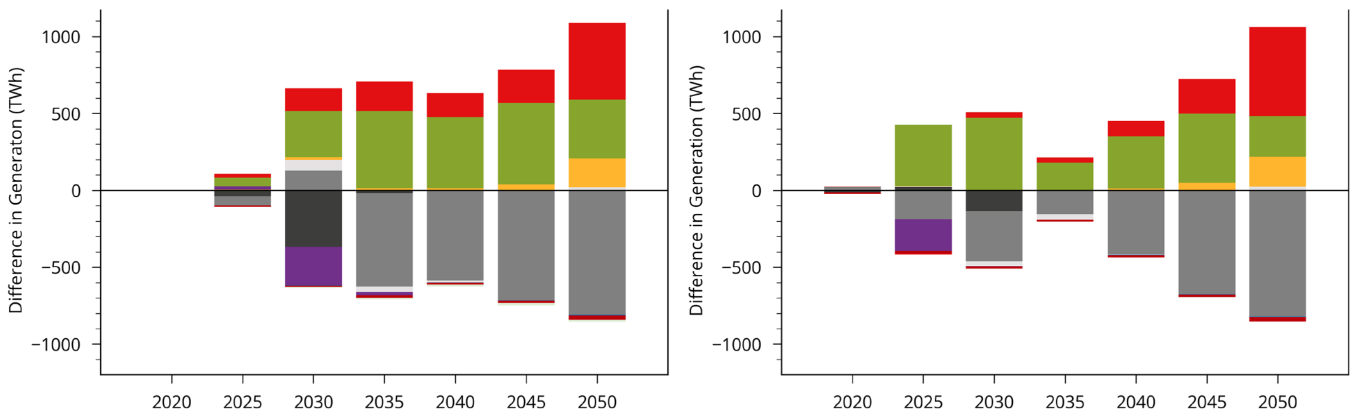


Figure 2: Generating capacity over time across scenarios



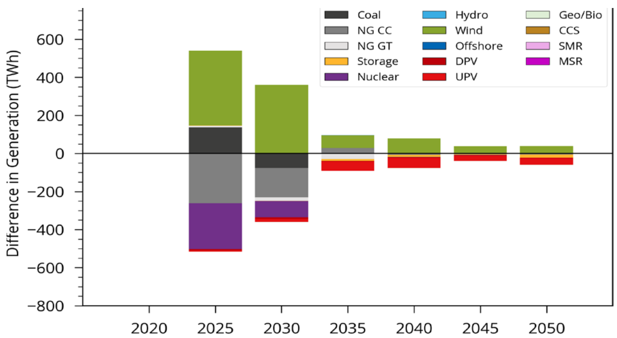
The following charts show the increase in wind, solar, and storage capacity in moving from the weak carbon policy case to the strong carbon policy case. The difference between the strong and weak carbon in the high solar deployment case is shown on the left, and the difference between the strong and weak carbon in the high wind deployment case is shown on the right. As discussed in subsequent sections, the added capacity in the strong carbon policy case is very similar regardless of wind and solar costs, and drives large increases in job creation and decreases in consumer costs.

Figure 3: Change in generating capacity in moving from weak carbon to strong carbon policy, with higher solar deployment (left) and high wind deployment (right)



The following chart shows the change in generating capacity in the strong carbon policy case in moving from high solar deployment to high wind deployment. It shows a modest shift to earlier wind deployment from later solar deployment.

Figure 4: Change in generating capacity in moving from high solar deployment to high wind deployment, with strong carbon policy



The location of generating capacity and transmission capacity additions in each of the four scenarios is shown in the maps in the final section of this report. The scenarios deploy distributed solar resources but they do not reduce the need for transmission, which is essential for capturing the diversity of renewable output across the entire region regardless of the size and location of solar resources.

In an initial model run, low wind costs were used to drive the high wind deployment case. However, this did not significantly change the resource build from the high solar deployment case. This indicates that the generation expansion was more heavily driven by fundamental physical factors related to wind and solar resource locations and output profiles than their future cost trajectories. To drive a differentiation in wind versus solar deployment to understand the impact on transmission needs, specified levels of wind deployment were then forced into the high wind deployment cases presented in this report.[3] Predictably, this slightly increased costs relative to allowing the model to economically optimize. In addition, the cost assumptions for wind and solar were changed between the high wind and high solar deployment cases, as outlined in Appendix A, so cost results between the high wind and high solar deployment scenarios are not directly comparable, though cost results between the weak carbon and strong carbon cases can be compared. As a result, many of the charts in this report focus on the high solar deployment cases in which the only constraints on economic optimization are the carbon emissions requirements.

While many of the same transmission upgrades are needed across scenarios, the scenarios with larger emissions reductions result in a larger transmission expansion, demonstrating that transmission is critical for achieving a decarbonized grid. The scenarios with high wind deployment drive somewhat larger transmission expansion than the high solar deployment cases, particularly in the earlier years. Interestingly, even with wind deployment forced at specified levels, there was significant convergence to a similar wind and solar generation mix between the wind deployment and solar deployment cases in the later years of the high carbon cases. This further indicates that the resource mix was heavily driven by fundamental physical factors governing the relationship between wind and solar output profiles and electricity demand patterns, and explains why many of the same transmission investments are needed regardless of future trends for wind and solar costs.

The roles of natural gas, coal, and other non-emitting resources are driven by the standard cost assumptions used in the study. Some natural gas capacity is maintained through most of the time period, reflecting that this resource has already been built and its value as a flexible capacity resource with essentially unlimited duration. The usage or "capacity factor" of gas plants declines over time, which drives a proportional decrease in their fuel use and emissions. Hydropower and biomass plants continue to serve as flexible capacity resources throughout the time period, though their share of total capacity in the Eastern U.S. is limited. The model deploys sufficient offshore wind to meet the state requirements that were in place when the model was initialized. Additional amounts of offshore wind were not deployed with the standard cost assumptions used in this study, but likely would be if costs continue to decline. Existing nuclear plants generally continue to operate until their licenses expire. New nuclear plants, including alternative nuclear designs, were not economically selected, though they could be if costs come down. Similarly, fossil plants with carbon capture, utilization, and storage (CCUS) could also play a role if their costs decline from the levels assumed here.

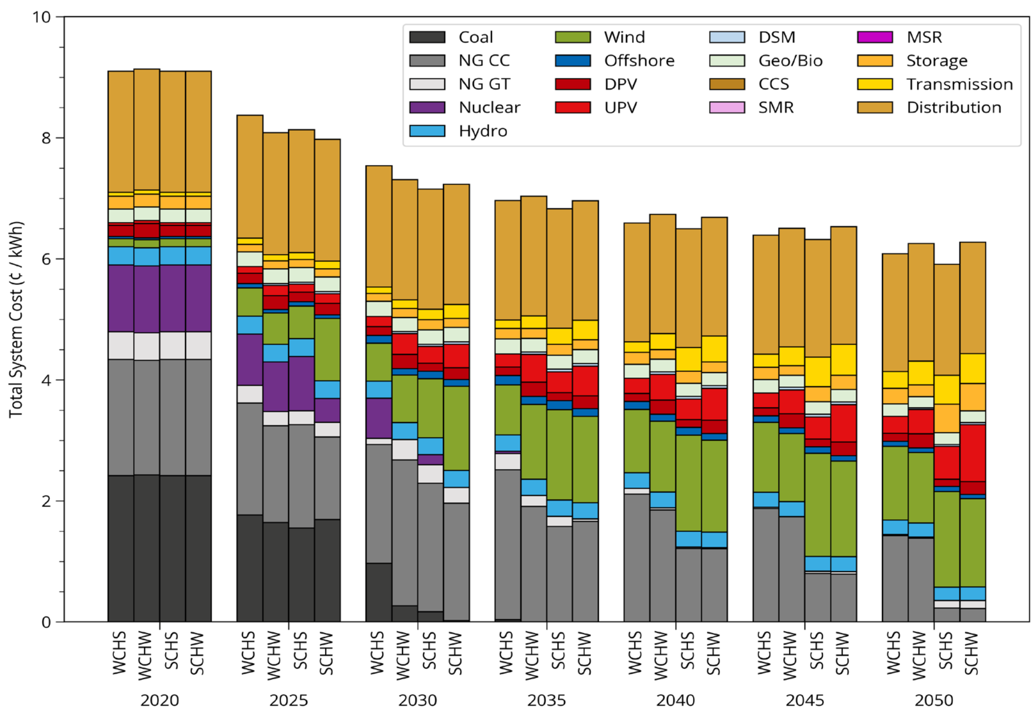
[3] It is important to note that the decision to force in wind and not solar to achieve the desired differentiation in renewable deployment was arbitrary, and does not indicate anything about the relative economics of either resource.

03

Consumer Savings

In all scenarios, transmission expansion and the resulting growth in wind and solar generation causes large reductions in consumer electric bills from current levels. As shown below, the average electric bill rate is decreased by more than one-third, from more than 9 cents/kWh today to approximately 6 cents/kWh by 2050. This would save a typical household more than $25 per month or $300 per year at current electricity consumption levels,[4] and significantly more as electricity consumption increases to displace gasoline consumption in cars and natural gas consumption for heating. Transmission primarily provides this benefit by accessing low-cost, high-quality wind and solar resources, reducing the generation cost component that currently comprises more than two-thirds of consumers' electric bills. The cost of transmission (shown in yellow) averages approximately a quarter cent per kWh ($2.7/MWh) over this period, accounting for only 3.6% of a consumer's total electric bill, even as transmission drives total electric bills down.

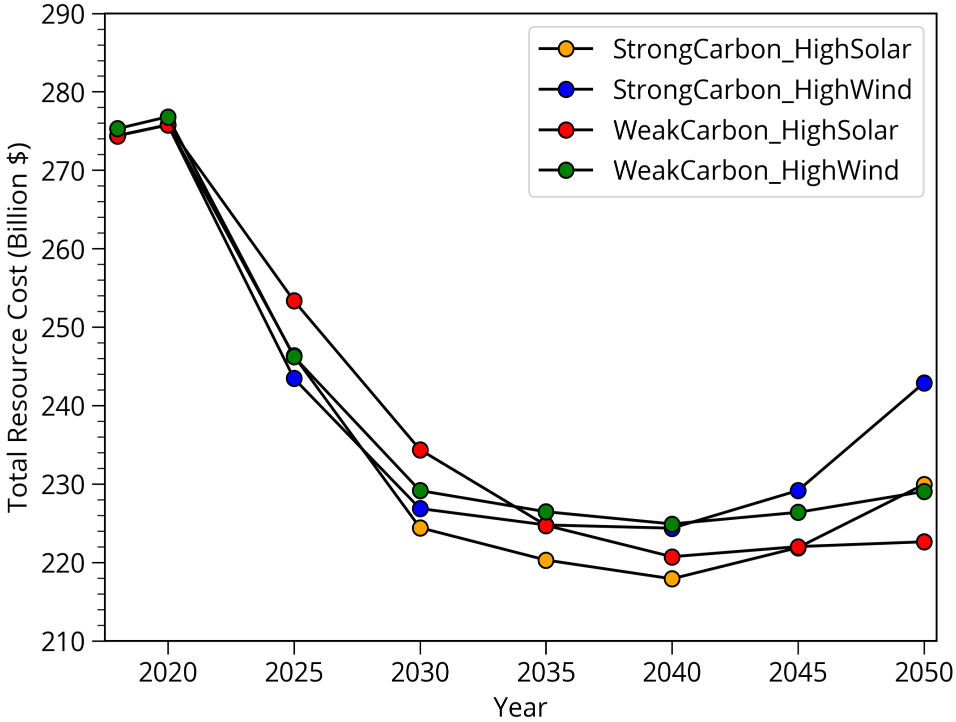
Figure 5: Retail rates by scenario, broken out by component



[4] U.S. Energy Information Administration. "How Much Electricity Does an American Home Use?" October 9, 2020. https://www.eia.gov/tools/faqs/faq.php?id=97

The scenario with 95% CO_2 emissions reductions and high solar deployment is more cost-effective than the high solar scenario with approximately 70% emissions reductions, with cumulative savings of more than $105 billion through 2050. This includes the cost of transmission investment, confirming the finding from numerous grid operator studies that investments in transmission more than pay for themselves by accessing low-cost sources of energy and providing other economic and reliability benefits.[5] As shown below, this scenario (shown in orange) offers significantly lower costs than other scenarios in the years 2030-2045. This indicates that strong action to reduce carbon emissions as soon as possible provides benefits not only for the environment and public health, but also for consumers.

Figure 6: Electric sector costs by scenario over time



The scenario with 95% emissions reductions and high wind deployment (shown in blue in the chart above) saves nearly $43 billion cumulatively through the year 2040, relative to the high wind case with approximately 70% emissions reductions (shown in green), further confirming the benefits of strong early action to address climate change. In the final decade, high curtailment from the forced wind deployment increases the cumulative cost of that scenario to be about $10 billion higher than the case with approximately 70% emissions reductions. This result is similar to that of many other studies that have found a significant increase in marginal cost for the last 5-10 percent of emissions reductions.[6]

Consumers in all regions of the eastern U.S. benefit from transmission and renewable expansion. The maps in Appendix B show the percentage decline in electric rates over the coming decades, relative to current rates.

[5] For example, see Southwest Power Pool. "The Value of Transmission." January 26, 2016. https://www.spp.org/documents/35297/the%20value%20of%20transmission%20report.pdf

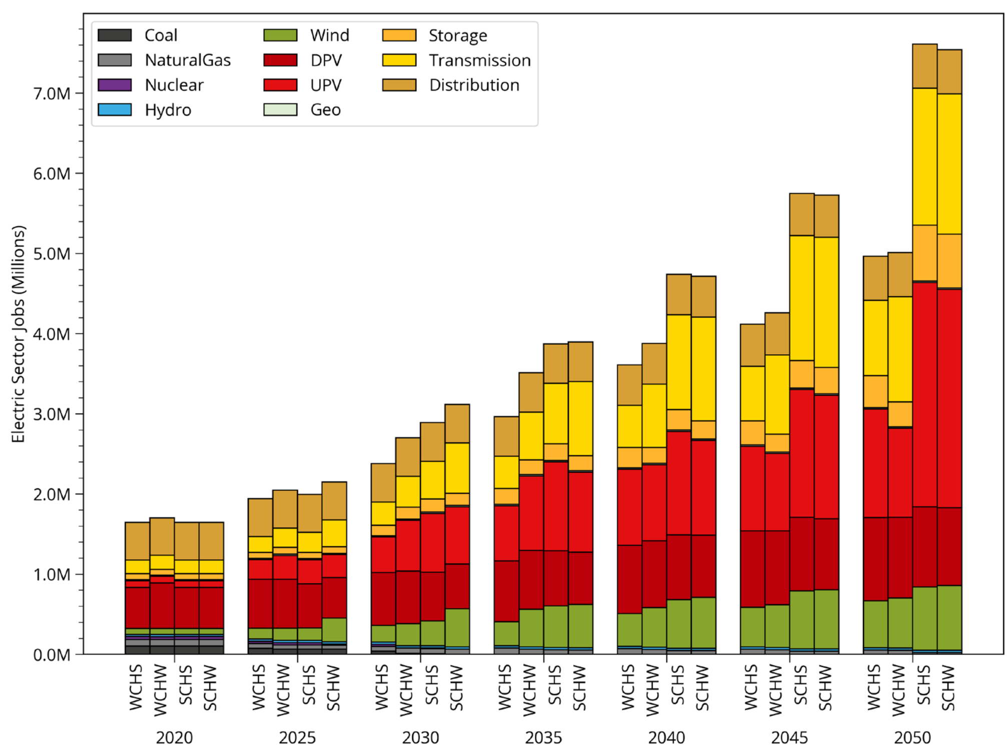
[6] For example, see Energy and Environmental Economics. "Pacifice Northwest Zero-Emitting Resources Study." January 29, 2020. https://www.energy-northwest.com/Documents/E3%20Study%20Executive%20Summary%20final.pdf

04

Job Creation

Investing in the transmission and renewable energy identified in this study would create more than 1 million net new jobs by 2030 and 6 million net new jobs by 2050 in the eastern U.S. alone. By 2050, 2.5 million more jobs are created in the scenarios with larger emissions reductions than in the "business as usual" scenarios, with more than 1.5 million jobs created in building and maintaining new transmission infrastructure, as shown below. These figures are net electric sector jobs, so they do account for the transition of employment away from existing energy sources to the energy sources of the future. Reduction in electricity costs for homes and businesses would likely drive further increases in job creation due to increased consumption and productivity, though the model does not assess these job impacts outside of the electric sector. A commitment to labor standards and utilization of domestic content could help ensure that these jobs are quality, family-sustaining jobs and that these investments deliver benefits outside of the electric sector in domestic manufacturing.

Figure 7: Jobs by scenario, broken out by electric sector component



These jobs are broadly spread across the eastern United States. The maps below show net new jobs by 2030 with high solar or high wind deployment. There was no net decrease in jobs in any state.

Figure 8: Change in jobs from 2018 to 2030 in the high solar case

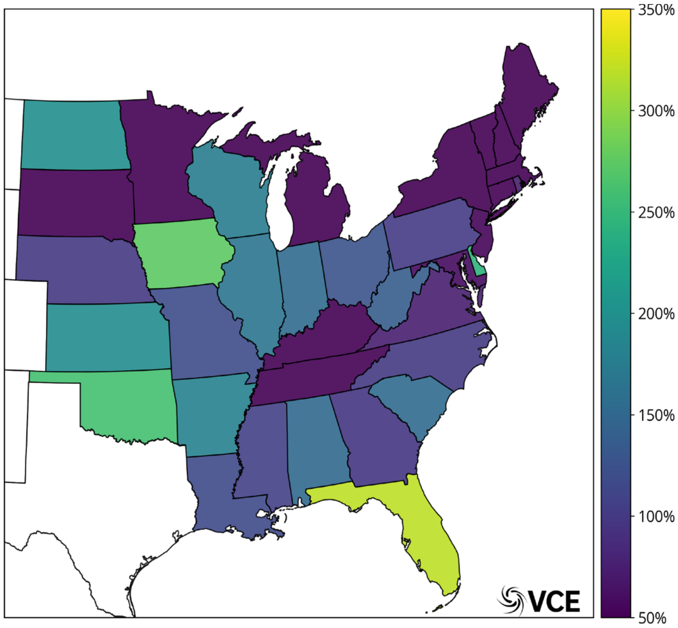
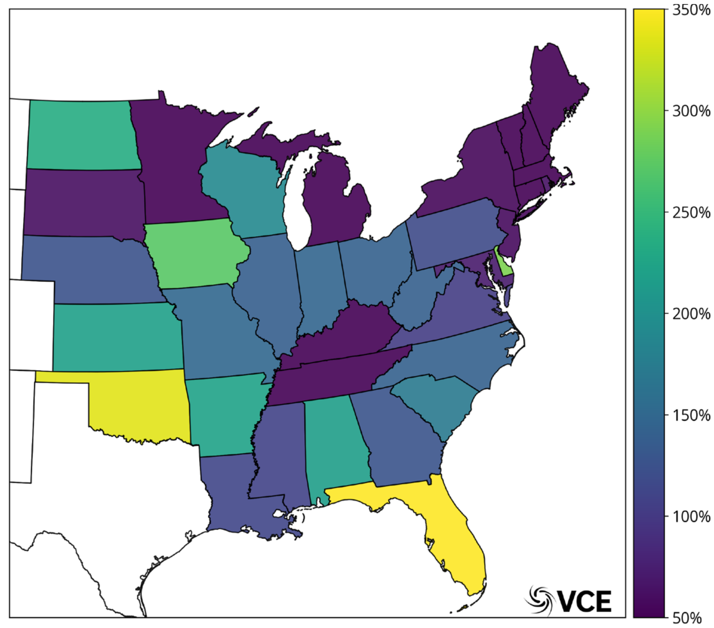


Figure 9: Change in jobs from 2018 to 2030 in the high wind case



Net job creation increases dramatically to achieve the strong emissions reductions required by 2050. Note that in the following maps of 2050 job creation, the color scale has increased by a factor of four relative to the 2030 maps above. Yellow now indicates a state creating 400,000 new net jobs, as opposed to 100,000 jobs in the maps above.

Figure 10: Change in jobs from 2018 to 2050 in the high solar case

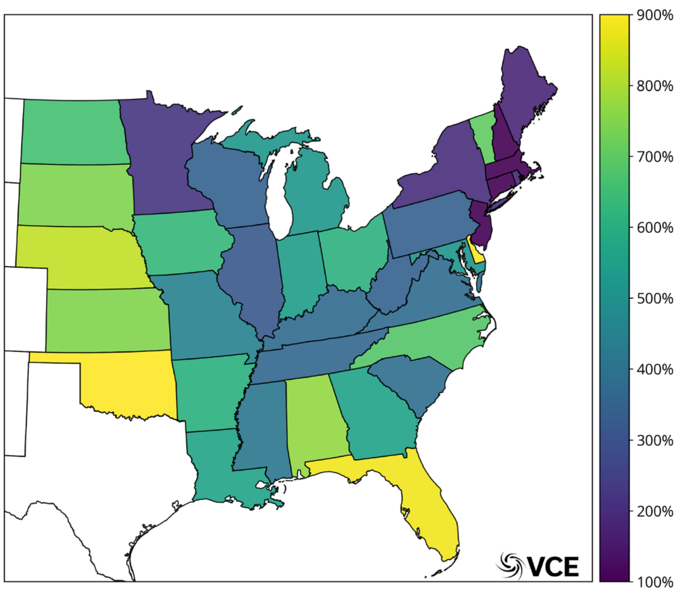


Figure 11: Change in jobs from 2018 to 2050 in the high wind case

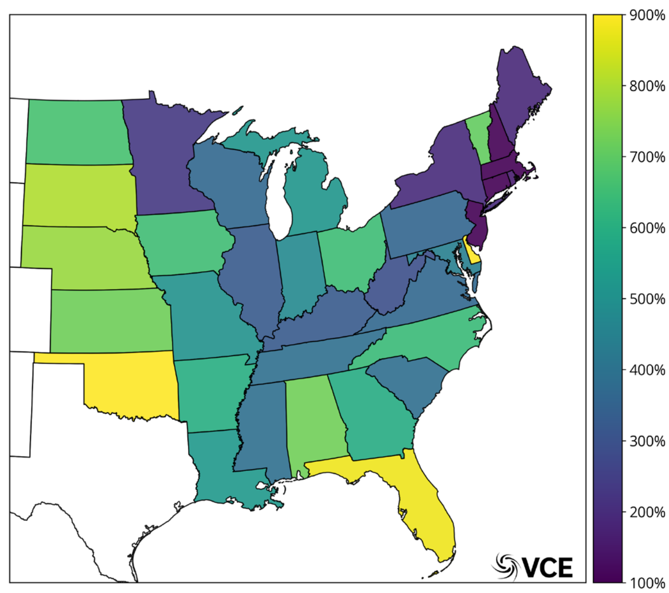


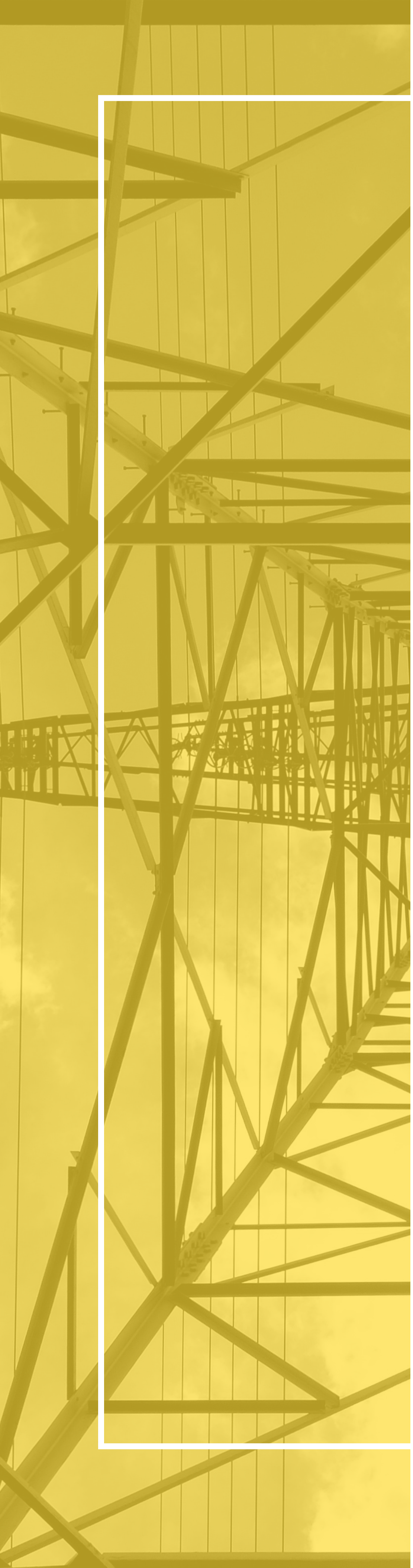
Table 2 provides state-level results for the increase in total electric sector jobs between 2018 and 2050, and the number of those jobs driven by transmission investment, in the high solar and high wind deployment cases with strong carbon policy. Under either scenario, every state stands to gain thousands of jobs, and in many cases hundreds of thousands of jobs, across the electric sector and from the investment in transmission alone.

Table 2: With Strong Carbon Policy, Increase in Total Electric Sector and Transmission Jobs by State, from 2018 to 2050

	High Solar		High Wind	
	Total Electric Sector	Transmission	Total Electric Sector	Transmission
Florida	725,865	55,250	723,590	54,089
North Carolina	456,268	49,916	425,994	52,119
Oklahoma	344,430	88,890	350,937	92,471
Georgia	319,643	69,417	335,670	83,431
Alabama	302,980	54,871	285,171	44,682
Ohio	299,184	67,001	316,943	76,745
Indiana	252,326	23,360	220,660	32,680
Michigan	251,458	22,143	248,834	21,772
Virginia	241,133	61,491	230,762	54,052
Pennsylvania	233,903	58,171	243,426	76,590
Missouri	217,103	147,835	242,059	167,418
Iowa	208,863	70,089	216,045	76,144
Illinois	208,316	42,346	211,723	47,790
Kansas	186,782	80,545	180,503	68,058
Louisiana	173,792	17,894	162,243	17,999
Tennessee	172,528	109,987	185,496	121,714
South Carolina	168,796	17,482	168,051	15,522
Arkansas	157,845	110,838	156,724	107,562
Nebraska	148,341	39,565	139,427	34,847

Table 2 (Continued): With Strong Carbon Policy, Increase in Total Electric Sector and Transmission Jobs by State, from 2018 to 2050

New York	147,637	17,414	143,707	17,963
Maryland	146,188	22,278	124,671	16,864
Kentucky	133,469	77,771	116,567	66,634
Wisconsin	102,818	38,992	107,542	42,950
Delaware	97,215	11,602	98,694	14,425
Mississippi	97,099	21,360	91,422	19,901
West Virginia	87,728	37,900	73,886	28,924
North Dakota	86,399	16,191	86,830	16,995
Minnesota	80,770	38,996	83,749	40,694
South Dakota	71,183	18,191	76,852	19,819
Vermont	48,734	7,573	49,087	8,141
Massachusetts	40,011	16,566	38,503	16,026
New Jersey	38,151	7,513	38,500	7,868
Connecticut	16,210	6,590	15,451	5,768
Maine	14,589	1,327	14,686	1,377
Washington DC	9,109	2,002	12,481	1,958
New Hampshire	7,540	5,524	8,128	5,799
Rhode Island	5,825	2,864	5,115	2,149
Total	**6,300,231**	**1,537,752**	**6,230,127**	**1,579,939**



This job creation is driven by as much as $7.8 trillion in generation and transmission investment across the eastern U.S. through the year 2050, as shown in the following maps for the high solar deployment and high wind deployment cases. Several states receive more than $400 billion in additional investment in generation and transmission, driving up tax revenue, indirect job creation outside of the electric sector, and broader economic development. The vast majority of this investment will flow to economically depressed rural areas.[7]

Figure 11: Cumulative capital investment through 2050 in the high solar case

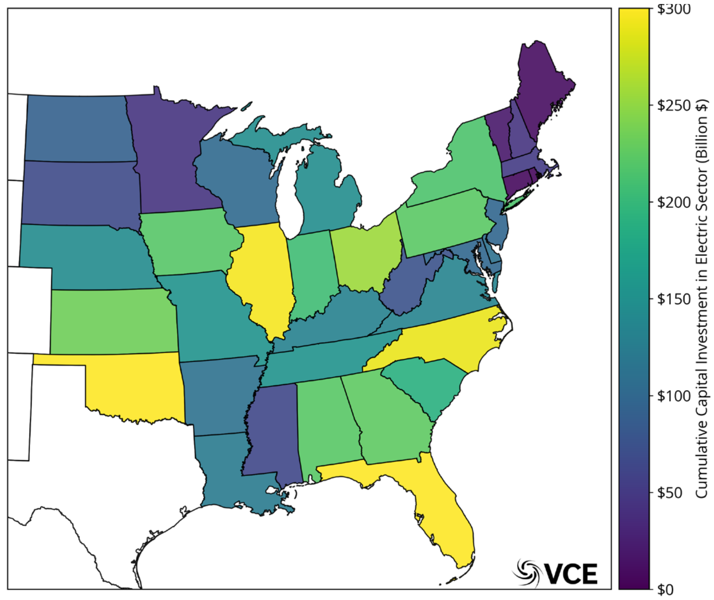
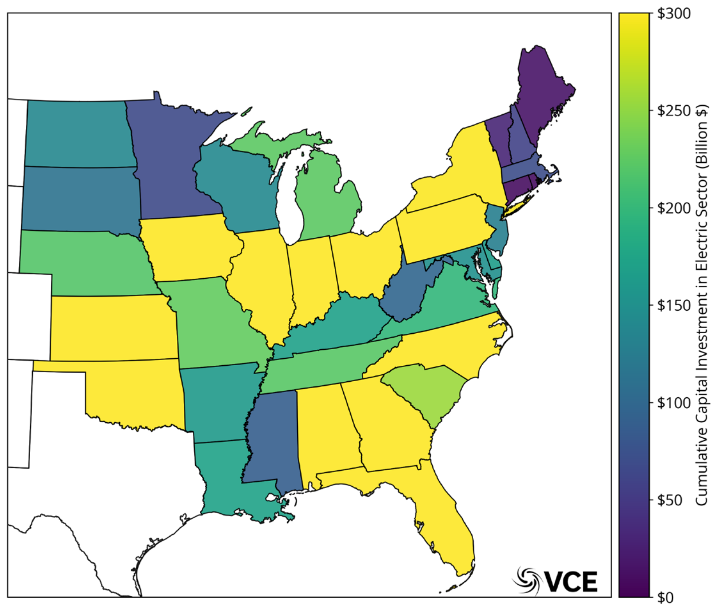


Figure 12: Cumulative capital investment through 2050 in the high wind case

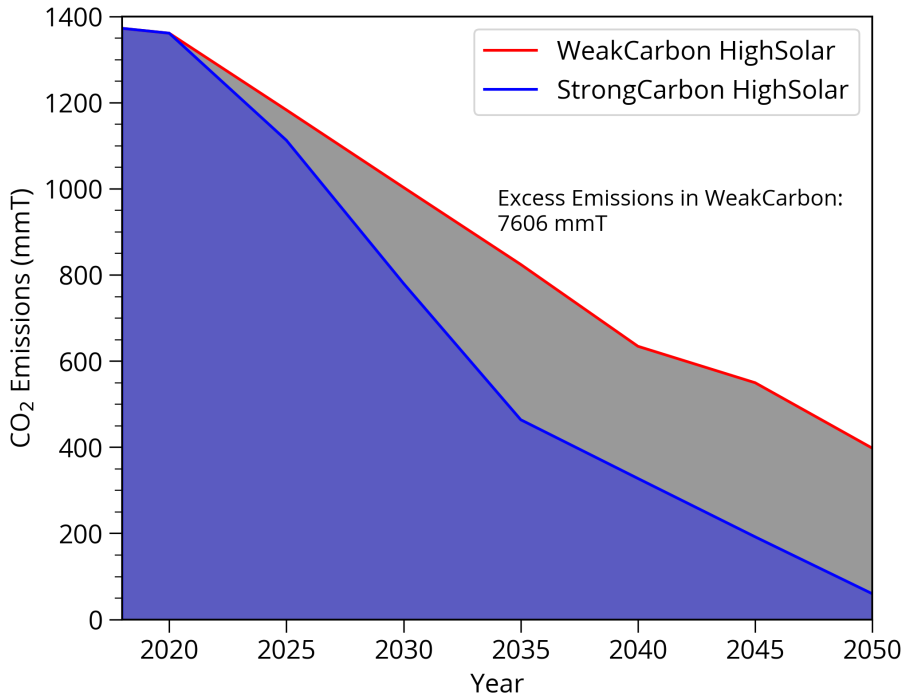


[7] American Wind Energy Association. "Wind Power Pays $222 Million a Year to Rural Landowners." March 22, 2016. https://www.awea.org/resources/news/2016/wind-power-pays-$222-million-a-year-to-rural-lando

Cleaner Air

While the consumer savings and job creation benefits alone are enough to justify an expansion of transmission and renewable energy, there is an additional benefit of reducing air pollution from greater use of renewable energy. Under all scenarios, air pollution declines dramatically from current levels. The strong emissions reduction case yields even larger benefits, with additional savings of 7.6 billion metric tons of CO_2 cumulatively through the year 2050 from the Eastern U.S. alone in the high solar deployment case, as shown below. For reference, these cumulative additional CO_2 savings from the eastern U.S.'s electric sector are more than all current annual greenhouse gas emissions from all sectors nationwide.[8]

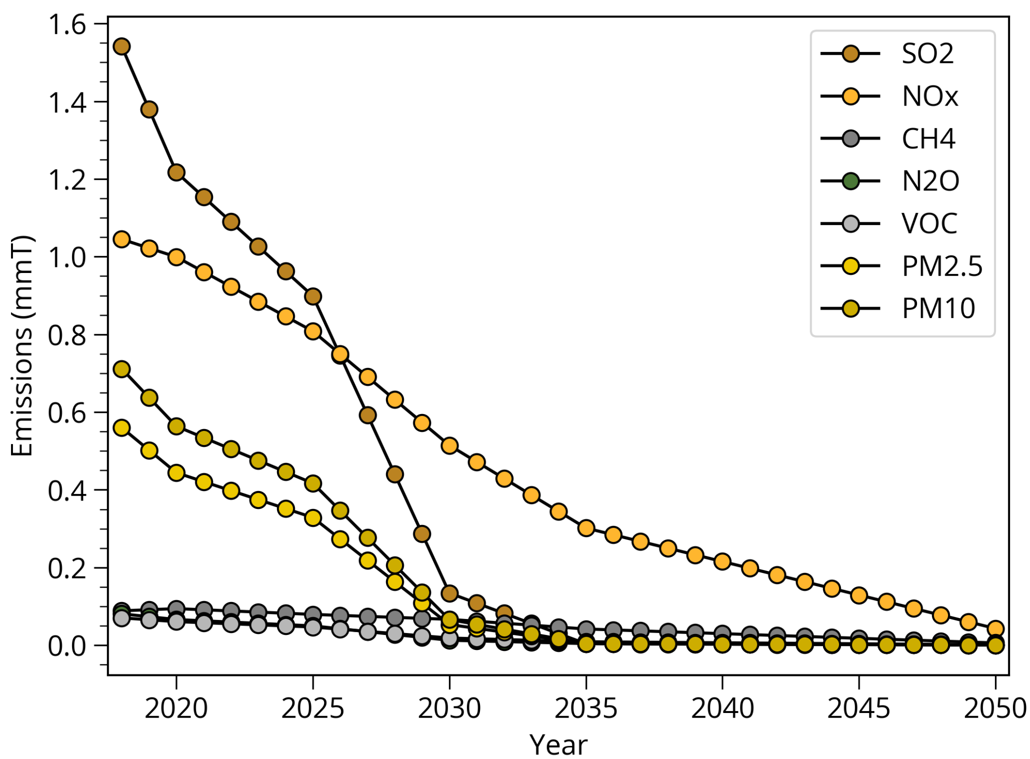
Figure 13: Carbon dioxide emissions in the weak carbon versus strong carbon cases with high solar deployment



[8] United States Envrionmental Protection Agency. "Greenhouse Gas Emissions: Inventory of U.S. Greenhouse Gas Emissions and Sinks." September 11, 2020. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

As shown below, investing in transmission and renewable energy can improve public health by greatly reducing or eliminating a range of harmful air pollutants over the next decade. These localized air pollutants increase the risk of illness or death from a range of health problems,[9] and have even been linked to increased risk of death from COVID-19.[10] By delivering clean energy to densely populated areas to replace polluting sources of energy, transmission plays a particularly important role in displacing harmful emissions. Many of the most polluting power plants are located in economically disadvantaged communities. We also observe dramatic declines in CH_4 and N_2O in all scenarios, which are more powerful greenhouse gases per-ton than CO_2.

Figure 14: Emissions of other pollutants in the strong carbon, high solar deployment case



[9] Buonocore JJ, Dong X, Spengler JD, Fu JS, Levy JI. "Using the Community Multiscale Air Quality (CMAQ) model to estimate public health impacts of PM2.5 from individual power plants." July 2014. https://pubmed.ncbi.nlm.nih.gov/24769126/

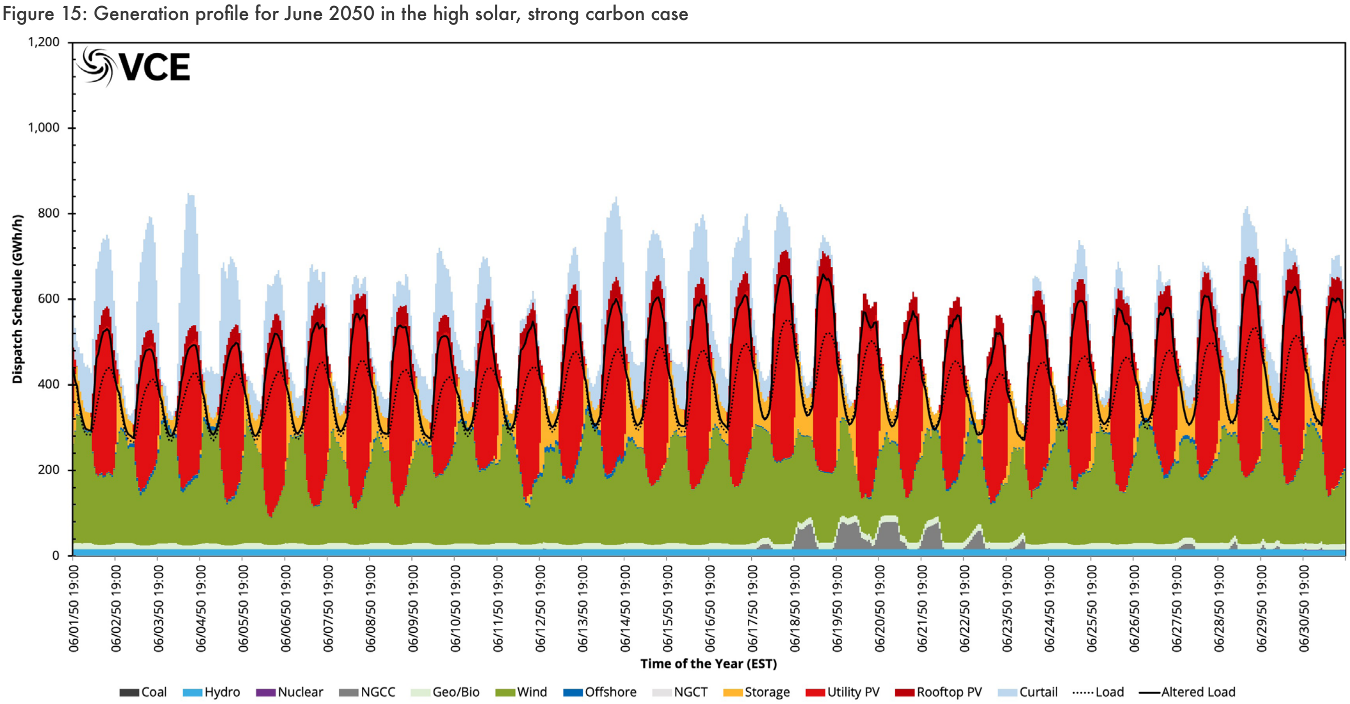
[10] Michael Petroni et al. "Hazardous Air Pollutant Exposure as a Contributing Factor to COVID-19 Mortality in the United States." September 2020. https://www.eenews.net/assets/2020/09/11/document_gw_15.pdf

06

Electric Reliability

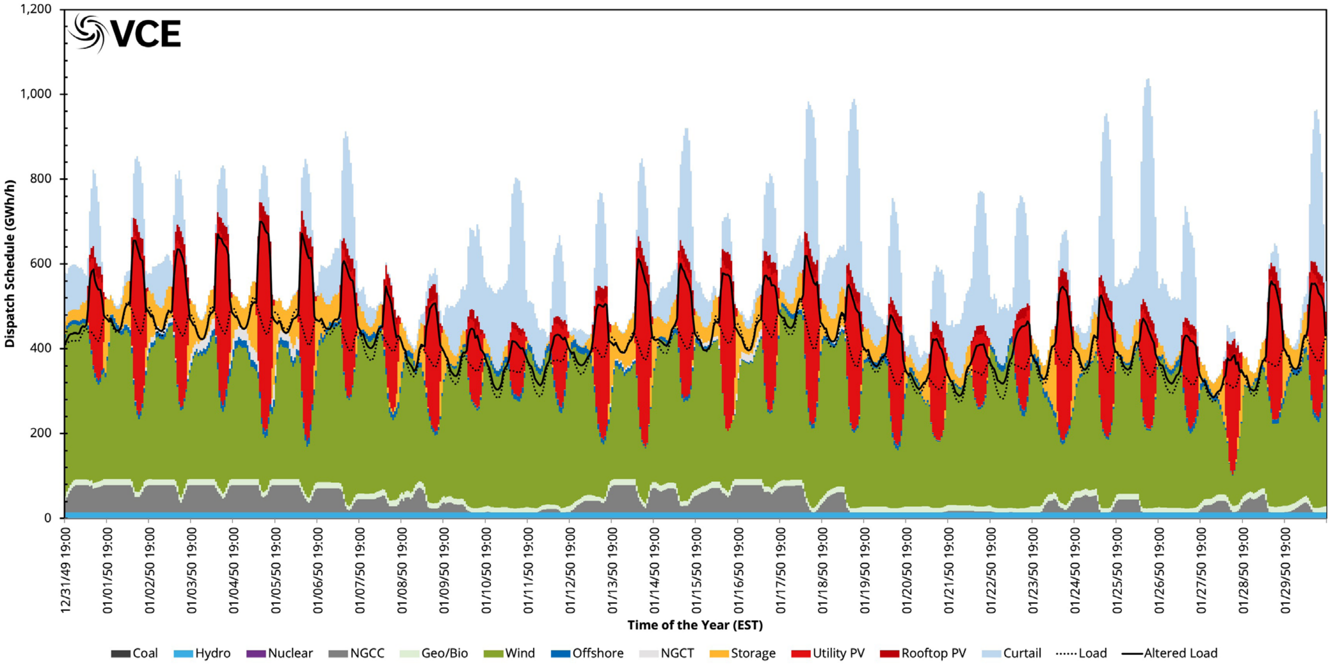
Our analysis found that with a strong transmission network, the power system can be operated reliably with very high penetrations of wind and solar. In all four scenarios, electricity demand was reliably met in every 5-minute interval of the year, even with wind and solar providing 82% of electricity in 2050 in the strong carbon policy cases. The following chart shows electricity supply and demand in June 2050 in the high solar deployment and strong carbon policy case. Notably, gas generation is offline for most of June, and only turned on for a few nights (the gray bumps at the bottom of the chart) when wind output is below average. Across all of 2050 in the strong carbon policy cases, fossil generation is offline or producing a negligible amount of power about 60% of the time, and providing only a small share of total power the remainder of the time.

Figure 15: Generation profile for June 2050 in the high solar, strong carbon case



Similarly, wind, solar, and storage work together to reliably meet demand throughout the winter, as shown in the following chart of January 2050 from the high solar and strong carbon policy case. Notably, winter electricity demand is markedly higher than it is today due to expanded electrification of building and water heating. In both winter and summer, batteries primarily charge during the day when solar is abundant (the upward shift from the dashed black line to the solid black line), and discharge at night (orange). There is significant curtailment of excess renewable output at times (the light blue areas at the top), which still results in a least-cost portfolio given the low and falling costs of renewable energy plants. As discussed at the end of the report, continent-scale transmission and other flexibility solutions that are not yet commercially available at scale could likely help reduce this curtailment, but they were not modeled as options in this analysis.

Figure 16: Generation profile for January 2050 in the high solar, strong carbon case



Expanding transmission is essential for cost-effectively integrating such high penetrations of wind and solar. A strong transmission network allows the primary wind-producing areas to export power when wind is abundant and import when it is not, just as the primary solar-producing areas export power during the day and import power at night.

A strong transmission network also cancels out localized swings in wind or solar output, and ensures that a higher level of wind and solar output is always available.[11] As a previous study by Dr. Clack[12] published in the journal Nature Climate Change concluded, "paradoxically, the variability of the weather can provide the answer to its perceived problems," because "the average variability of weather decreases as size increases; if wind or solar power are not available in a small area, they are more likely to be available somewhere in a larger area."[13] A larger, more integrated transmission system is the most cost-effective solution for canceling out wind and solar variability by increasing the geographic diversity in wind and solar resources. For the same reason, at high renewable penetrations, accommodating the variability of distributed solar resources requires as much transmission as utility-scale resources.

[11] Due to geographic diversity in wind and solar output across the entire eastern U.S., the model indicates that the lowest level of combined wind and solar output for any hour in 2050 is 72,700 MW. The lowest combined output of wind and solar in an hour with above average demand is 88,800 MW, and the lowest combined output for an hour in the 95th percentile of highest load hours is 186,400 MW.

[12] This study used the NEWS model, which was created by Dr. Clack at NOAA to study continental scale transmission and renewables. The WIS:dom®-P optimization model used in this study contains some similar concepts, but is more detailed and expansive.

[13] MacDonald, A., Clack, C., Alexander, A. et al. "Future Cost-Competitive Electricity Systems and their Impact on U.S. CO_2 Emissions." January 25, 2016. https://www.nature.com/articles/nclimate2921

07

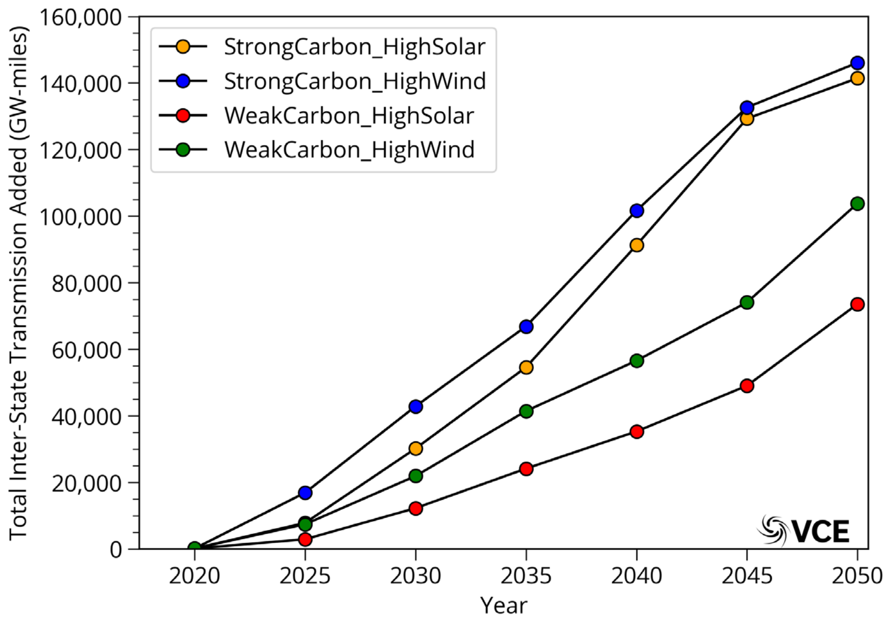
The Location and Quantity of Transmission Need

While many of the same transmission upgrades are needed in all scenarios, shifts in transmission need across the four scenarios provide insight about the value of transmission. Patterns in the location and quantity of transmission and storage deployment also provide insight into the value of those resources, and how they work together.

Many findings are intuitive. For example, scenarios with larger emissions reductions result in a larger transmission expansion. The scenarios with high wind deployment also generally drive somewhat larger transmission expansion than the high solar deployment cases, as shown in the figure below. This chart shows GW-miles; for example, a 500-mile transmission line that delivers 2 GW provides 1,000 GW-miles of transmission capacity. The figure below makes clear that, regardless of future trends in carbon emissions or wind and solar costs, large amounts of new high-capacity transmission will be required.

Other findings are less intuitive. As solar penetrations reach high levels in the later years of the strong carbon high solar deployment case, the incremental transmission need catches up to that seen in the high wind deployment case. As discussed below, it appears that at these high solar penetrations, large daily swings in daytime solar exports and nighttime imports of other resources create a large need for transmission between the primary solar producing areas and other regions.

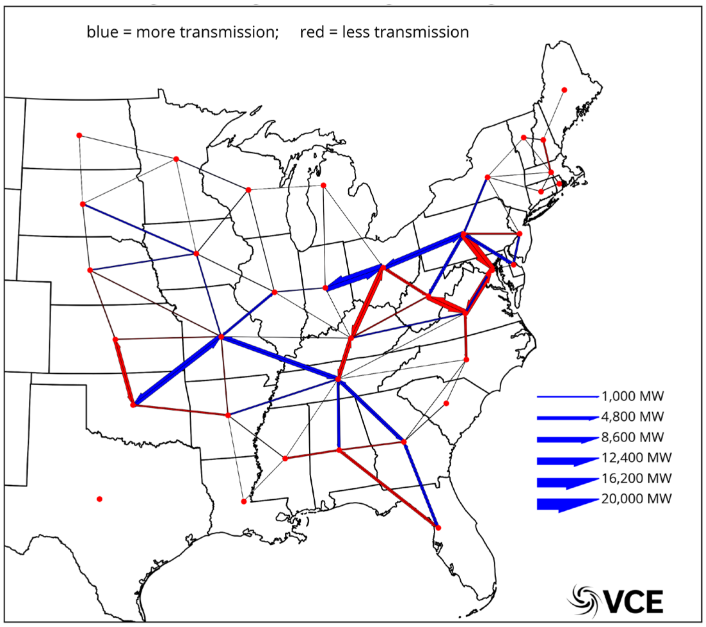
Figure 17: Transmission investment by scenario



The maps in Appendix C show the location of existing and new generating resources and new transmission capacity in the years 2030 and 2050 under the four scenarios. As mentioned earlier, fundamental physical factors caused the generation mix between the high wind and high solar cases to converge at higher renewable penetrations, driving common transmission needs regardless of future cost trends for wind and solar. However, significant differences in generation and transmission build can also be seen in many cases.

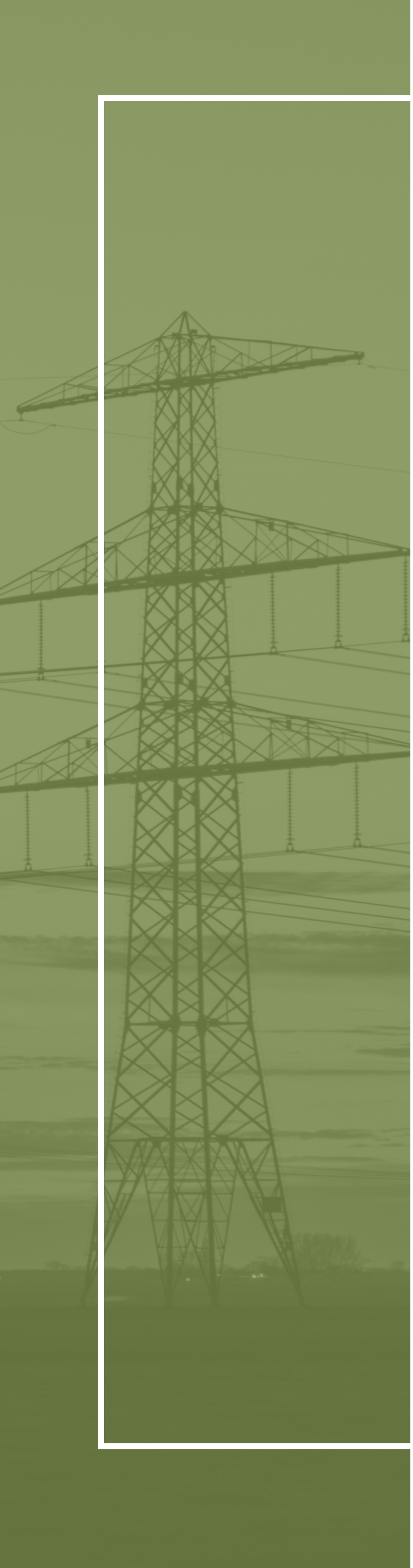
The following maps highlight the difference in transmission build between different scenarios. As noted above, these differences generally follow expected patterns. For example, the following map shows how as more wind generation is deployed in the western part of the Eastern Interconnect, more transmission (indicated by blue arrows) is required to deliver that energy to load centers in the Southeast and Northeast is required, while less transmission (red arrows) is required to deliver Southeast solar generation to the Northeast.

Figure 18: Change in transmission needs in the high wind case relative to the high solar case



As mentioned earlier, a less intuitive result is that in moving from the weak carbon to the strong carbon cases, the high solar deployment case drives significantly more incremental transmission investment than in moving from weak carbon to strong carbon in the high wind deployment case. As shown in the first map below, in the high solar deployment case, moving from weak carbon to strong carbon drives a large increase in import and export transmission between the Southeast's heavy solar states and the heavy wind states in the Midwest and Plains. A likely explanation is that as the Southeast increases its deployment of solar generation, it needs additional transmission capacity to export excess solar production during daylight hours, and more importantly to import wind generation to meet electricity demand during nighttime hours. The westward transmission expansion could also be tapping into the time zone diversity between the Southeast and Plains states like Oklahoma and Kansas, where the sun setting as much as two hours later allows those states to ship solar power eastward to meet evening peak demand after the sun has already set in the Southeast.

The transmission expansion is much larger and extends much deeper into the Southeast than in the high wind case, shown in the second map below. This highlights that more transmission capacity is needed to accommodate the larger swing between daytime solar exports and nighttime imports in the solar case. Other reports have discussed how solar can actually drive more transmission need than wind at higher penetrations, reflecting that solar output is concentrated into daytime hours with



none at night, while wind output tends to be more evenly dispersed across the day.[14] In moving from the weak carbon to the strong carbon case in the high wind deployment scenario, most of the incremental transmission lines delivering wind from the Plains stop at Tennessee and do not extend as deeply into the Southeast. This likely indicates that with less solar deployment, the Southeast has less need for large swings in import and export capacity. As above, blue indicates more transmission is needed in the strong carbon case, while red indicates more transmission is needed in the weak carbon case.

Figure 19: Increase in 2050 transmission need in moving from weak carbon to strong carbon in the high solar case

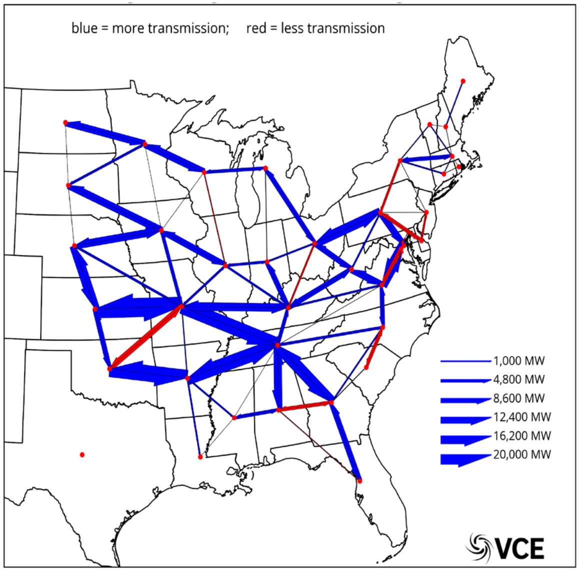
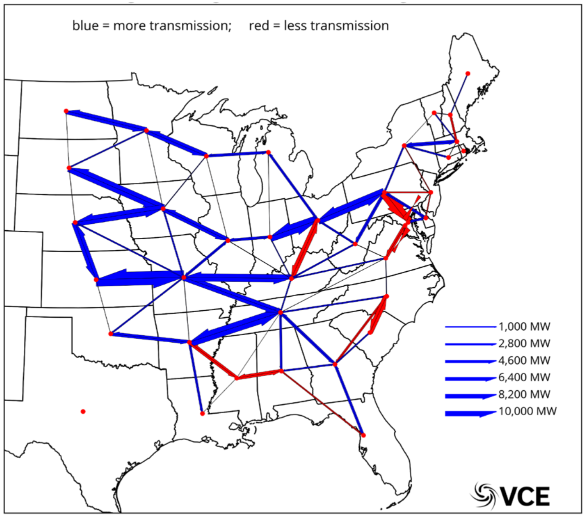


Figure 20: Increase in 2050 transmission need in moving from weak carbon to strong carbon in the high wind case



14 For example, see Chapter 2 of American Wind Energy Association. "Grid Vision: The Electric Highway to a 21st Century Economy." May 2019. https://www.awea.org/Awea/media/Resources/Publications%20and%20Reports/White%20Papers/Grid-Vision-The-Electric-Highway-to-a-21st-Century-Economy.pdf

08

Storage is a Transmission Complement, not a Substitute

The following maps also reveal how storage, particularly storage that is strategically sited near wind and solar resource areas, can complement transmission investment by increasing the utilization factor of transmission lines, a conclusion found in other studies.[15, 16] In the high solar deployment scenario, much of the storage deployment is concentrated in the East, and particularly the Southeast. That storage helps shift excess daytime solar production to the nighttime, when solar is unavailable to meet electricity demand and when export transmission capacity is not being fully utilized by solar generation. In the high wind deployment scenario, a significant amount of that storage shifts to western states like Kansas and South Dakota, where it similarly helps shift excess wind production to periods of lower wind output when export transmission is not being fully utilized. Notably, much of that storage shifted out of Indiana and Pennsylvania, where expanded west-east transmission delivering wind generation to the Northeast steps in to replace the need for storage.

Figure 20: Map of transmission and storage deployment in strong carbon high solar case by 2050

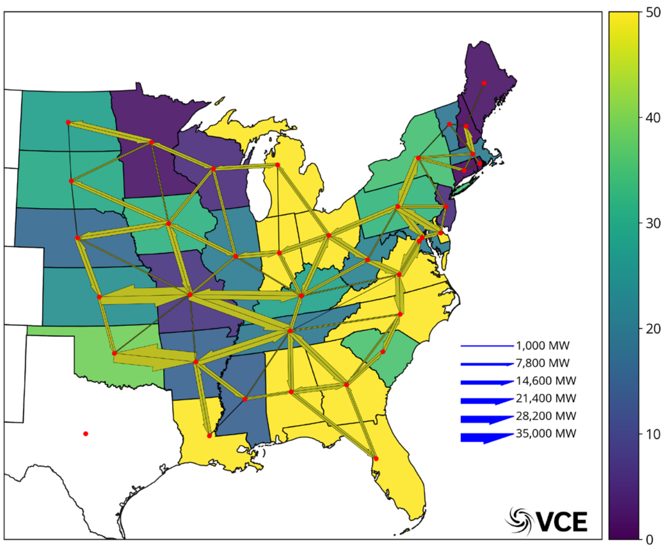
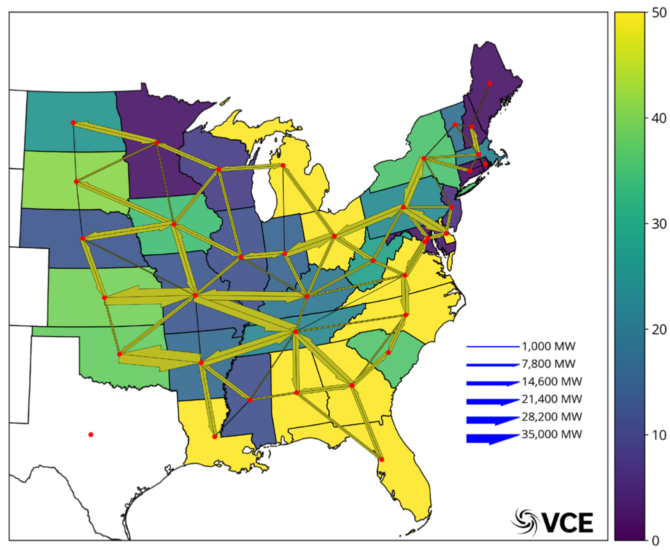


Figure 21: Map of transmission and storage deployment in strong carbon high wind case by 2050.



15 Vibrant Clean Energy. "Modernizing Minnesota's Grid: An Economic Analysis of Energy Storage Opportunities MISO-wide Electricity Co-Optimized Planning Scenarios." July 11, 2017. http://energytransition.umn.edu/wp-content/uploads/2017/07/EDITED-VCE-Slides-7.11.17.pdf

16 Vibrant Clean Energy. "Minnesota's Smarter Grid: Pathways Toward a Clean, Reliable and Affordable Transporation and Energy System." 2018. https://www.vibrantcleanenergy.com/wp-content/uploads/2018/07/Minnesotas-SmarterGrid_FullReport.pdf

The shift in storage deployment is more obvious in the weaker carbon reduction cases in 2050, shown in the maps below. The storage deployment shifts westward in moving from the high solar case in the first map to the high wind case in the second map. Even though west-east transmission capacity to export that wind has expanded dramatically, storage helps use that transmission more efficiently by shifting excess wind production to periods of lower wind output when export transmission is not being fully utilized.

Figure 22: Map of transmission and storage deployment in weak carbon high solar case by 2050

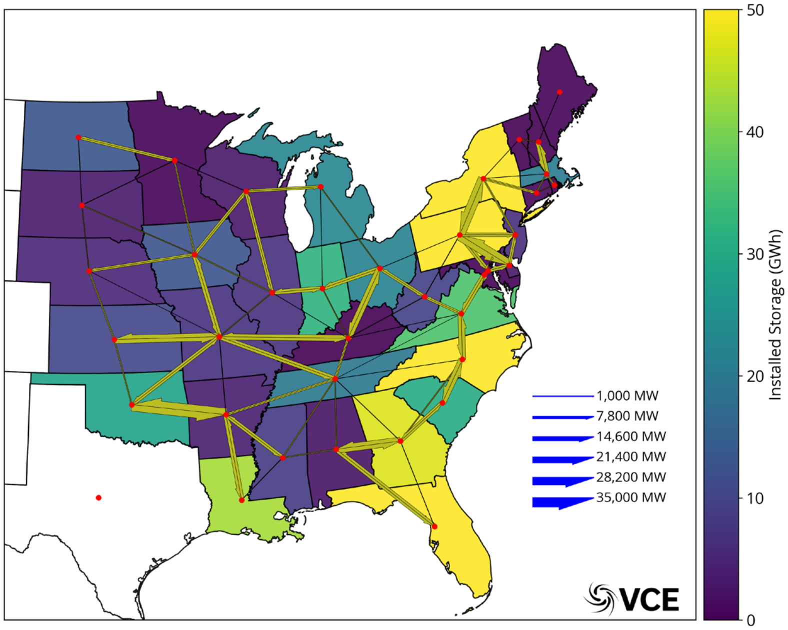
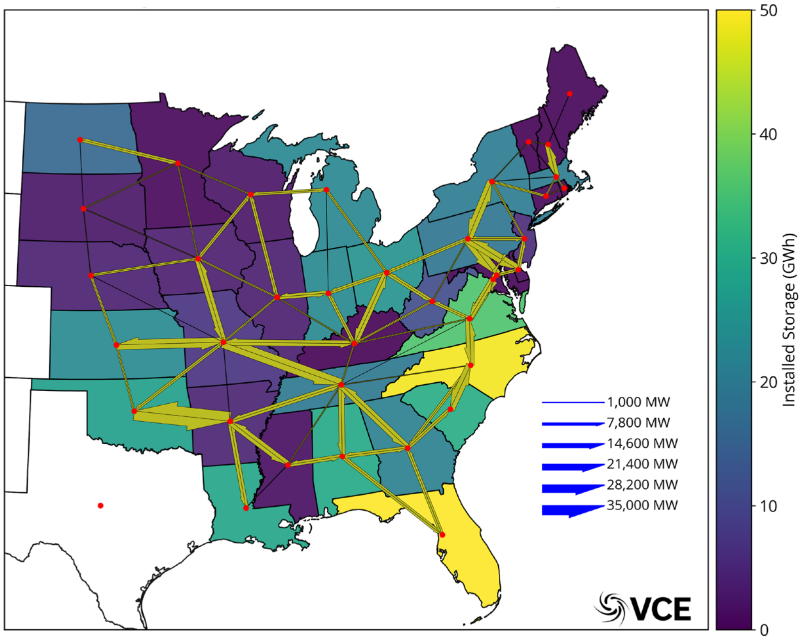


Figure 23: Map of transmission and storage deployment in strong carbon high wind case by 2050



The large need for incremental transmission and storage in all scenarios demonstrates that storage and transmission are complements. Transmission's unique role is to deliver energy from one place to another, which will be critical in a future that requires delivering large amounts of wind and solar from regions where they are more economically produced, and shifting power from region to region as solar and wind output shift with the weather. Storage can help transmission provide that service by charging when renewable supply exceeds transmission export capacity and discharging once transmission capacity becomes available. Correspondingly, transmission provides storage with the ability to access abundant low-cost renewable resources when the storage is charging, and deliver that power to high-priced demand centers when it is discharging. Both transmission and storage will play essential roles in cost-effectively and reliably reaching very high renewable penetrations.

As shown in the table below, and reflected in the maps on the preceding pages, storage capacity is significantly higher in the high solar deployment cases than in the high wind deployment cases. This makes intuitive sense, as it is widely appreciated that short-duration battery storage is better suited for helping to shift daytime solar output into the evening than to accommodate the longer-duration fluctuations in wind output. However, as noted above, storage also plays a critical role in increasing the utilization of wind export transmission lines in the high wind cases, particularly earlier in the period. This table reports the capacity of all forms of energy storage, including existing and new pumped hydro and battery resources.

Table 3: Existing and New Storage MW by Scenario and Year

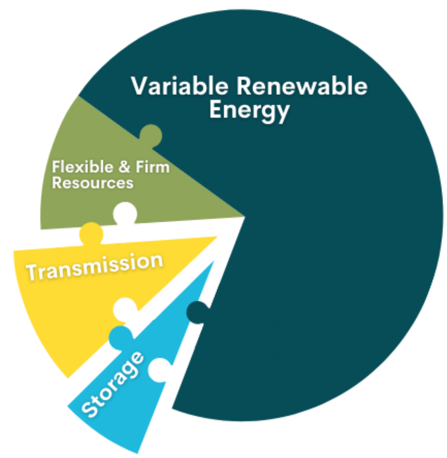
	Weak carbon high solar	Weak carbon high wind	Strong carbon high solar	Strong carbon high wind
2025	18,256	23,803	21,168	21,801
2030	43,541	50,068	54,408	51,646
2035	70,133	64,106	72,610	65,154
2040	92,880	69,348	89,788	81,572
2045	108,692	77,841	119,023	113,834
2050	140,712	111,727	211,660	204,406

As occurs today, wind and solar generation in the model is curtailed if it is produced at a location where there is insufficient transmission to deliver it to customers or at a time when electricity supply exceeds demand. The levels of wind and solar curtailment observed in the model are economically manageable, but they do increase as wind and solar penetrations approach 80% in the later years of the model. This can be seen in Figure 1 at the beginning of the report, as total generation increases in 2050 in the strong carbon cases due to increased curtailment.

Notably, the model only used energy storage technologies that are commercially available today, and did not have the option to deploy potential long-duration and seasonal storage technologies that would have reduced this curtailment while also providing flexible capacity during periods when renewables are not abundant. Continental-scale transmission to expand transmission ties from the eastern U.S. to the western U.S., ERCOT, and Canada would also help reduce curtailment, reduce costs, and improve reliability by capturing greater geographic diversity of renewable resources and providing greater access to flexible capacity resources. Notably, expanding these transmission ties would increase access to hydropower reservoirs that offer the only form of seasonal energy storage commercially available today. Other promising sources of seasonal energy storage include using electrolysis to produce hydrogen, which could also include the production of hydrogen-based solid, liquid, and gaseous fuels that can be stored more easily. The electrification of vehicles and building and water heating could also help provide shorter-duration flexibility and reduce curtailment if the dispatch of these resources is coordinated with wholesale electricity markets.

Conclusion

Investing in transmission is a win-win-win for American consumers, workers, and the environment. Most of America's world-class renewable resources are currently stranded in remote areas where the power grid is weak to nonexistent. Wind, solar, storage, and other flexible sources of capacity work together, and each play both unique and complementary roles, never truly replacing each other. This full picture only becomes clear through detailed analysis identifying electricity needs and supplies for every point in time and location in the country. Regardless of their relative costs, these five sources all serve as different pieces of the electricity portfolio puzzle and are each essential to achieve the environmental, consumer, and employment benefits found in this study.



This study confirms that large-scale transmission expansion is critical for maintaining affordable and reliable electric service under any scenario for future renewable costs or carbon emissions. However, policy shortcomings in how we plan, pay for, and permit transmission are blocking private investment in modernizing our power grid.[17] Overcoming those challenges can unleash as much as $7.8 trillion in investment in rural America, create more than 6 million net new domestic jobs, save consumers more than $100 billion, and provide all Americans with cleaner air.

[17] See Chapter 3 of American Wind Energy Association. "Grid Vision: The Electric Highway to a 21st Century Economy." May 2019. https://www.awea.org/Awea/media/Resources/Publications%20and%20Reports/White%20Papers/Grid-Vision-The-Electric-Highway-to-a-21st-Century-Economy.pdf

Appendix

Appendix A: Model Assumptions

Technical documentation of the WIS:dom®-P model and its datasets is available here: https://vibrantcleanenergy.com/wp-content/uploads/2020/08/WISdomP-Model_Description(August2020).pdf

The assumptions used to create the four scenarios specific to this study are as follows:

- Strong carbon policy cases: Benchmarked to the Paris Agreement target of 80% economy-wide emissions reductions by 2050, but with the assumption that the electric sector must reduce emissions by around 95% because other sectors of the economy have less cost-effective options for emissions reductions.[18] This requires reducing electric sector carbon emissions by 5.83% per year (relative to the preceding year's emissions) on average between now and 2050. This will reduce electric sector carbon emissions by 66% from 2017 levels by 2035.

- Weak carbon policy cases: To provide a "business as usual" scenario, the average rate of U.S. electric sector carbon emissions reductions observed from 2005-2017 (2.68% per year relative to the preceding year) is forecast to continue, achieving approximately 70% emissions reductions from 2005 levels by 2050. This will reduce electric carbon emissions by 39% from 2017 levels by 2035.

- High solar deployment cases: The model was allowed to economically optimize using NREL 2019 Annual Technology Baseline low solar costs, and medium wind costs.

- High wind deployment cases: The model was allowed to economically optimize using NREL 2019 Annual Technology Baseline low wind costs, and medium solar costs.[19] To better differentiate these cases from the high solar deployment cases, wind generation was forced to provide the following shares of electricity in the model.

	Weak carbon	Strong carbon
2025	15.00%	16.81%
2030	23.00%	32.58%
2035	30.00%	45.39%
2040	38.00%	50.40%
2045	43.00%	55.91%
2050	48.00%	57.34%

18 Various models have confirmed that the electric sector needs to achieve 90%+ carbon emissions reductions to achieve 80% economy-wide reductions. For example, see Ceres. "New Ceres Framework Enables U.S. Electric Power Industry to Assess Climate Change Risks and Opportunities." April 10, 2018. https://www.ceres.org/news-center/press-releases/new-ceres-framework-enables-us-electric-power-industry-assess-climate

19 National Renewable Energy Laboratory. "2019 ATB." https://atb.nrel.gov/electricity/2019/

Appendix B: Regional Consumer Benefits

Consumers in all regions of the Eastern U.S. benefit from transmission and renewable expansion. The following maps show the percentage decline in electric rates over the coming decades, relative to current rates.

Figure 24: Change in retail electric rates from present to 2050

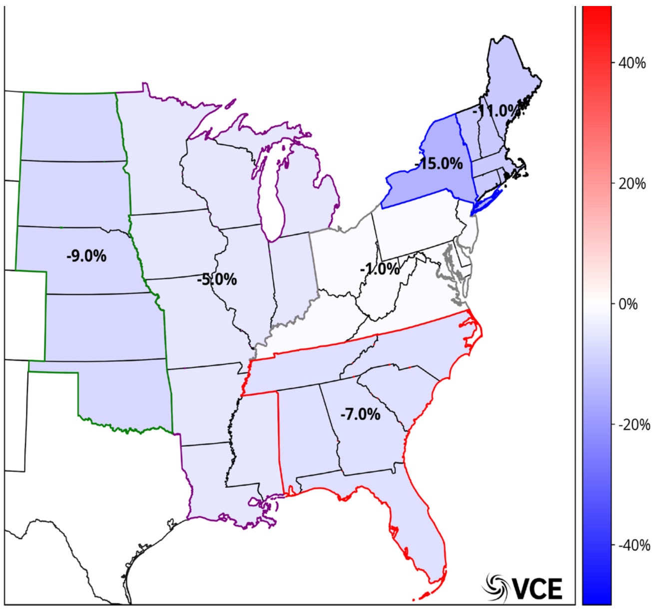


Figure 25: Change in retail elextric rates from present to 2035

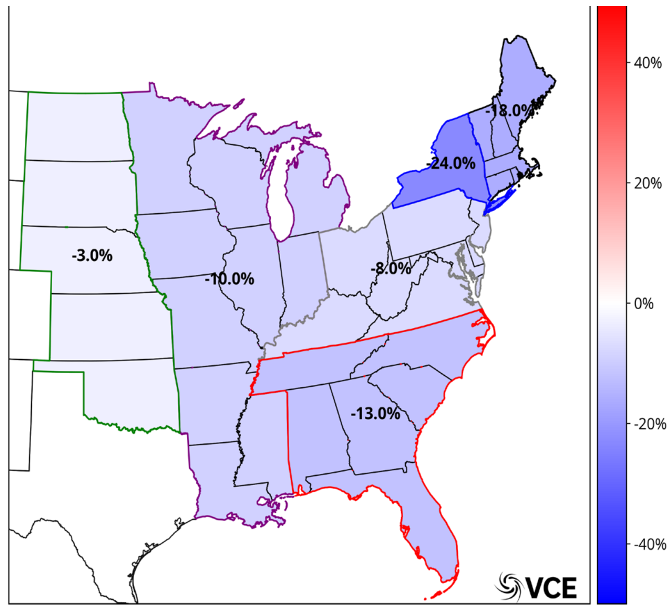


Figure 26: Change in retail electric rates from present to 2045

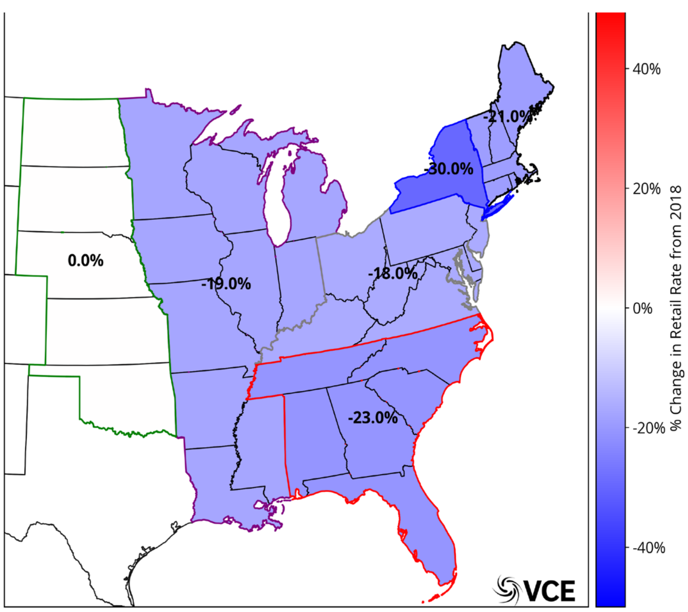
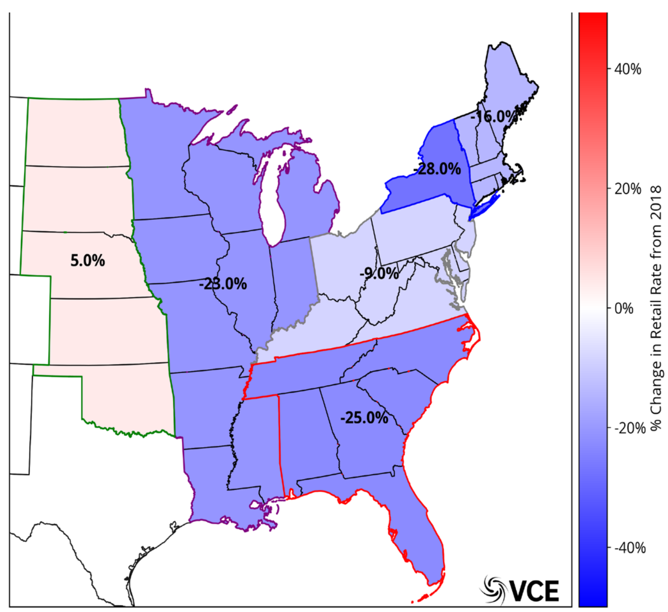


Figure 27: Change in retail electric rates from present to 2050



Most regions see significant rate reductions in most years in both the high wind and high solar deployment cases, and all regions see cumulative savings through the year 2050. However, as shown in the last map showing the last year of the model run, the westernmost states in the Eastern U.S. saw a slight increase in electric rates, after experiencing significantly lower rates in earlier years. As discussed in the final section of this report, this uptick in costs is likely due to significant renewable curtailment in the last year of the model run due to the model conservatively using only technologies that are commercially available today, and not deploying long-duration storage or continent-scale transmission that would reduce curtailment at very high renewable penetrations. Also, those westernmost states currently have some of the lowest electric rates in the Eastern U.S., in part due to their extensive use of low-cost wind energy today, so it was difficult for their electric rates to go any lower.

More importantly, the model assigns generation costs to the state and transmission costs to the region in which those resources are built. In reality, a large share of these costs would almost certainly flow to consumers in other regions, either through power purchase agreements with utilities in other regions or through the broad allocation of transmission costs. As a result, all consumers across the Eastern U.S. are likely to broadly share in the more than $100 billion in benefits created by expanding transmission and renewable energy. Customers in all regions also receive other benefits of transmission that are not accounted for in this analysis, such as increased electric reliability, greater resilience to reliability threats, increased electricity market competition, and greater hedging against all types of uncertainty on the power system.[20]

[20] For more benefits, see Chapter 1 at American Wind Energy Association. "Grid Vision: The Electric Highway to a 21st Century Economy." May 2019. https://www.awea.org/Awea/media/Resources/Publications%20and%20Reports/White%20Papers/Grid-Vision-The-Electric-Highway-to-a-21st-Century-Economy.pdf; and Appendix A at The Brattle Group. "The Benefits of Electric Transmission: Identifying and Analyzing the Value of Investments." July 2013. https://cleanenergygrid.org/uploads/WIRES%20Brattle%20Rpt%20Benefits%20Transmission%20July%202013.pdf

Appendix C: Maps of Transmission Expansion and Generation Location

Figure 28: Strong carbon, high solar deployment, 2030

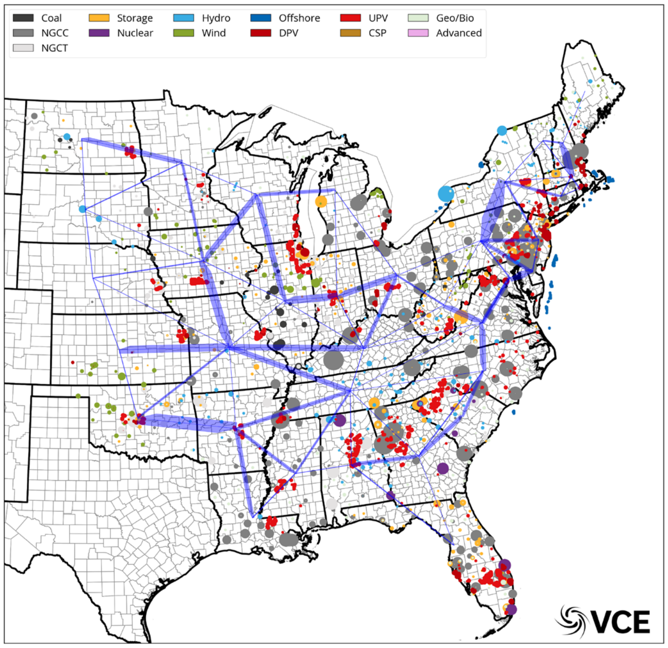


Figure 29: Strong carbon, high wind deployment, 2030

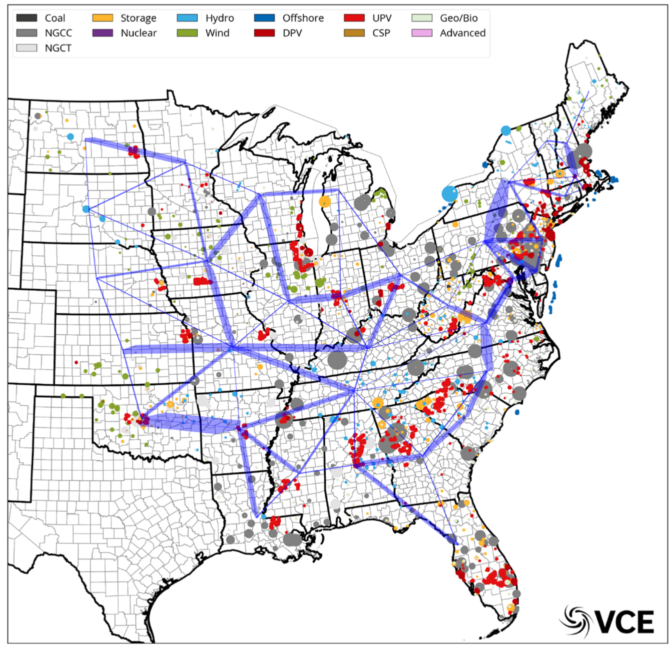


Figure 30: Weak carbon, high solar deployment, 2030

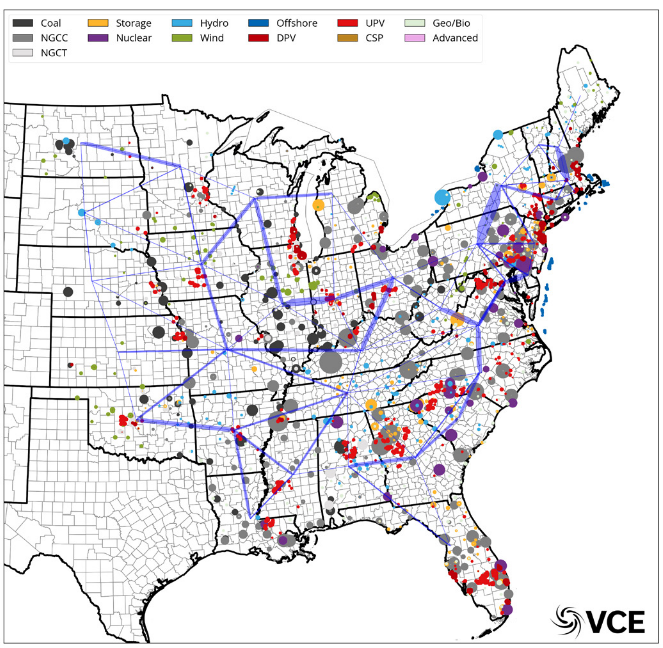


Figure 31: Weak carbon, high wind deployment, 2030

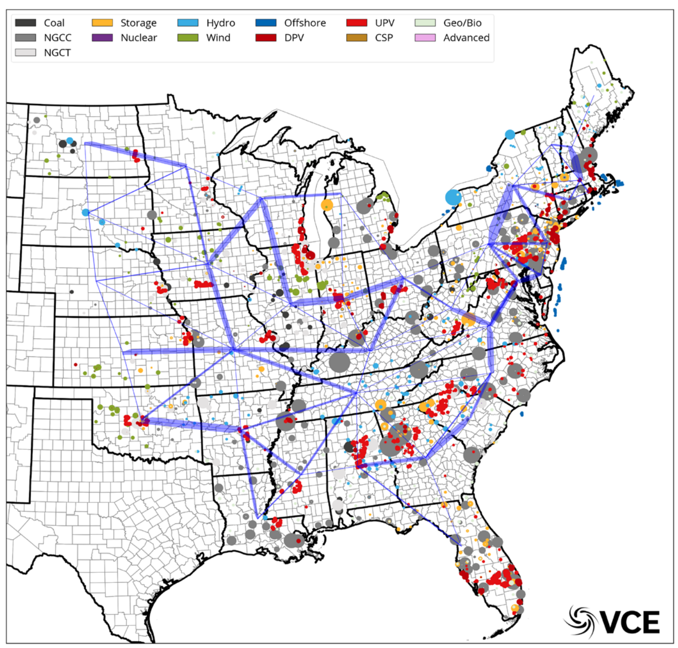


Figure 32: Strong carbon, high solar deployment, 2050

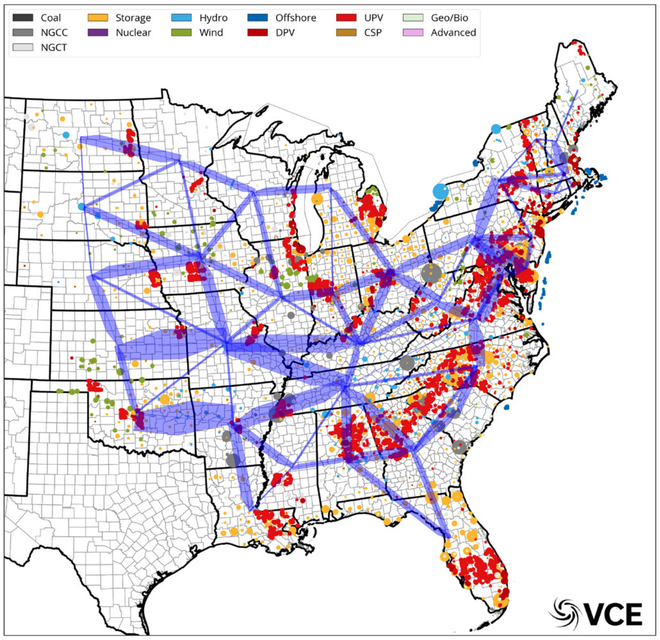


Figure 33: Strong carbon, high wind deployment, 2050

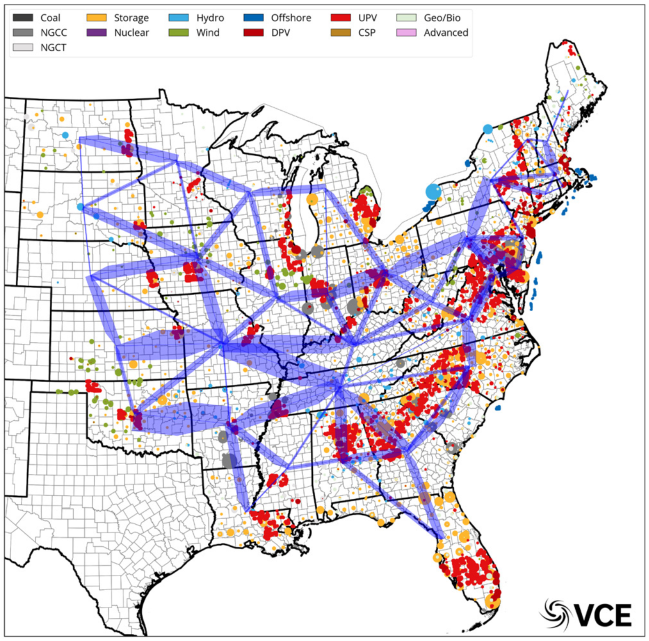


Figure 34: Weak carbon, high solar deployment, 2050

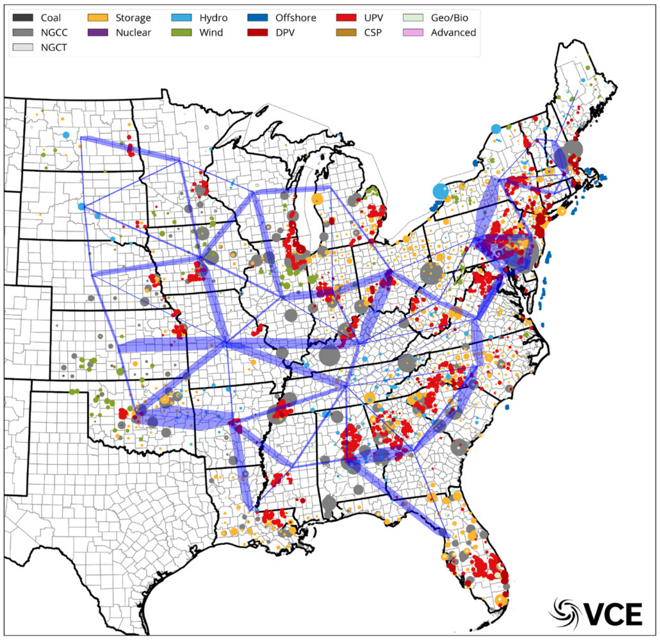
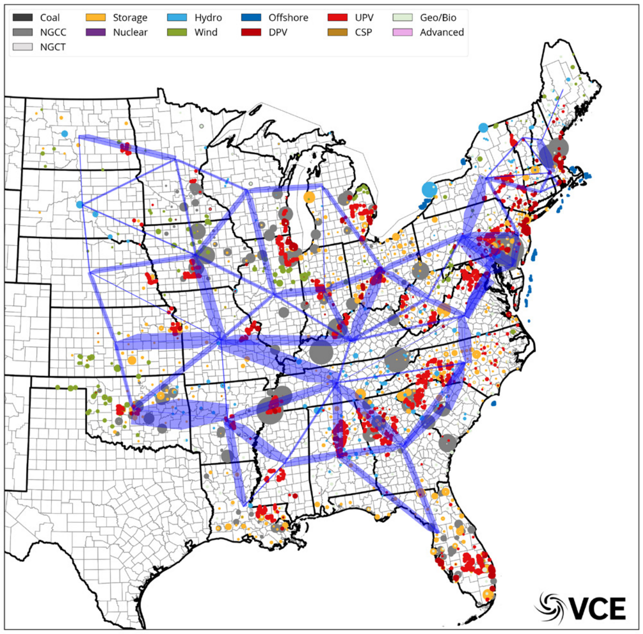


Figure 35: Weak carbon, high wind deployment, 2050



About the Authors

Christoper T.M. Clack, Vibrant Clean Energy LLC

CTMC Founder and CEO at VCE®. Also, the inventor, and software & dataset developer, of the WIS:dom® optimization software suite. Works with utilities, developers, ISO/RTOs, and others to study development of clean energy pathways in the US and abroad. Published high-impact peer-reviewed studies on the future of US electricity in Science, Nature Climate Change and the Proceedings of the National Academies of Sciences.

Michael Goggin, Grid Strategies LLC

Michael Goggin is Vice President at Grid Strategies, LLC, a consulting firm focused on grid and market issues for clients in the clean energy industry. He was previously at the American Wind Energy Association for a decade, where he directed the research team and also focused on transmission and market issues. Michael has an undergraduate degree with honors from Harvard and lives in Washington, DC.

Aditya Choukulkar, Vibrant Clean Energy LLC

AC Energy Data Scientist at VCE®. Leads the further development of all core WIS:dom® datasets to produce finer granularity and higher fidelity outputs. Uses and customizes the software to study deep decarbonization. Previously at NOAA and worked on improving wind energy estimates using LiDAR and weather models.

Brianna Cote, Vibrant Clean Energy LLC

BC Energy Data Analyst at VCE®. Expands the fidelity and granularity of all core WIS:dom® inputs. Leads deployment and validation of the VCE® weather and power datasets. Previously worked in the commercial sector providing and maintaining large datasets.

Sarah McKee, Vibrant Clean Energy LLC

SM Director of Operations at VCE®. Coordinates and assists with validation and development of all datasets and products for WIS:dom®. Provides graphic design, writing, and modeling support across VCE® clients. Previously, managing editor at largest Respiratory Journal in Europe.

October 2020

Americans for a Clean Energy Grid (ACEG) is the only non-profit broad-based public interest advocacy coalition focused on the need to expand, integrate, and modernize the North American high-voltage grid.

ACEG brings together the diverse support for an expanded and modernized grid from business, labor, consumer and environmental groups, and other transmission supporters to educate policymakers and key opinion leaders to support policy which recognizes the benefits of a robust transmission grid. ACEG is a 501(c)(3) organization.

3100 Clarendon Blvd., Suite 800 Arlington, VA 22201 | 703.717.5590 | cleanenergygrid.org

Americans for a Clean Energy Grid