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A Plan for Economy-Wide Decarbonization of the United States

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1 Introduction and Study Description

In order to avoid the worst impacts of climate change the world needs to accelerate its transition to an emission free economy. The United States (US) is in a unique position to provide leadership on this issue through the recently announced plans by the Biden administration to reduce economy-wide emissions by 50% by 2030 and reaching a net-zero carbon emission economy by 2050.[1] This study uses the WIS:dom®-P optimization model to evaluate the pathways the US can take to meet the carbon reduction goals set by the Biden administration through two scenarios. This study was commissioned by the Coalition for Community Solar Access on behalf of a wide coalition of solar advocates including VoteSolar, Sunrun, SunPower, and Local Solar for All.

The modeling was performed using WIS:dom-P, a state-of-the-art model capable of performing detailed capacity expansion and production cost while co-optimizing utility-scale generation, storage, transmission, and distributed energy resources (DERs). The modeled scenarios use the National Renewable Energy Laboratory (NREL) Annual Technology Baseline (ATB) 2021 "moderate" cost projections for installed capital and Operation and Maintenance (O&M) costs. In this modeling the rooftop solar and community solar was merged into one category called Distributed Photovoltaics (DPV) and used average capital costs of commercial and residential solar. As a result, the costs for distributed solar are modeled to be conservative and hence the results in this modeling present a more conservative outlook of distributed solar deployment potential.

For fuel costs, forecasts from the Annual Energy Outlook (AEO) 2021 High Oil and Gas supply scenario[2] are used. The scenarios modeled in this study allow novel technologies to be deployed, but make conservative assumptions on the timeline of their availability and possible deployment rates. Carbon capture and sequestration (*CCS*) is allowed to be deployed starting in 2035, Small Modular Reactors (*SMR*) are allowed to be deployed starting from 2040 and Molten Salt Reactors (*MSR*) are allowed to be deployed starting in 2045 to model the pathways for decarbonization if the market readiness of these clean firm generation technologies is delayed. In addition, the model allows the variable renewable energy (VRE) technology supply chains to be ramped up aggressively to ensure enough VRE deployments can occur to meet the carbon reduction goals. The details of the deployment rates for VREs are discussed in Section 2.2.

Two scenarios are modeled in this study to investigate the decarbonization pathways the US can take to meet the decarbonization goals set by the Biden administration. The description of the scenarios modeled in this study are given below:

(1) **Decarbonization of the US economy with predominantly utility-scale generation ("Utility-Scale Only"):** In this scenario, the US aims to achieve at least 50% economy-wide emission reductions by 2030, with the electricity sector reducing emissions by

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[1] https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/

[2] https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2020&region=1-0&cases=highogs&start=2018&end=2050&f=A&linechart=highogs-d112619a.3-3-AEO2020.1-0~highogs-d112619a.36-3-AEO2020.1-0~highogs-d112619a.37-3-AEO2020.1-0~highogs-d112619a.38-3-AEO2020.1-0~highogs-d112619a.39-3-AEO2020.1-0~highogs-d112619a.40-3-AEO2020.1-0&map=highogs-d112619a.4-3-AEO2020.1-0&sourcekey=0

80%. The US then continues to completely electrify energy related activities by 2050 with the electricity sector decarbonizing by at least 95%. Large-scale transmission is allowed to expand, but the model does not co-optimize the distribution system with the utility-scale generation. In this scenario, the distributed solar is not allowed to grow beyond 2021 installed capacities of 36 GW and no deployment of distributed storage is allowed.

(2) **Decarbonization of the US economy with utility-scale and distribution system co-optimization ("Optimized Local Solar & Storage"):** In this scenario, the US aims to achieve at least 50% economy-wide carbon emission reductions by 2030, with the electricity sector reducing emissions by at least 80%. The US then continues to completely electrify energy related activities by 2050 and the electricity sector decarbonizes by at least 95%. Large-scale transmission is allowed to expand ***and*** the model co-optimizes the distribution system with the utility-scale generation. Distributed energy resources are allowed to grow subject to supply chain constraints.

The scenarios are initialized and calibrated with 2020 generator, generation, and transmission topology datasets. The scenarios then determine a pathway from 2020 through 2050 with results outputted every 5 years. As part of the optimal capacity expansion, WIS:dom-P must ensure each grid meets reliability constraints through enforcing the planning reserve margins specified by the North American Electric Reliability Corporation (NERC) and having a 7% load following reserve available at all times. Detailed technical documentation describes the mathematics and formulation of the WIS:dom-P software along with input datasets and assumptions.[3]

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[3] https://vibrantcleanenergy.com/wp-content/uploads/2020/08/WISdomP-Model_Description(August2020).pdf

1.1 WIS:dom®-P Model Setup

To study the pathways for the United States to meet the decarbonization goals set by the Biden administration, WIS:dom-P modeled the contiguous United States (CONUS) with its existing generator topology, transmission, and weather inputs obtained from National Oceanic and Atmospheric Administration (NOAA) High Resolution Rapid Refresh (HRRR) model[4] at 3-km horizontal resolution and 5-minute time resolution. The CONUS is modeled along with all its import and export connections to Canada and Mexico. The import and export capacities to Canada and Mexico are assumed to remain at 2020 levels for the whole modeling period.

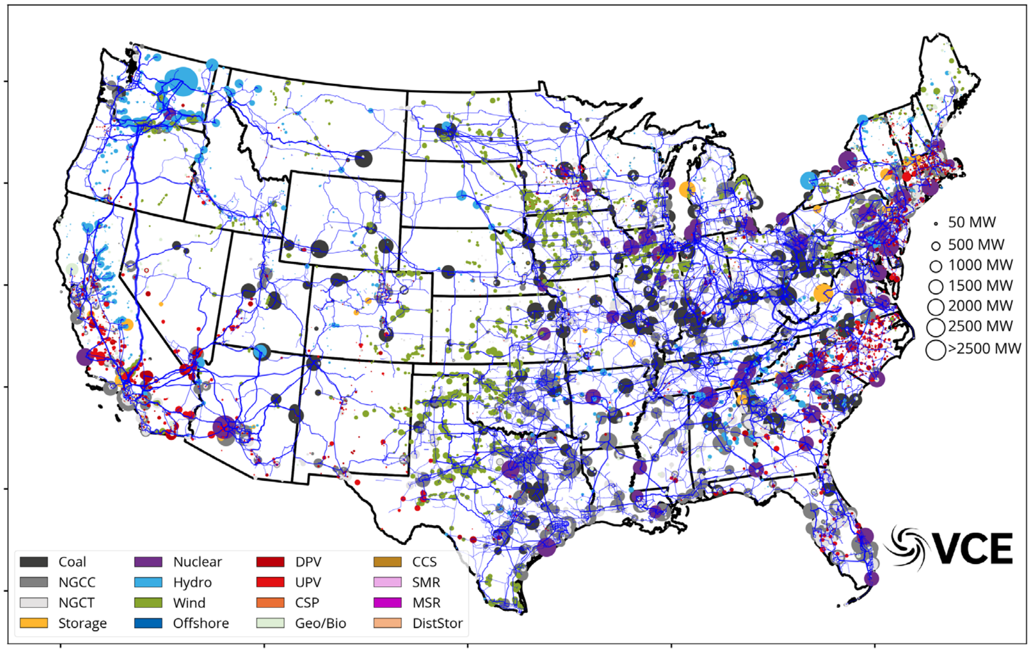

Figure 1.1: The installed generators over the CONUS in 2020 along with transmission path down to 115 kV.

The initialized generator dataset is created by aligning the Energy Information Administration Form 860 (EIA-860) dataset[5] with the 3-km HRRR model grid. The existing generator topology over the CONUS in 2020 along with existing transmission (down to 115 kV) at 3-km resolution is shown in Figure 1.1.

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[4] https://rapidrefresh.noaa.gov/hrrr/

[5] https://www.eia.gov/electricity/data/eia860/

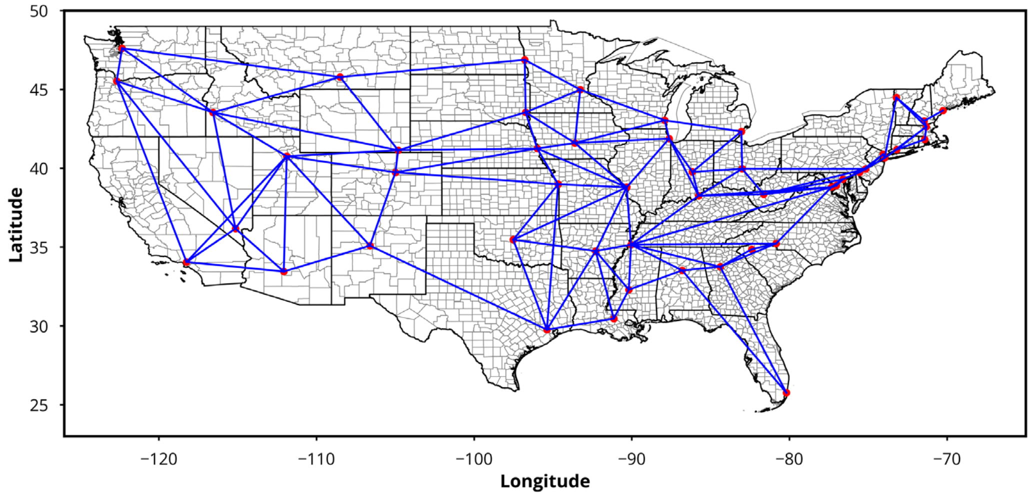

Figure 1.2: State-level aggregated transmission topology for the CONUS.

WIS:dom-P resolves the transmission topology of the modeled grid down to each 69-kV substation resolution. The transmission topology can then be aggregated to create a reduced-form (county- or state- level) as required for each model simulation. Figure 1.2 shows the state-level reduced form transmission topology used in the WIS:dom-P modeling for the current study.

A unique feature of WIS:dom-P is its ability to resolve the utility-scale electricity grid with detailed granularity over large spatial domains. This unique feature has recently been expanded to allow for the model to co-optimize and coordinate the utility grid with the distribution grid. The tractability of such a co-optimization requires parameterization of all the distribution-level grid topology and infrastructure. Therefore, WIS:dom-P disaggregates the DER technologies, but aggregates the distribution lines and other infrastructure as an interface (or "*grid edge*") that electricity must pass across. The model does assign costs and can compute inferred capacities and distances from the solutions, but cannot (with current computation power) resolve explicitly all the infrastructure in a disaggregated manner.

The main components of deriving the utility-distribution (U-D) interface are:

a. Utility-observed peak distribution demand;
b. Utility-observed peak distribution generation;
c. Utility-observed distribution electricity consumption.

The definition of "*Utility-observed*" is the appearance of the metric at 69-kV transmission substation or above. Below the 69-kV, the model is implicitly solving with combinations of DERs, and what remains is exposed to the utility-scale grid at the substation. Figure 1.3 is a schematic of how WIS:dom-P represents the U-D interface and Fig. 1.4 displays an illustration of how the distribution co-optimization results in two distinct concerts playing out: DERs coordinating to reshape the demand exposed to the utility-scale (*load shifting to supply*) and utility-scale generation and transmission coordinating to serve the demand that appears at the 69-kV substation (*supply shifting to load*). Further details of the distribution co-optimization are available in Section 1.9 of the WIS:dom-P technical documentation.

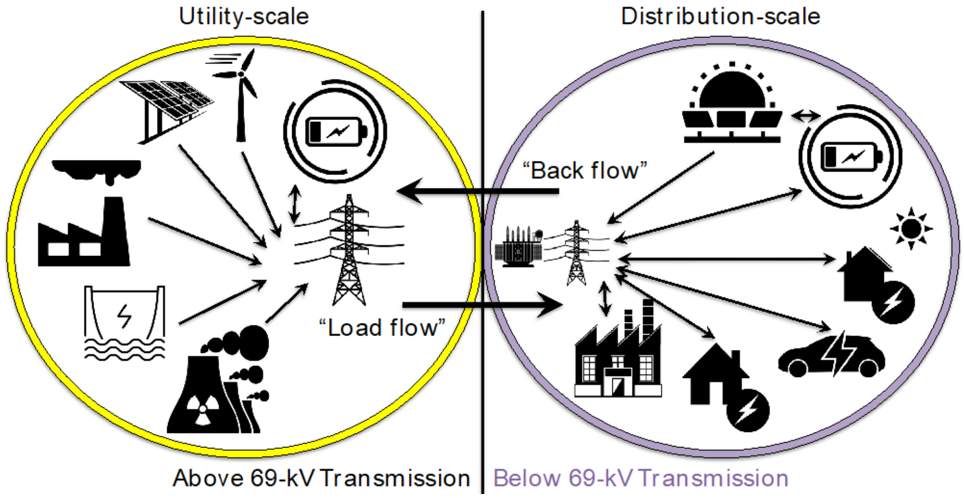

Figure 1.3: A schematic picture of the U-D interface within the WIS:dom-P modeling platform.

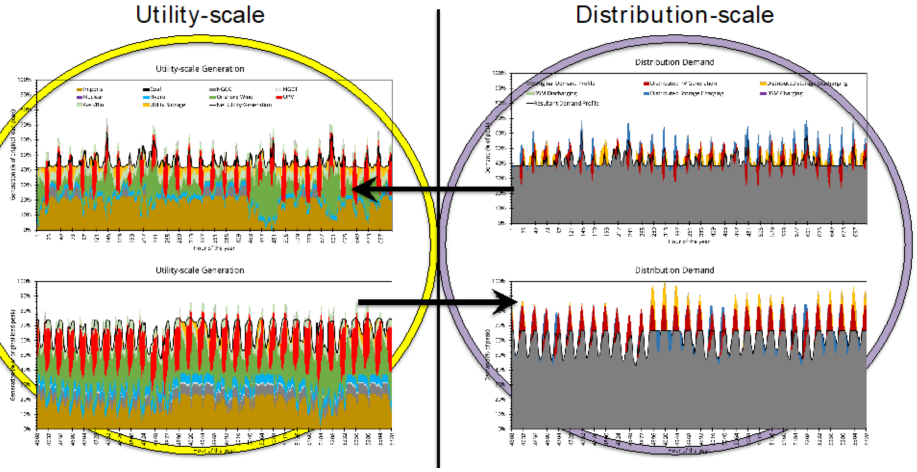

Figure 1.4: Example coordination at the utility- and distribution-scale within the WIS:dom-P model.

2 Modeling Results

2.1 System Costs, Retail Rates & Jobs

The evolution of the total resource cost over the CONUS in the two scenarios modeled is shown in Fig. 2.1. The “Utility-Scale Only” scenario starts with a total resource cost of $371 billion in 2020 and reduces to $313 billion by 2025 as a result of retirement of a significant amount of older fossil fuel generation to stay on the trajectory to reduce electricity sector emissions by 80% by 2030. The total resource costs in the “Utility-Scale Only” scenario increase to $326 billion in 2030 as the US almost doubles its installed wind capacity and almost triples its installed utility-scale photovoltaic (UPV) and utility-scale storage on the grid. After 2030, the costs in “Utility-Scale Only” scenario increase steadily as a result of increasing load due to electrification. By 2050, the total resource costs in the “Utility-Scale Only” scenario reach $488 billion over the CONUS.

In the “Optimized Local Solar & Storage” scenario, the costs steadily reduce from $371 billion in 2020 to $304 billion in 2030 as this scenario not only reduces costs through not only retiring older fossil fuel generation and replacing it with lower cost VRE generation, but also, co-optimizing the distribution grid through strategic deployment of DPV and distributed storage. As a result, the cost increase observed in the “Utility-Scale Only” in 2030 scenario is not observed in the “Optimal Local Solar & Storage” scenario. By 2050, the total resource costs in the “Optimized Local Solar & Storage” scenario reach $465 billion over the CONUS.

Co-optimizing the distribution system and allowing DER such as DPV and distributed storage to be deployed, saves the US $109 billion in total resource costs by 2030. Cumulatively by 2050, the “Optimized Local Solar & Storage” scenario saves over $515 billion in total resource costs for the CONUS over the “Utility-Scale Only” scenario.

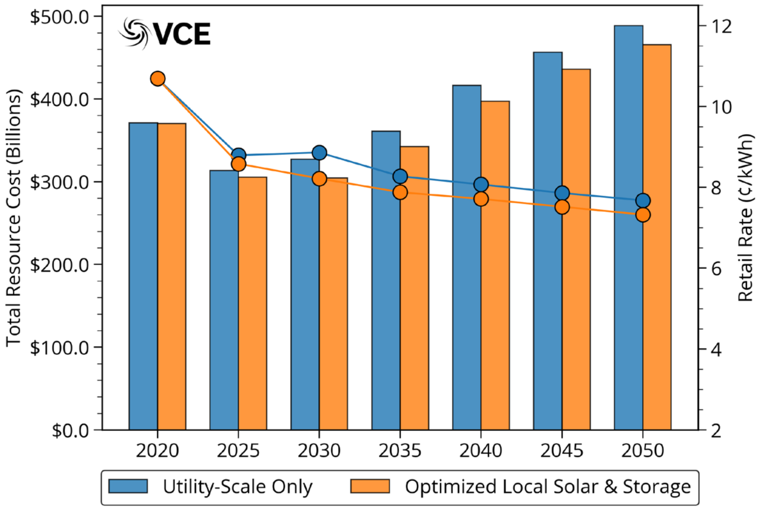

Figure 2.1: Total system cost (bars) and retail rates (solid lines) over the CONUS for the scenarios modeled.

The retail rates in the “Utility-Scale Only” scenario reduce from a CONUS average of 10.7 ¢/kWh in 2020 to 7.67 ¢/kWh in 2050, while in the “Optimized Local Solar & Storage” scenario they reduce to 7.32 ¢/kWh in 2050. The "Utility-Scale Only" scenario shows a slight increase in retail rates between 2025 and 2030 just as the rate of electrification is increasing to meet the economy-wide decarbonization goals, which would result in a higher energy burden for customers as they electrify their energy related activities. In the "Optimized Local Solar & Storage" scenario, retail rates do not increase, mainly from savings in the distribution system, ensuring that customers are able to reduce their energy costs through electrification.

Figure 2.2 shows the difference in annual retail spending in the two scenarios modeled. In both scenarios, retail spending increases from 2020 to 2050 as more energy related activities are electrified which increases spending in the electricity sector while reducing in other sectors such as natural gas and petroleum products. The retail spending in the "Utility-Scale Only" scenario is higher than the "Optimized Local Solar & Storage" scenario in every investment period due to the higher retail rates in the "Utility-Scale Only" scenario. By 2030, the "Optimized Local Solar & Storage" scenario saves customers $120 billion in retail spending over the "Utility-Scale Only" scenario. Cumulatively by 2050, the "Optimized Local Solar & Storage" scenario saves customers $555 billion in retail spending over the "Utility-Scale Only" scenario. That is, all the savings in total resource costs in the "Optimized Local Solar & Storage" scenario are passed on to customers in the form of retail rate savings.

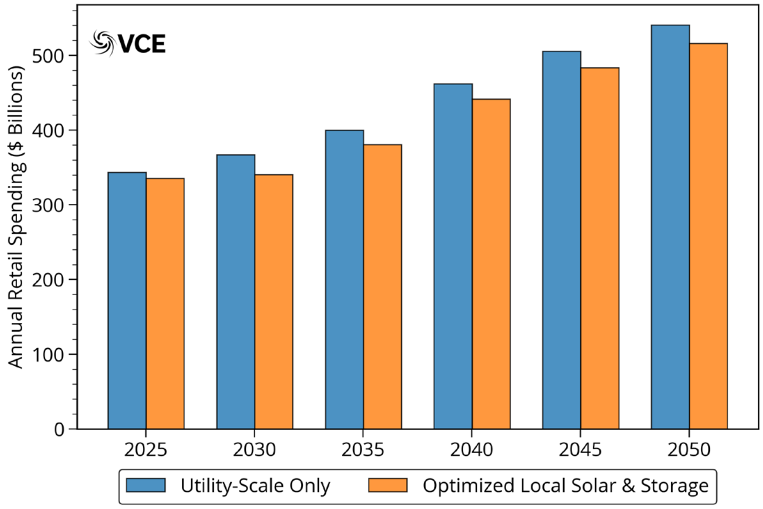

Figure 2.2: Retail spending over the CONUS in the two scenarios modeled.

The electrification of the economy-wide energy related activities uses energy efficiency measures as well fuel-switching non-electric energy appliances to high efficiency electric appliances such as heat pumps. By 2050, 95% of space and water heating is provided by heat pumps and heat pump water heaters (with 36% penetration by 2030), 90% of vehicles (with 39% penetration by 2030) are electrified with some heavy transport vehicles switch to using hydrogen as fuel and 85% of industrial processes (5% by 2030) are electrified with some high heat processes using hydrogen as fuel. The average change in energy burden for combined residential and commercial customers over the modeling period as a result of electrification is shown in Fig. 2.3. In the "Optimized Local Solar & Storage" scenario, average annual energy burden is seen to reduce by almost 27% from the "Reference"[6] case which assumes no electrification beyond what exists in 2020. The spending in traditional electricity which includes air conditioning, lighting, cooking etc. is reduced by approximately $700 per year, while heating and transportation costs are almost halved compared to the "Reference" case. Therefore, electrification of economy-wide energy related activities alone brings significant cost savings to customers.

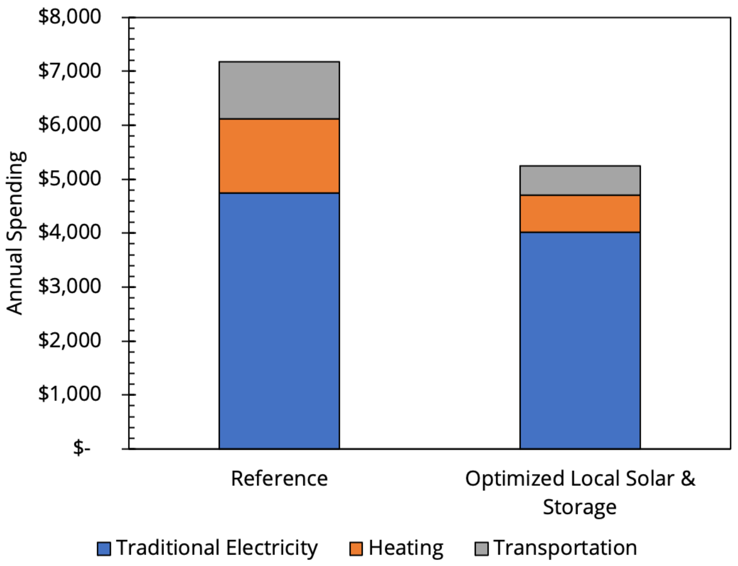

Figure 2.3: Average annual energy burden over the modeling period on combined residential and commercial retail customers as a result of electrification compared to a "Reference" scenario of no electrification.

The contributions to the cost of energy from the various sources of generation and energy infrastructure is shown in Fig. 2.4. As seen in Fig. 2.4, almost half the cost of energy in 2020 is from fossil fuel generation sources. As these fossil fuel generators (especially coal) is retired, the cost of energy reduces from approximately 9.75 ¢/kWh in 2020 to 6.9 ¢/kWh in 2050 in the "Utility-Scale Only" scenario. In the "Optimized Local Solar & Storage" scenario, the cost of energy in 2050 is 6.57 ¢/kWh. Comparing the "Utility-Scale Only" and "Optimized Local Solar & Storage" scenarios, it is seen that the contributions from the various industries is approximately the same, except that the "Optimized Local Solar & Storage" scenario has lower costs in the distribution system.

In both scenarios, the model builds a significant amount of transmission. In spite of the large transmission buildout the contribution of transmission to cost of energy is less than 0.1 ¢/kWh over the whole modeling period. In 2050, the distribution system is the largest contributor to costs as significant investments in the distribution system need to be made as a result of economy-wide electrification. Therefore, co-optimizing the distribution system with the utility-scale generation is key to keeping costs down and ensuring electrification not only reduces emissions, but also saves customers money.

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[6] The "Reference" scenario assumes similar electrification levels as 2020 with retail rates reducing by 10% by 2050. This scenario uses EIA projections for price of gasoline, natural gas, coal and oil.

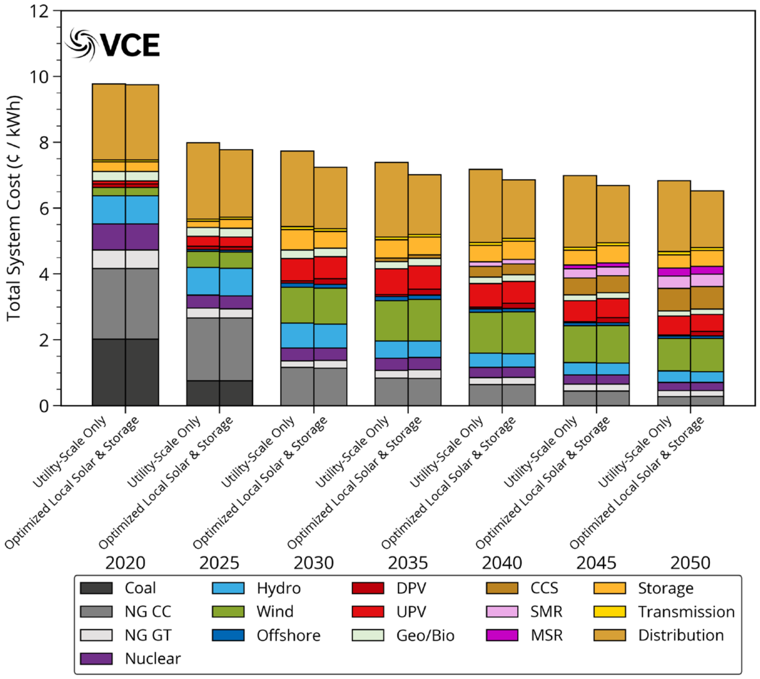

Figure 2.4: Contribution to total system cost per kWh load from each energy system sector in the scenarios modeled for the CONUS.

The total direct and indirect full-time equivalent jobs supported by the electricity sector broken out by industry is shown in Fig. 2.5. Both scenarios result in significant increase in jobs supported compared to 2020 levels which show the economic benefits of electrifying and decarbonizing the economy. By 2030, the “Optimized Local Solar & Storage” scenario creates 304,142 additional jobs over the “Utility-Scale Only” scenario. The total jobs in the electricity sector increase from a little over 2 million in 2020 to approximately 8.4 million in 2050 in the “Utility-Scale Only” scenario, while in the “Optimized Local Solar & Storage” scenario, the total jobs supported by the electricity sector in 2050 is approximately 9.25 million. The largest jobs growth occurs in the solar industry. In the “Optimized Local Solar & Storage” scenario, the additional deployment of distributed solar supports over 860,000 jobs in 2030 and over 1.3 million jobs in 2050 which helps this scenario edge out the “Utility-Scale Only” scenario in job creation.

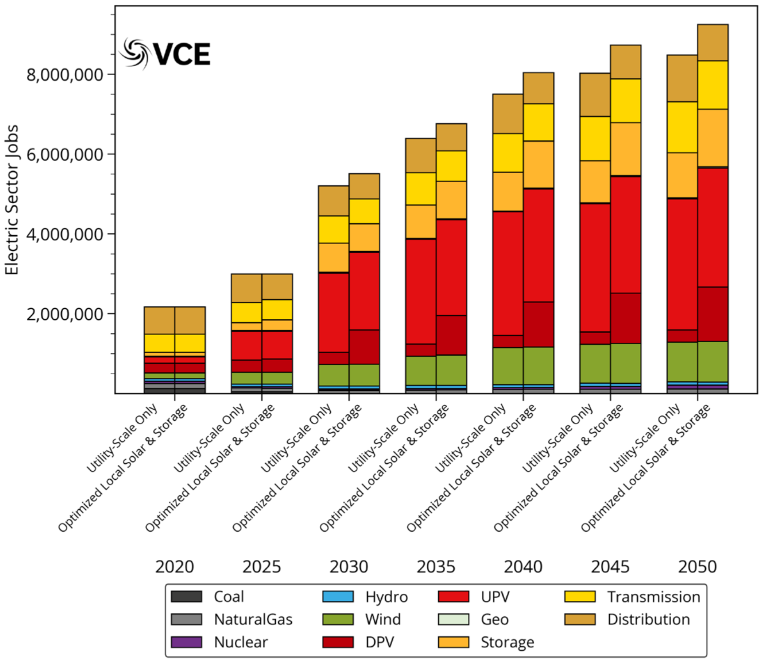

Figure 2.5: Full-time equivalent jobs created in the electricity sector by industry in the scenarios modeled.

2.2 Installed Capacity, Generation & Transmission

The changes to the installed capacities on the grid and the resultant generation in the "Optimized Local Solar & Storage" scenario is shown in Fig 2.6. The grid changes from being dominated by fossil fuel generation in 2020 to dominated by clean energy sources by 2030. In 2020, almost 60% of the generation comes from fossil fuel generation. By 2030, 81% of the electricity generated comes from carbon free sources, of which 60% is from VREs. The share of clean electricity continues to increase to 97.25% by 2050 of which 62% comes from VRE generation.

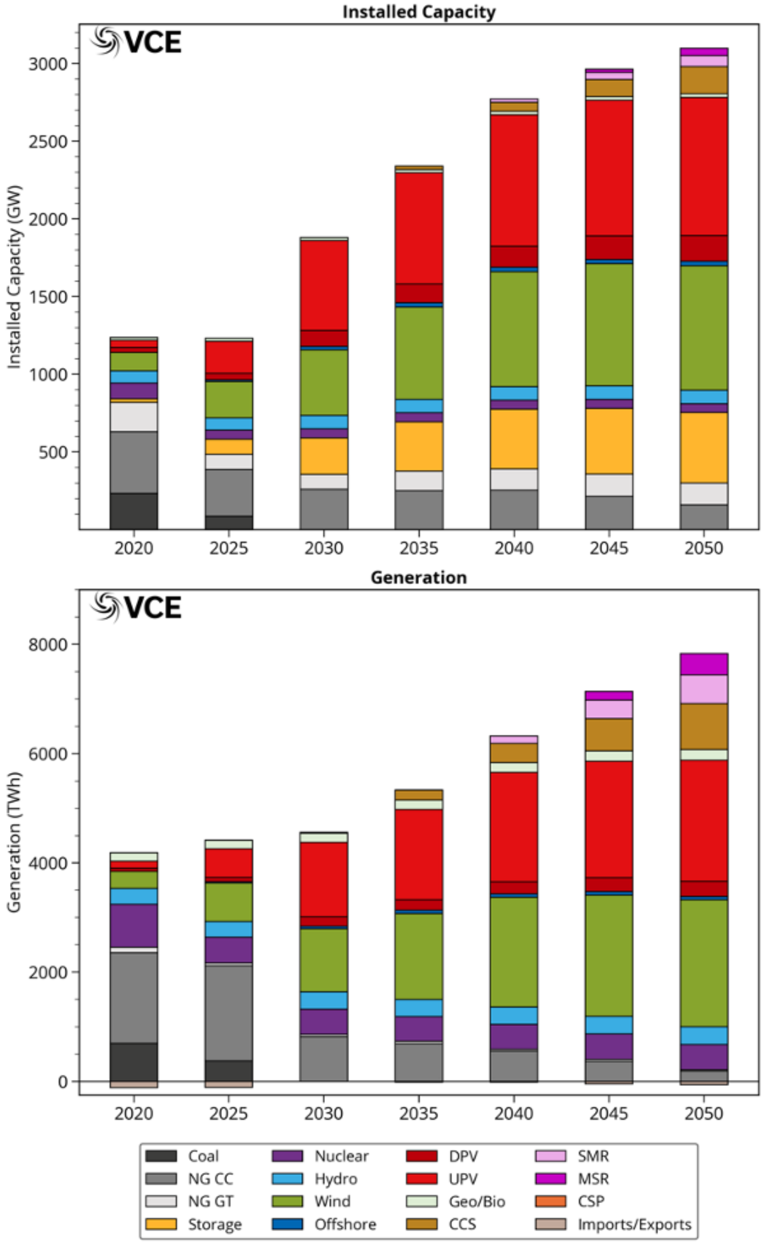

Figure 2.6: WIS:dom-P installed capacities (top) and generation (bottom) for the "Optimized Local Solar & Storage" scenario.

In order to meet the decarbonization targets given the assumption of late entry of the novel technologies (*CCS*, *MSR* and *SMR*), the VREs must be deployed at substantially higher rates compared to historical values. Figure 2.7 shows the annual deployment rates of wind, solar and storage in the various investment periods. Solar capacity (including both utility and distributed) is deployed at the rate of approximately 36 GW/year between 2020 and 2025, which is three times the rates of solar deployment over the last six years (2014 – 2020). The rate of solar deployment is seen to almost triple again between 2025 and 2030 to approximately 87 GW/year.

The deployment rate of wind between 2020 and 2025 is a little over 20 GW/year which is twice the average deployment rate over the last six years (2014 – 2020). The average deployment rate of wind doubles again to almost 38 GW/year between 2025 and 2030. Storage deployments (including utility and distributed storage) see the largest increase compared to historical trends. The "Optimized Local Solar & Storage" scenario deploys storage at an average rate of 14 GW/year which is substantially higher than the 150 MW/year average storage deployment over the last five years (2015 – 2020). However, storage additions have grown significantly in 2021[7] which show there is potential to ramp up deployment given the right incentives. Storage deployments peak at about 27 GW/year between 2025 and 2030. This shows that achieving a carbon free economy will need substantial investments in VRE production and supply chains which will bring about significant economic benefits from job creation in those sectors.

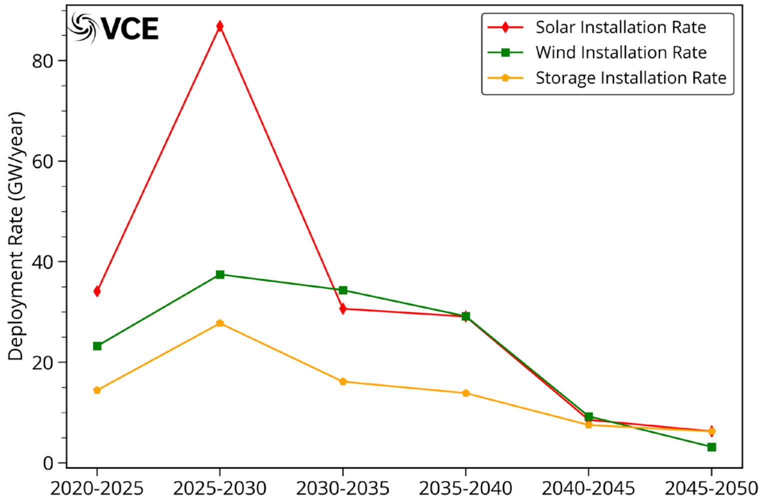

Figure 2.7: Deployment rates for wind, solar and storage in the "Optimized Local Solar & Storage" scenario over the investment periods.

The storage deployments broken out by utility-scale and distribution-scale are shown in Fig. 2.8. From 2020 to 2030, the majority of new storage deployed is on the distribution grid. By 2030, there is 234 GW of storage installed on the grid in the "Optimized Local Solar & Storage" scenario, increasing the deployed storage ten-fold over the 2020 levels. The model installs more distributed storage initially to more effectively utilize the existing DPV and reduce distribution costs as the load increases due to electrification. After 2030, utility-

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[7] https://www.energy-storage.news/eia-us-battery-storage-installed-capacity-hit-1650mw-by-end-of-2020/

scale storage deployments speed up to more effectively utilize the VRE generation installed on the utility grid and reduce curtailment.

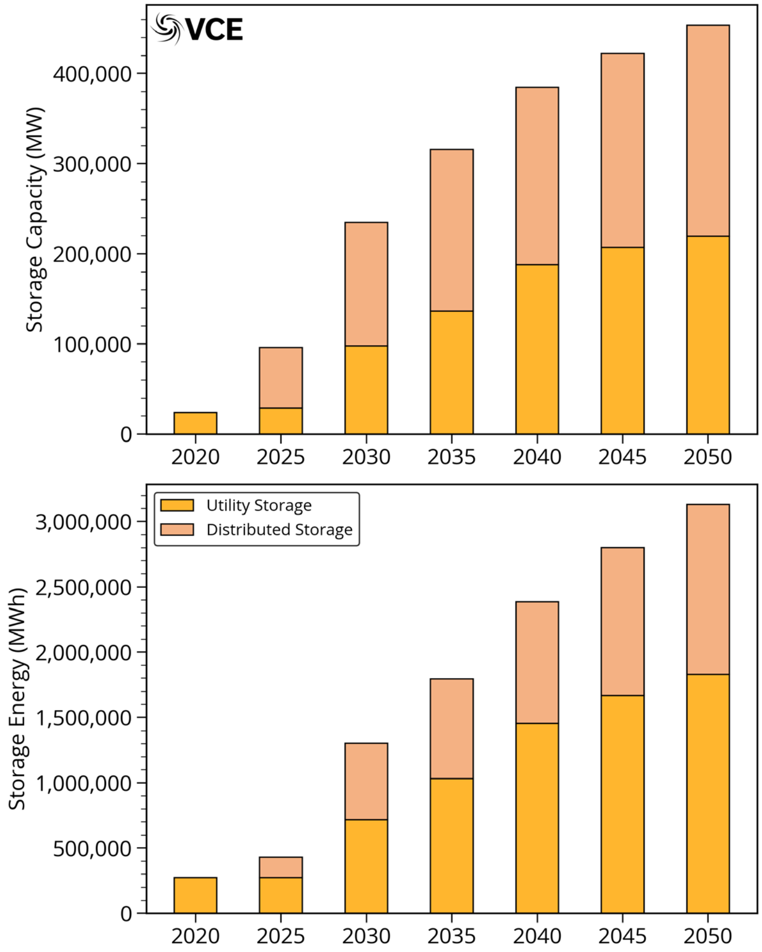

Figure 2.8: Utility storage and distributed storage installed in each investment period for the scenarios modeled.

In addition to storage, transmission is expanded in the "Optimized Local Solar & Storage" scenario to more effectively utilize the VRE generation installed and ensure that the VRE are optimally sited. Figure 2.9 shows the inter-state transmission built by each state in the "Optimized Local Solar & Storage" scenario. It is seen that every state with the exception of Montana and Oregon significantly increase upon their existing transmission capacity. The largest new transmission buildout is seen in the northeast US, while the WECC region which already has significant transmission built, shows lower new transmission buildout compared to the northeast US.

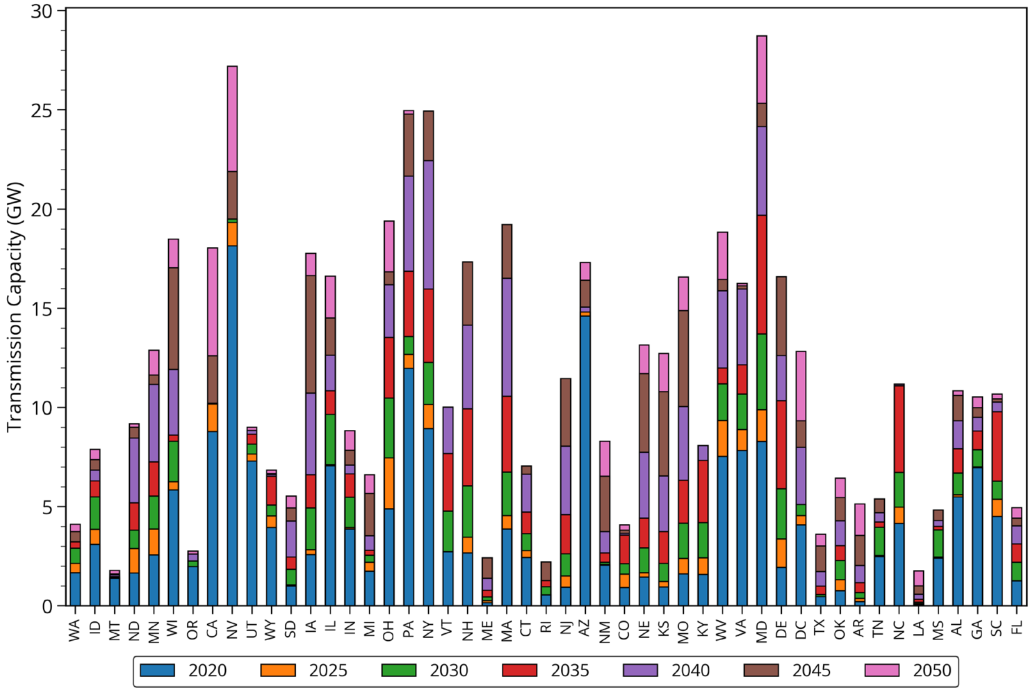

Figure 2.9: Bulk transmission built by each state over the investment periods in the "Optimized Local Solar & Storage" scenario.

2.3 CO₂ Emissions & Pollutants

The annual change in economy-wide energy related activities carbon dioxide emissions in the "Optimized Local Solar & Storage" scenario over the modeling period is shown in Fig. 2.10. The carbon dioxide emissions are seen to reduce faster initially from 2020 to 2030 as a result of the 80% emission reduction target of the electricity sector combined with the 50% economy-wide emission reduction target. After 2030, emissions continue to decline reaching 74% reduction by 2040 and 95% reduction by 2050.

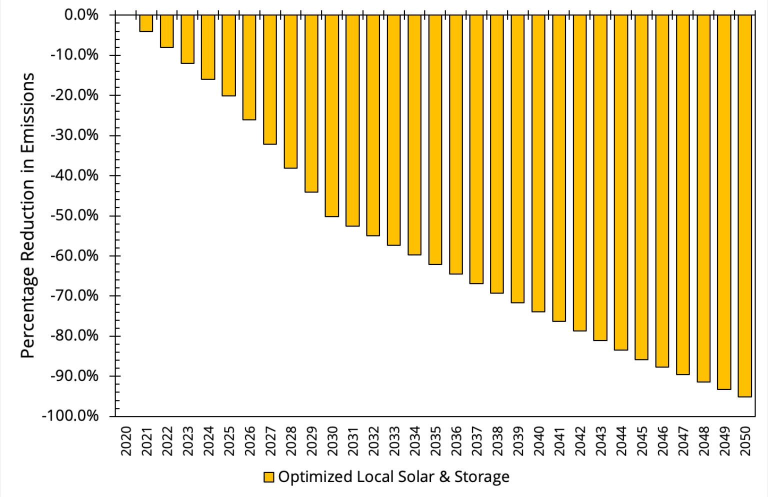

Figure 2.10: Annual change in economy-wide carbon dioxide emissions.

Figure 2.11 shows the cumulative economy-wide energy related carbon dioxide emissions over the modeling period. As a result of electrification alone, the US saves a cumulative 50.14 billion metric tons of carbon dioxide emissions by 2050. The decarbonization of the electricity sector saves an additional 39.16 billion metric tons of carbon emissions. Therefore, the total carbon emissions savings from the "Optimized Local Solar & Storage" scenario are 89.3 billion metric tons by 2050. This reduction in carbon emissions is equivalent to 2.5 years of current global carbon dioxide emissions.

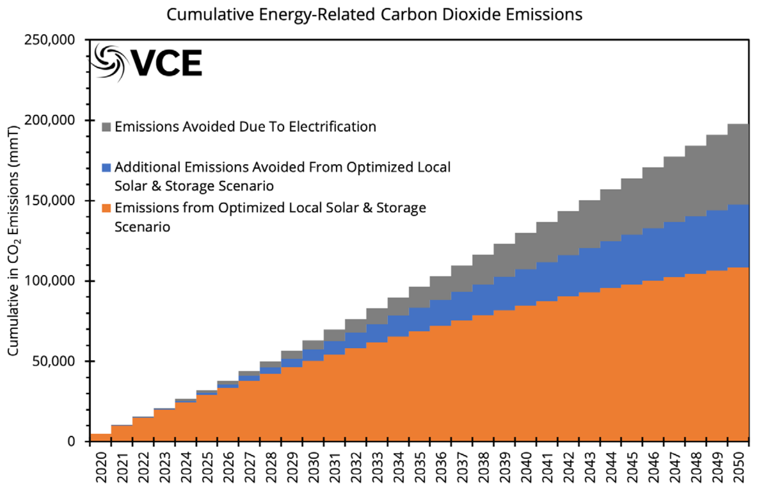

Figure 2.11: Cumulative electric sector emissions in the scenarios modeled.

The change in emissions of criteria air pollutants from the electricity sector tracked by WIS:dom-P are shown in Fig. 2.12. Emissions of all criteria air pollutants see steep reductions between 2020 and 2030 as the electricity sector decarbonizes by 80%. Emissions of SO_2, PM10, PM2.5 are completely eliminated by 2030 as all the coal generation is retired. Only small amounts of NO_x, VOC and CH_4 emissions remain as some of the natural gas generation remains on the grid.

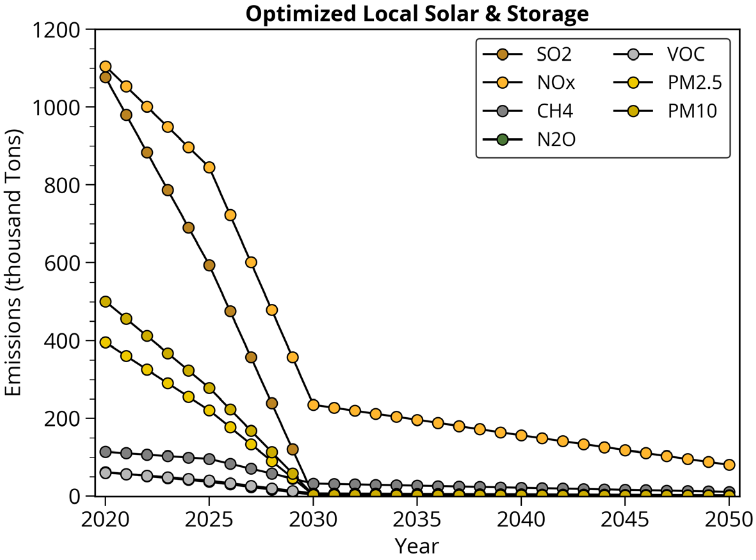

Figure 2.12: Emissions from other criteria pollutants tracked by WIS:dom-P.

These reductions in carbon dioxide emissions are achieved while reducing the electricity retail rates and creating 7 million jobs in the electricity sector which will result in significant positive economic outcomes. In addition, the reductions in criteria air pollutants improves local air quality and health outcomes for populations that live in the vicinity of fossil fuel generators. The results from this modeling show that the US can make significant contributions to reducing global carbon emissions and provide leadership in building a decarbonized economy which can bring improved health and economic outcomes.