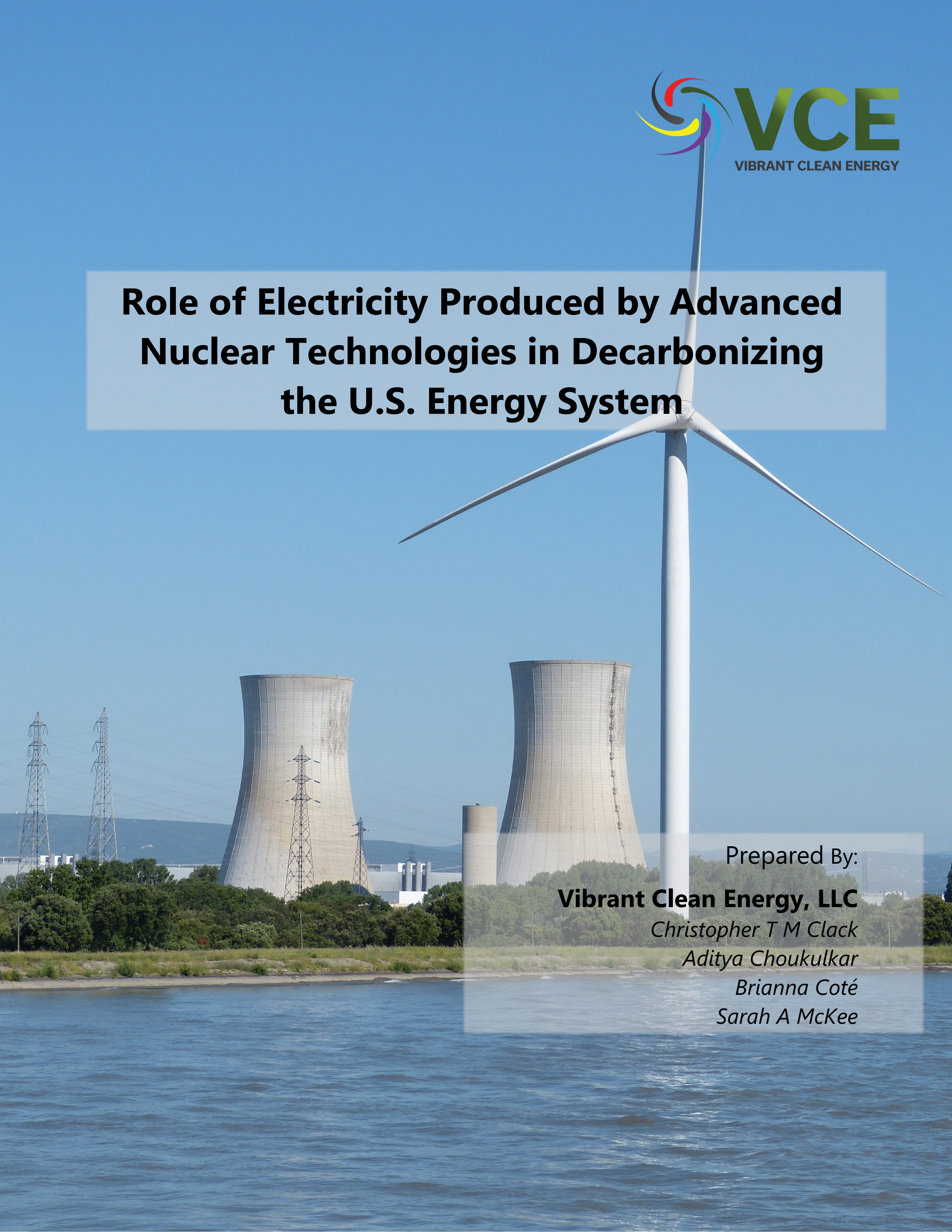

VIBRANT CLEAN ENERGY

Role of Electricity Produced by Advanced Nuclear Technologies in Decarbonizing the U.S. Energy System

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1 Summary

The present study, commissioned by the Nuclear Energy Institute, investigates the role advanced nuclear technologies can play in providing clean dispatchable generation in an electrified and decarbonized energy system. This study assumes the contiguous United States (CONUS) undergoes economy-wide electrification following the "Medium Electrification" scenario outlined in the National Renewable Energy Laboratory's (NREL) Electrification Futures Study[1] while the electricity sector decarbonizes by at least 95% by 2050. While advanced nuclear can play other roles in support of economy-wide decarbonization (e.g., hydrogen production, industrial heat, etc.), this study focuses on the role of advanced nuclear in generating carbon-free electricity as part of greater electrification. The various advanced nuclear technologies that are undergoing proof-of-concept and demonstration are modeled as one blended advanced nuclear technology with two first-of-a-kind (FOAK) costs for each of the two scenarios modeled and a 5% learning rate. Other technologies use NREL Annual Technology Baseline (ATB) 2021 "moderate" cost projections for capital, fixed and variable O&M costs. The forecasts for fuel costs come from Annual Energy Outlook (AEO) 2022 High Oil and Gas Supply scenario[2].

Two scenarios are modeled using the Vibrant Clean Energy (VCE®) flagship capacity expansion and production cost modeling suite known as Weather Informed energy Systems: for design, operations and markets – Planning version (WIS:dom®-P) to test the influence of cost and supply chain constraints on deployment of advanced nuclear and the impact they have on the eventual generation mix. WIS:dom-P is one of the first capacity expansion and production cost modeling suite to feature endogenous learning for technologies deployed by the model. The two scenarios modeled in this study are:

(1) **Representative first-of-its-kind (FOAK) capital cost for advanced nuclear and no deployment constraints ("Nominal" scenario):** In this scenario, the CONUS undergo economy-wide electrification and the electricity sector is required to decarbonize by 95% by 2050. Advanced nuclear is available for the model to deploy starting 2030 with demonstration projects coming online in 2028 and 2029. A representative FOAK capital cost of $3,800/kW is assumed for the advanced nuclear technologies with a learning rate of 5%. It is assumed that the supply chain along with availability of qualified workforce ramp up quickly in response to demand along with minimal delays due to licensing from the Nuclear Regulatory Commission (NRC). It is ensured that the model is only constrained in terms of economics when deploying advanced nuclear generators.

(2) **Higher FOAK capital cost for advanced nuclear with constraints in advanced nuclear deployment ("Constrained" scenario):** This scenario investigates the impact of constraints such as delays in procuring NRC licenses and permits, slower supply chain ramp up, and limited workforce availability for advanced nuclear on the eventual generation mix installed on the grid. These constraints result in a roughly three-year lag in the response of supply to demand within the model in addition to a slower growth of the supply availability. Similar to the previous scenario, the CONUS

[1] https://www.nrel.gov/docs/fy18osti/71500.pdf
[2] https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2022&region=1-0&cases=ref2022~highogs&start=2022&end=2050&f=A&chartindexed=2&sourcekey=0

undergoes economy-wide electrification and the electricity sector is required to decarbonize by 95% by 2050. Advanced nuclear is available for the model to deploy starting 2030 with demonstration projects coming online in 2028 and 2029. A higher FOAK capital cost of $5,500/kW is assumed for advanced nuclear with a learning rate of 5%.

Results show that in the "Nominal" scenario, the model deploys 336 GW of advanced nuclear to the grid by 2050, while in the "Constrained" scenario, the model only deploys 59.7 GW of advanced nuclear by 2050. It is found that the significantly lower deployment in the "Constrained" scenario is due to the inability of the model to deploy sufficient advanced nuclear between 2030 and 2035 where the deployment of advanced nuclear is held back due to supply constraints, increased regulatory hurdles and unavailability of trained workforce. After 2035, the "Constrained" scenario begins to deploy more advanced nuclear. However, due to the investments already made in deploying renewables, storage and transmission, the model is locked into a path of a variable renewable energy dominated grid resulting in significantly lower deployment of advanced nuclear.

Due to the limited capacity of clean dispatchable generation deployed in the "Constrained" scenario, the model deploys twice the utility-scale solar and 70% more wind compared with the "Nominal" scenario. Storage is the main source of flexibility in the "Constrained" scenario, needed to maintain reliability on the grid and the model deploys twice the storage deployed in the "Nominal" scenario. As a result, the "Constrained" scenario results in $346 billion cumulative additional spending in total system costs by 2050 over the "Nominal" scenario. This additional spending results in higher retail rates in the "Constrained" scenario starting 2030, which results in $449 billion in cumulative additional retail spending by customers as the economy is undergoing electrification. These results show that timely availability and deployment of clean dispatchable generation can result in significant savings in terms of system costs and retail spending for customers.

In both scenarios modeled, the emissions of carbon dioxide are significantly reduced due to electrification of economy-wide activities along with 95% decarbonization of the electricity sector. Annual economy-wide emissions reduce by 61% by 2050 resulting in a cumulative reduction of 55,566 million metric tons (mmT) of carbon dioxide by 2050. This significant reduction in carbon dioxide emissions is accompanied by almost a complete elimination of criteria air pollutants due to full retirement of coal generation and drastic reduction in natural gas generation. These reductions in emissions of carbon dioxide and criterial pollutants come along with significant job creation and approximately 26% reduction in retail rates compared to 2020 levels. The "Nominal" scenario replaces most of the job losses in the coal and gas sector with jobs in the nuclear industry. These jobs are also created in the same communities where the original coal and gas generation was located as the decommissioned sites are converted to advanced nuclear facilities. Therefore, a timely deployment of advanced nuclear generation can preserve jobs in communities most vulnerable in the energy transition.

Overall, this study shows that nuclear generation can play an important role in decarbonizing the electricity sector by providing over 40% of total generation in 2050, requiring more than 300 GW of new nuclear. However, this study also provides several additional insights:

- Deployment pace is a key factor in influencing the ultimate role that advanced nuclear will play. Electricity sector costs could be significantly higher if clean dispatchable generation like advanced nuclear is not available at scale.

- For advanced nuclear to become a significant part of the energy mix, it needs to be deployed on time with regulators, permitting and supply chains responding quickly.

- Delays in deployment of advanced nuclear will have outsized impact on share of generation. Ramping up deployments in the mid-2030s will be key.

- The capital cost of advanced nuclear plays a smaller role, compared with deployment rate, in amount of advanced nuclear deployed to the grid.

2 Study Description

The United States will have to undergo economy-wide decarbonization in order to do its part in halting the emission of greenhouse gases and avert the more harmful effects of climate change. An important aspect of a decarbonized electricity grid is the role of clean dispatchable generation and how the electrical grid would evolve depending on when they become commercially viable and how fast they can be deployed. The present study, commissioned by the Nuclear Energy Institute, investigates the role traditional and advanced nuclear generation technologies can play in decarbonizing the electricity sector. This study models two scenarios to test the impact of capital costs and deployment constraints such as supply chain ramp up, ramp up of qualified workforce, efficiency of regulatory processes such as licensing from the Nuclear Regulatory Commission (NRC) which can have significant impact on how fast advanced nuclear technologies can be deployed and their contribution to the eventual generation mix. In this study, the US economy is assumed to undergo economy-wide electrification along the lines of the "Medium Electrification" scenario outlined in the National Renewable Energy Laboratory's Electrification Futures Study[3].

The modeling in this study was performed through 2050 using the Vibrant Clean Energy (VCE®) Weather Informed energy Systems: for design, operations and markets – Planning version (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. For fuel costs, projections from the Annual Energy Outlook (AEO) 2022 High Oil and Gas supply scenario (HRT) are used.[4] This study also modeled endogenous learning for capital costs of advanced nuclear assuming a learning rate of 5%. WIS:dom-P is the first capacity expansion and planning model to include capability of endogenous learning for technology costs based on actual deployments made by the model. More details on the endogenous learning are discussed in Section 2.2.

Two scenarios were modeled in this study to evaluate the role of advanced nuclear technologies. The scenarios modeled in the present study are as follows:

(1) **Representative first-of-its-kind (FOAK) capital cost for advanced nuclear and no deployment constraints ("Nominal" scenario):** In this scenario, the contiguous United States (CONUS) undergo economy-wide electrification following the "Medium Electrification" scenario from NREL's Electrification Futures study. The electricity sector is required to decarbonize by 95% by 2050. Advanced nuclear is available for the model to deploy starting 2030 with demonstration projects coming online in 2028 and 2029. A representative FOAK capital cost of $3,800/kW is assumed for the advanced nuclear technologies with a learning rate of 5%. It is assumed that the supply chain along with availability of qualified workforce ramps up quickly in response to demand along with minimal delays due to regulatory processes such as siting and licensing by the NRC.

[3] https://www.nrel.gov/docs/fy18osti/71500.pdf
[4] https://www.eia.gov/outlooks/aeo/data/browser/#/?id=3-AEO2022&region=1-0&cases=ref2022~highogs&start=2022&end=2050&f=A&chartindexed=2&sourcekey=0

The model is only constrained in terms of economics of advanced nuclear versus other technologies and never in terms of logistics of deploying advanced nuclear generators.

(2) **Higher FOAK capital cost for advanced nuclear with significant constraints in advanced nuclear deployment ("Constrained" scenario):** This scenario investigates the impact of logistical constraints such as a supply chain that is slower to ramp up, limited availability of qualified workforce and delays in regulatory processes for advanced nuclear on the eventual generation mix installed on the grid. These constraints result in a roughly three-year lag in the response of supply to demand within the model in addition to a slower growth of the supply availability. Similar to the previous scenario, the CONUS undergoes economy-wide electrification following the "Medium Electrification" scenario from NREL's Electrification Futures study. The electricity sector is required to decarbonize by 95% by 2050. Advanced nuclear is available for the model to deploy starting 2030 with demonstration projects coming online in 2028 and 2029. A higher FOAK capital cost of $5,500/kW is assumed for advanced nuclear with a learning rate of 5%.

In both of the scenarios modeled, power plants with carbon capture and sequestration (CCS) are not allowed to be deployed by the model. The reason for this is that the costs associated with permanent carbon dioxide storage, the space requirements and accessibility across the CONUS are currently not determined with high degree of confidence. In addition, the capture efficiencies of CCS systems currently range between 60%-70% and are much less than the 95% decarbonization goal. In addition, adding CCS to power plants reduces power output and increases fuel consumption which can have significant impact on costs especially during times of high fuel price volatility which makes the results sensitive to fuel cost projections. Given the above reasons, which can cause wide fluctuations in buildout depending on the assumptions made, and in order to focus the analysis on the impact of clean dispatchable generation on the grid buildout, power plants with CCS were not included.

The scenarios are initialized and calibrated with 2020 generator, generation, and transmission topology datasets. The model then determines a pathway from 2021 through 2050 with results outputted every year. 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.[5]

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

2.1 WIS:dom®-P Model Setup

To investigate the two scenarios described in the previous section, WIS:dom-P modeled the CONUS with its existing generator topology, transmission, and weather inputs obtained from National Oceanic and Atmospheric Administration (NOAA) High Resolution Rapid Refresh (HRRR) model[6] at 3-km horizontal resolution and 5-minute time resolution. The initialized generator dataset is created by aligning the Energy Information Administration Form 860 (EIA-860) dataset[7] with the 3-km HRRR model grid. The existing generator topology over the CONUS in 2020 along with existing transmission at 3-km resolution is shown in Figure 2.1.

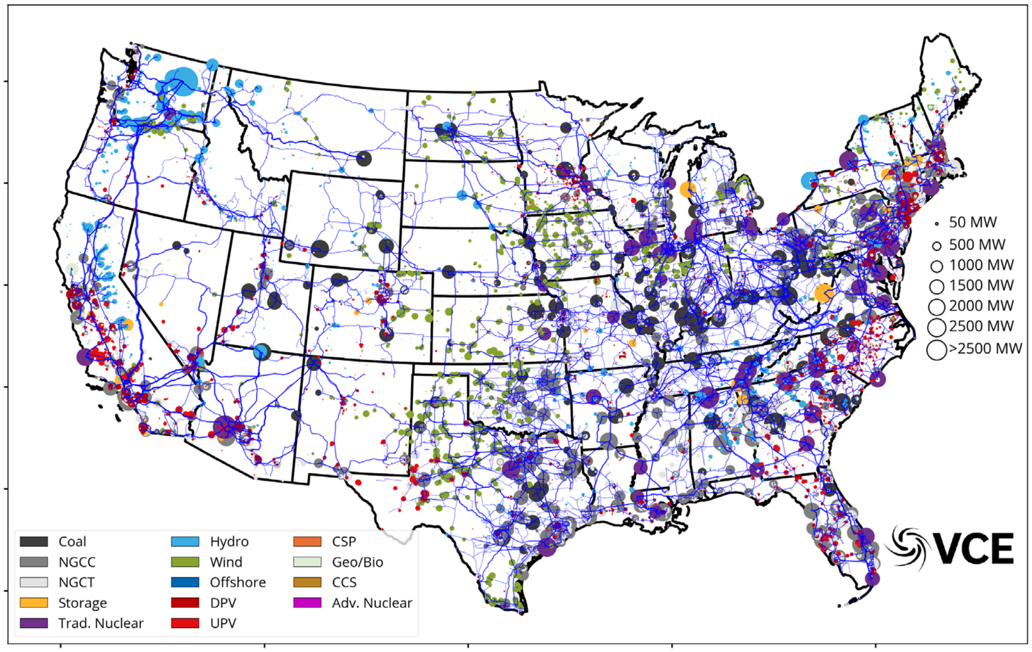


Figure 2.1: WIS:dom-P model domain and existing generators with transmission in 2020.

More details on creation of the generator dataset can be found in Section 4.1. As seen from Fig. 2.1, the current state of the electric grid has coal generation deployed along the Ohio River and various inter-mountain west states. Natural gas generation is present in most states making up for retired coal generation. Nuclear generation has larger deployments the eastern half of the CONUS. Wind is generally observed along the central Plains and Upper Midwest, while solar is prominent in the Desert Southwest and the West Coast, in particular, California. Minnesota and many Atlantic states are also home to several solar plants as well.

A generic advanced nuclear technology was modeled in this study. Two FOAK capital costs were modeled for each of the scenario with the "Nominal" scenario having a lower FOAK cost of $3,800/kW and the "Constrained" scenario having a higher FOAK capital cost of $5,500/kW. Both scenarios were modeled with a learning rate of 5%. The blended advanced nuclear technology modeled in the two scenarios used average characteristics of Small

[6] https://rapidrefresh.noaa.gov/hrrr/
[7] https://www.eia.gov/electricity/data/eia860/

Modular Reactors (SMR) and Molten Salt Reactor (MSR) technologies. Table 2.1 shows the attributes of the blended advanced nuclear technology used in the modeling.

FOAK Cost - Nominal Scenario ($/kw)	$3,800
FOAK Cost - Constrained Scenario ($/kw)	$5,500
Fixed Cost ($/kw-yr)	$84.8
Variable Cost ($/MWh)	$0
New Build Heat Rate (MMBtu/MWh)	9.025
Ramp Rate (% Capacity/hour)	54%
Minimum Generation (% Capacity)	0%
Maximum Generation (% Capacity)	95%

Table 2.1: The general inputs applied to the advanced nuclear technology.

Figure 2.2 shows the fuel costs used for the advanced nuclear technology. The advanced nuclear fuel costs are assumed to start decreasing after 2030 as initial production hurdles are overcome and demand increases allowing for greater economies of scale. For comparison, the fuel costs for traditional nuclear fuel from the AEO HRT 2022 costs are also plotted.

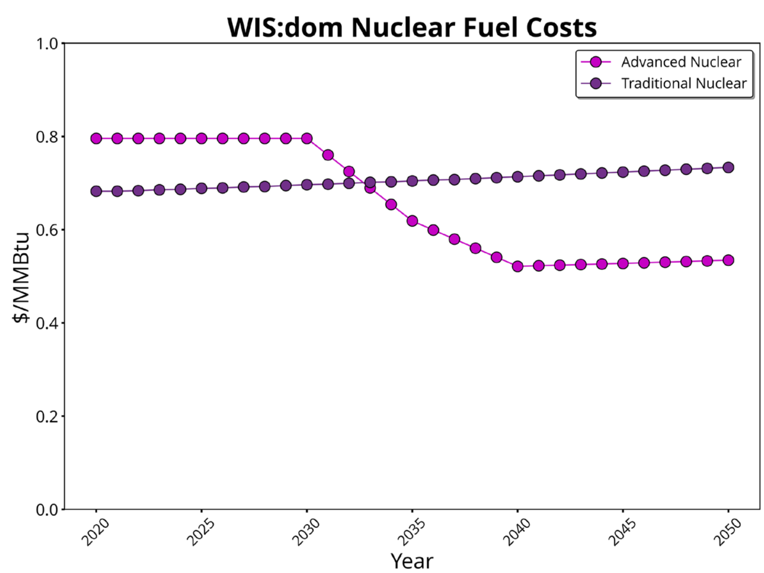


Figure 2.2: The fuel costs applied to traditional and advanced nuclear technologies modeled.

2.1.1 Load Dataset

The load forecasts used in this study are from NREL's Electrification Futures Study and follow the "Medium Electrification" scenario. Figure 2.3 shows the breakout of these demands into five main components: (1) Space heating demand, (2) water heating demand, (3) transportation demand, (4) conventional demand (including industrial demands, residential cooling demands, lighting demands, cooking, etc.) and (5) hydrogen demand.

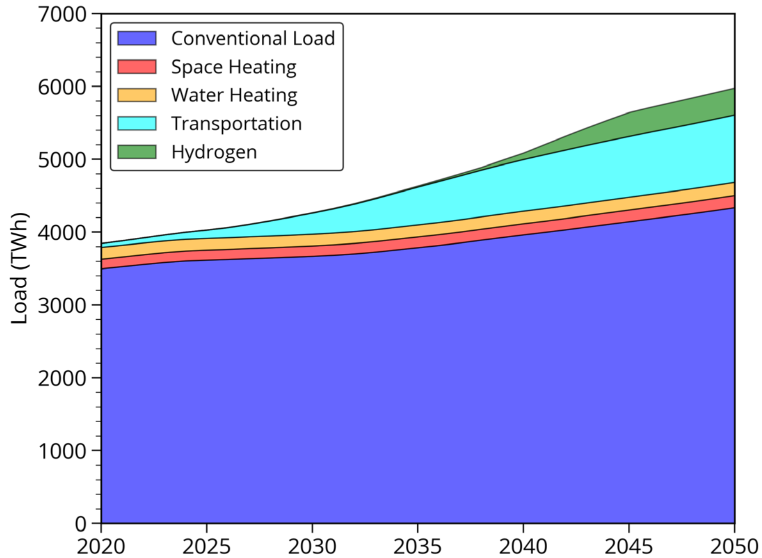


Figure 2.3: Conventional, Space Heating, Water Heating, Transport and Hydrogen annual demands in TWh used the scenarios modeled.

The conventional load increases from approximately 3,500 TWh in 2020 to 4,334 TWh in 2050 driven by electrification of cooking, drying and some process heat. The space and water heating demands stay fairly constant from 2020 to 2050 as any addition to the load from electrification of furnaces or gas-fired water heaters is offset by increased efficiencies achieved from switching some of the heating to air-source heat pumps, ground-source heat pumps and heat pump water heaters. The transportation load increases mainly from electrification of light-duty cars and trucks, some medium-duty vehicles and transit buses. Some of the remaining processes that use natural gas are converted to using green hydrogen which contributes 368 TWh to the annual load in 2050.

2.2 Endogenous Learning

WIS:dom-P is the first capacity expansion and planning model to feature endogenous learning for technology costs based on actual deployments made by the model. In this study, endogenous learning is only applied to the advanced nuclear technology although WIS:dom-P is able to apply endogenous learning to all technologies modeled.

By applying endogenous learning only to the advanced nuclear technology, it is possible to characterize the impact of FOAK capital cost of advanced nuclear and supply chain constraints on expected deployment rates and the role advanced nuclear might play in a decarbonized electric grid. The endogenous learning is modeled in WIS:dom-P as shown in Equations (1) and (2).

$$learnedCapCost(t) = FOAK_{CapCost} * \left(\frac{CumInstalledCapacity}{RefCapacity}\right)^{\beta} \quad (1)$$

$$\text{where } \beta = \log_2(1 - LR) \quad (2)$$

where, t *is the investment period currently being solved over*

$FOAK_{CapCost}$ is the first-of-a-kind capital cost

CumInstalledCapacity is the cumulative capacity installed

β is the learning coefficient

LR is the learning rate, 5% in this study

RefCapacity is minimum capacity needed to start learning (set at 720 MW for this study) and capacity additions needed for learning to progress.

Figure 2.4 shows the learning curves based on Equations (1) and (2) using reference capacities of 720 MW and 150 MW. As seen from Fig. 2.3, in addition to the learning rate, the reference capacity not only controls when the learning begins, but also the capacity that needs to be doubled to reduce the cost by the learning rate. In this study, we used a conservative reference capacity of 720 MW to control the advancement of learning. As shown in Fig. 2.3, a smaller reference capacity can result in faster initial learning for the same learning rate which can significantly impact economics of the technology in the modeling.

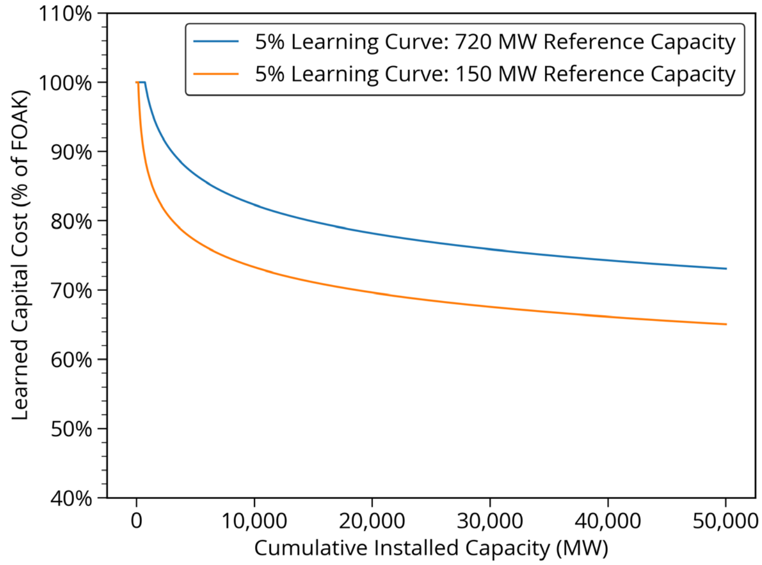


Figure 2.4: Learning curves based on Equations (1) and (2) for 5% learning rate and reference capacities of 720 MW (blue) and 150 MW (orange).

Both scenarios modeled in this study introduce known demonstration projects that are underway to get the endogenous learning started in the model. Table 2.2 shows the demonstration projects, their location and completion year that were included in the scenarios. The Department of Energy (DOE) has awarded cost sharing to these projects from the Bipartisan Infrastructure Bill.

Project	Capacity (MW)	Location	Online Date
TerraPower	345	Wyoming	2028
X-energy	360	Washington	2028
NuScale	462	Idaho	2029

Table 2.2: Demonstration pilot projects for advanced nuclear technologies along with the expected operational dates included in the scenarios.

The actual learned capital costs from endogenous learning modeled in the two scenarios is shown in Fig. 2.5. In the "Nominal" scenario due to the rapid deployment of advanced nuclear generators to the grid starting 2030, the capital costs show rapid reduction in the early years and reduce from $3,800/kW in 2030 to $2,713/kW in 2035. After 2035 the rate of learning slows driven by the lower learning rate assumed and the final learned capital cost in the "Nominal" scenario $2,334/kW in 2050, a 38.5% reduction from the FOAK capital cost.

In the "Constrained" scenario on the other hand, due to limitations of supply, the deployment of advanced nuclear generators is slowed down. As a result, the capital costs see a slower reduction as compared to the "Nominal" scenario and reduce from $5,500/kW in 2030 to $4,331/kW in 2035. After 2035, cost reductions continue at a slow but steady pace as new advanced nuclear generation is added to the grid. By 2050, the learned capital cost in the "Constrained" scenario is $3,883/kW, a 30% reduction from the FOAK capital cost.

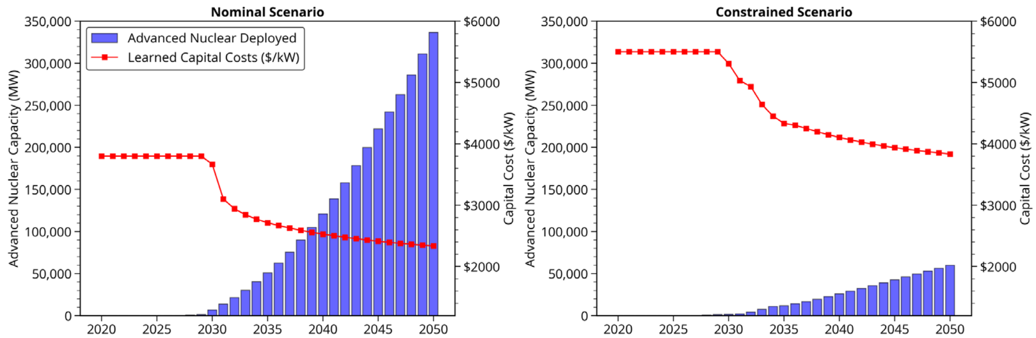


Figure 2.5: Learned capital costs versus capacity deployed in the "Nominal" scenario (left) and "Constrained" scenario (right).

3 Modeling Results

3.1 Capacity Buildout and Generation

The change in capacity on the grid in the two scenarios modeled is shown in Figure 3.1. In both scenarios, coal is steadily retired over the years and is completely retired by 2035 and 2036 in the "Nominal" and "Constrained" scenarios respectively. Both scenarios also gradually retire the natural gas combined cycle (NGCC) generation over the years with about 117 GW remaining on the grid in the "Nominal" scenario and 140 GW in the "Constrained" scenario for capacity value and providing generation during periods of high demand. Both scenarios also retire the natural gas-fired gas turbine (NGGT) in the early years and then add some once the coal is retired to meet peak load and capacity value requirements.

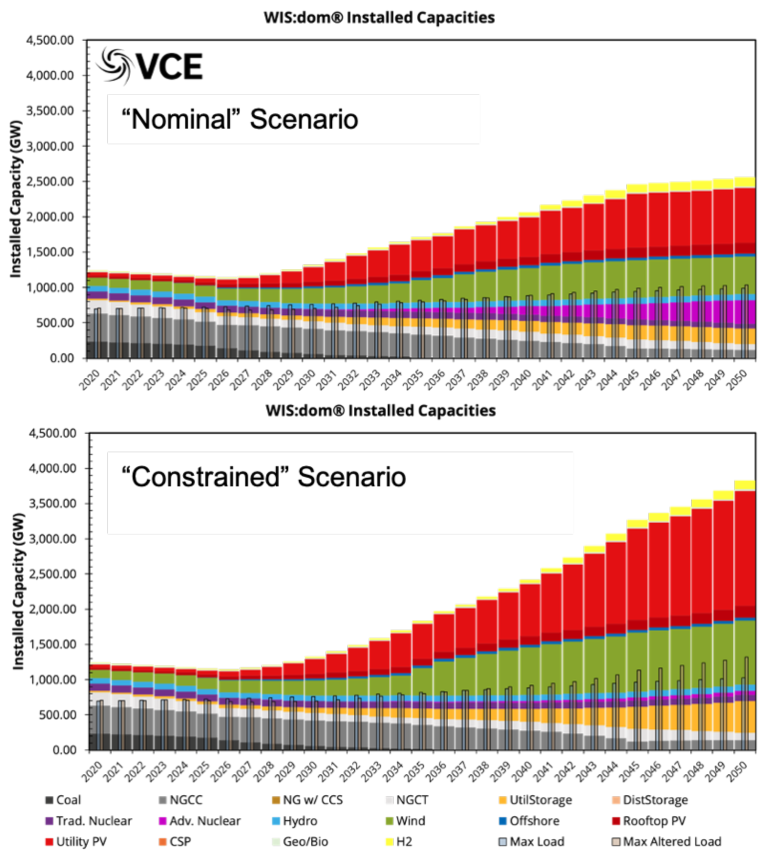


Figure 3.1: Installed capacities over the CONUS in the "Nominal" scenario (top) and "Constrained" scenario (bottom).

The model is not allowed to deploy any advanced nuclear until 2030. However, both scenarios have demonstration projects that come online in 2028 and 2029 that add about 1.1 GW of advanced nuclear to the grid. Starting 2030, the "Nominal" scenario rapidly starts to deploy advanced nuclear to the grid, reaching 50 GW of installed capacity by 2035. In the "Constrained" scenario on the other hand, due to slow response of supply chains and regulatory hurdles (as described in Section 2) and, to a lesser extent, higher FOAK capital costs, the deployment is slower and result in only 11.8 GW of advanced nuclear on the grid by 2035. Figure 3.2 shows how the supply chain constraints and regulatory hurdles in the two model runs allow or hinder the deployment of advanced nuclear generation to the grid. In the "Nominal" scenario, the model is only constrained by economic considerations when deploying advanced nuclear, while in the "Constrained" scenario, the model is supply limited until 2035 due to delays in getting the necessary permits, supply chain ramping up slowly, unavailability of qualified workforce etc.

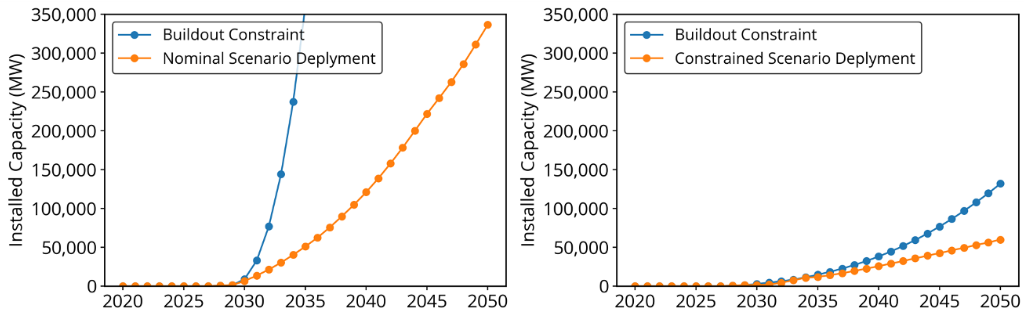


Figure 3.2: Buildout constraint versus actual model deployment of advanced nuclear in the "Nominal" scenario (left) and "Constrained" scenario (right).

After 2035, advanced nuclear deployment rate in the "Nominal" scenario continues to increase from approximately 10 GW/year in 2035 to about 25 GW/year in 2050 resulting in 336 GW of advanced nuclear on the grid by 2050. In the "Constrained" scenario, the deployment rate of advanced nuclear stalls around 3.5 GW/year (even though more deployment is possible as shown in Fig. 3.2) due to the deployment delays causing advanced nuclear to lose out to renewables and as a result the grid has only 59.7 GW of advanced nuclear by 2050. The "Constrained" scenario retains about 20 GW more of traditional nuclear compared to the "Nominal" scenario to make up for the lack of clean dispatchable generation available to it.

The generation mix on the grid in each investment year modeled is shown in Fig. 3.3 (for the "Nominal" scenario) and Fig. 3.4 (for the "Constrained" scenario). As a result of the faster deployment of advanced nuclear in the "Nominal" scenario about 36% of generation comes from advanced nuclear and 43% from combination of advanced and traditional nuclear generation. While in the "Constrained" scenario, advanced nuclear makes up only 4% of the total generation in 2050 and traditional and advanced nuclear combined make up 13% of the generation. These vastly different outcomes show the importance of timing for a new technology to be deployed. Delays in deployment of advanced nuclear by 2035, lock the model into a path where it is more economical for the model to pursue deployment of renewables over advanced nuclear due to the investments already made in installing storage, transmission and renewables already on the grid.

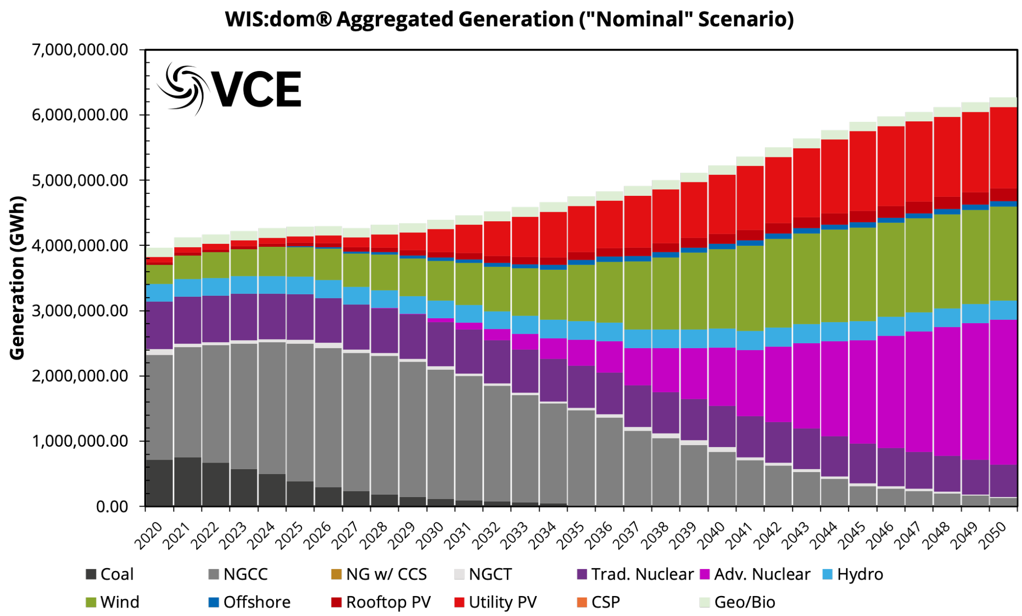


Figure 3.3: Aggregated generation over the investment periods in the "Nominal" scenario.

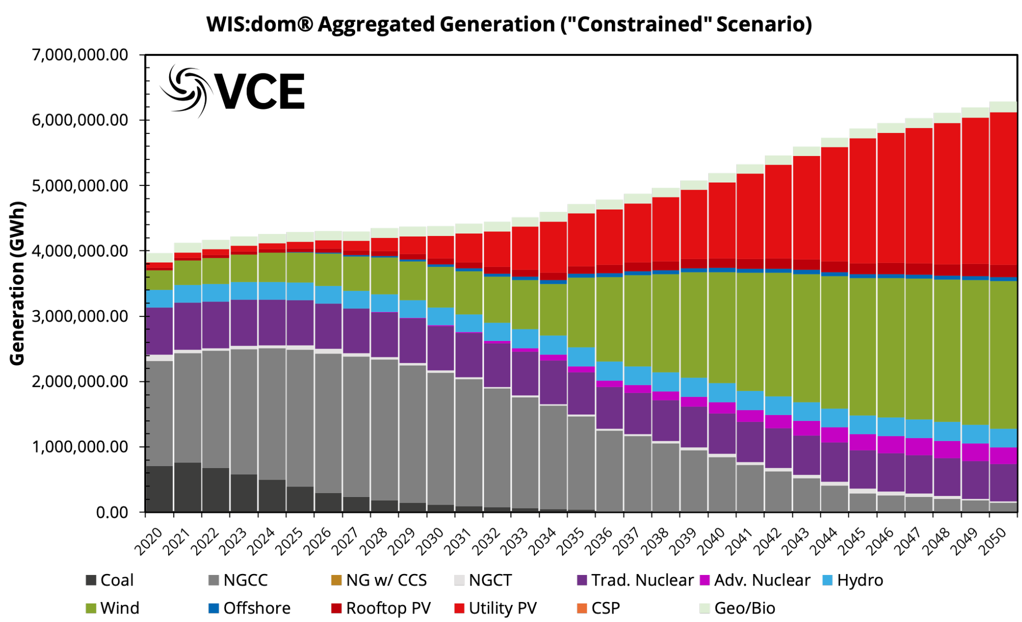


Figure 3.4: Aggregated generation over the investment periods in the "Constrained" scenario.

In the "Constrained" scenario, the model installs significantly more wind, solar and storage in place of advanced nuclear which is slowed down due to costs and supply constraints. In the "Constrained" scenario, the model installs 1.6 TW of utility-scale solar and 168 GW of distributed solar along with 909 GW of onshore wind and 449 GW of storage by 2050. By contrast, in the "Nominal" scenario the model installs 778 GW of utility-scale solar and 158 GW of distributed solar with 532 GW of onshore wind and 222 GW of storage by 2050. Therefore, to make up for the lack of advanced nuclear the model needs more than double the utility-scale solar and storage capacity and 70% more wind capacity.

This increased installation of renewables requires the supply chain to react quickly in order to produce the solar panels and wind turbines needed. Figure 3.5 shows the yearly capacity additions of wind, solar, storage and advanced nuclear in the two scenarios modeled. In both scenarios, we see waves of deployment for wind and solar over the modeling period as a result of changing needs of the grid. However, in the "Constrained" scenario, the waves of wind and solar installations show much larger amplitudes especially in the mid-2030s coinciding with significant retirement of coal and gas generation (due to decarbonization constraints) along with increasing load due to electrification. Similar trends are observed in the "Nominal" scenario, but the amplitudes are much smaller due to the advanced nuclear deployments able to provide clean dispatchable generation that reduces the burden on renewables and storage to provide clean energy while ensuring reliability.

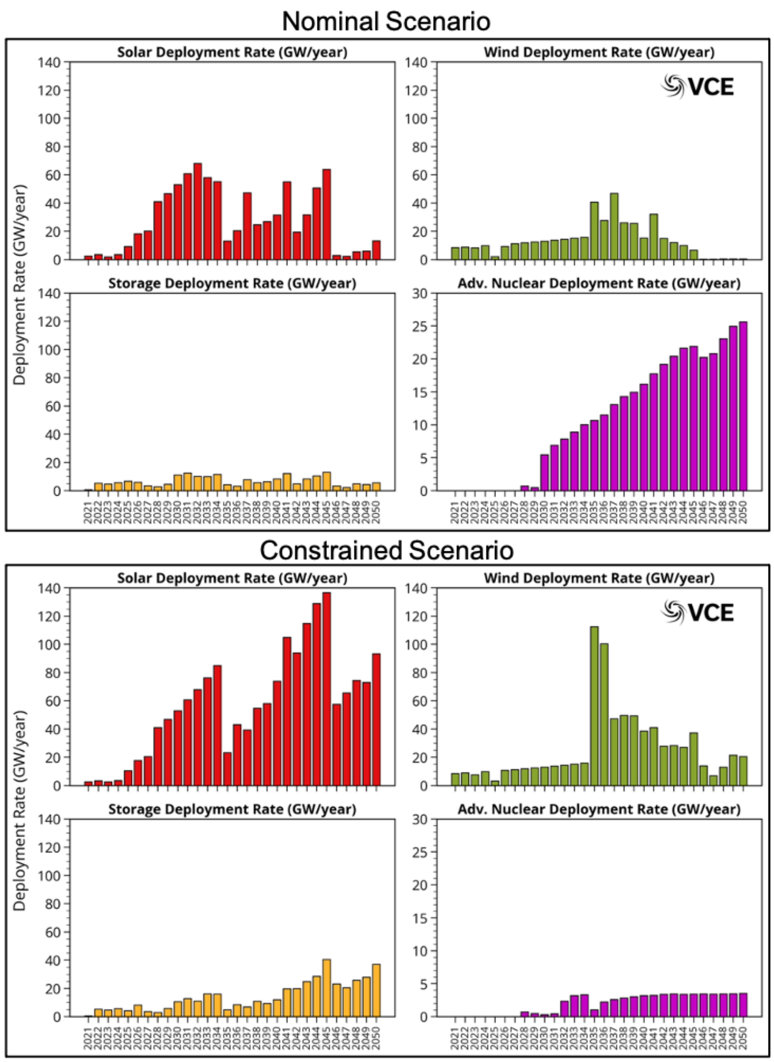


Figure 3.5: Installation rates for wind, solar, storage and advanced nuclear in the "Nominal" scenario (top) and "Constrained" scenario (bottom). Note that the y-axis is different for the advanced nuclear installation rate subplots.

The aggregated daily dispatch over the CONUS in 2050 for the two scenarios modeled is shown in Fig. 3.6. In the "Nominal" scenario, the remaining traditional nuclear is dispatched as "baseload" throughout the year while the advanced nuclear provides clean flexible generation by ramping around the generation from renewables and storage. During a few days in the year when renewable generation is low and demand is high, the model dispatches the NGCC and NGGT generators to meet demand and ensure reliability. In the "Constrained" scenario, most of the load is met by renewables with storage providing the required flexibility to meet load during peak demand periods. The advanced nuclear on the grid helps storage provide clean flexible generation. The remaining NGCC and NGGT generation is seen to be dispatched during more days compared to the "Nominal" scenario due to the lack of advanced nuclear on the grid. The curtailment of renewable generation is also significantly higher compared to the "Nominal" scenario (even with the presence of flexible loads such as hydrogen and electrified demands) due to the significant overbuilding required to ensure reliability.

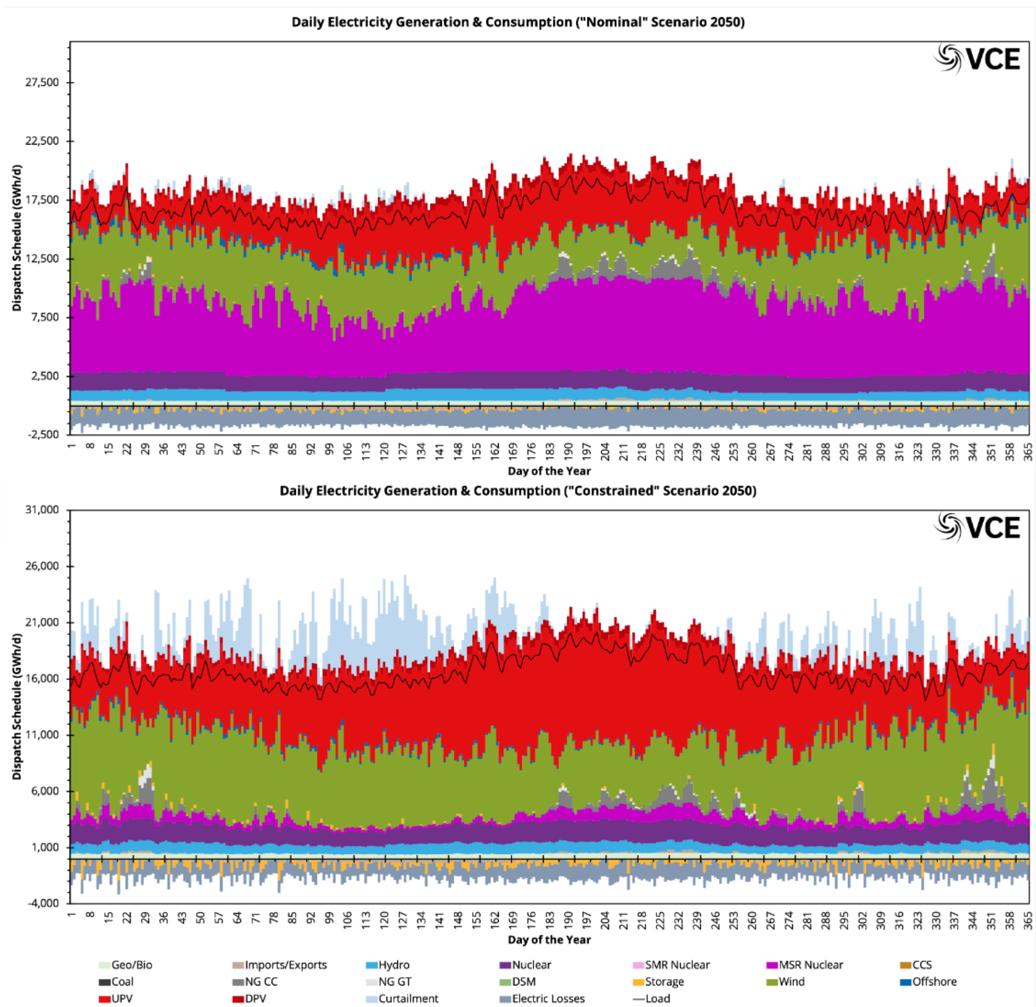


Figure 3.6: Aggregated daily dispatch over a year in 2050 in the "Nominal" scenario (top) and "Constrained" scenario (bottom).

3.2 System Costs, Retail Rates & Jobs

The changes in total system costs (electricity sector and hydrogen production costs) and retail rates over the CONUS in the two scenarios modeled is shown in Fig. 3.7. Before 2030, there is not much difference between the costs in the two scenarios as they both reduce costs through retirement of older fossil fuel generators (both coal and gas) and deploying renewables. As a result, both scenarios see reduction in total system costs and retail rate from 2020 to 2030. The total system costs start to increase after 2030 due to additional generation needed on the grid as a result of electrification. It is seen that the "Constrained" scenario results in increased costs compared to the "Nominal" scenario due to slower retirement of coal and gas generation as well as increased deployments of renewables and storage to help meet the decarbonization constraints.

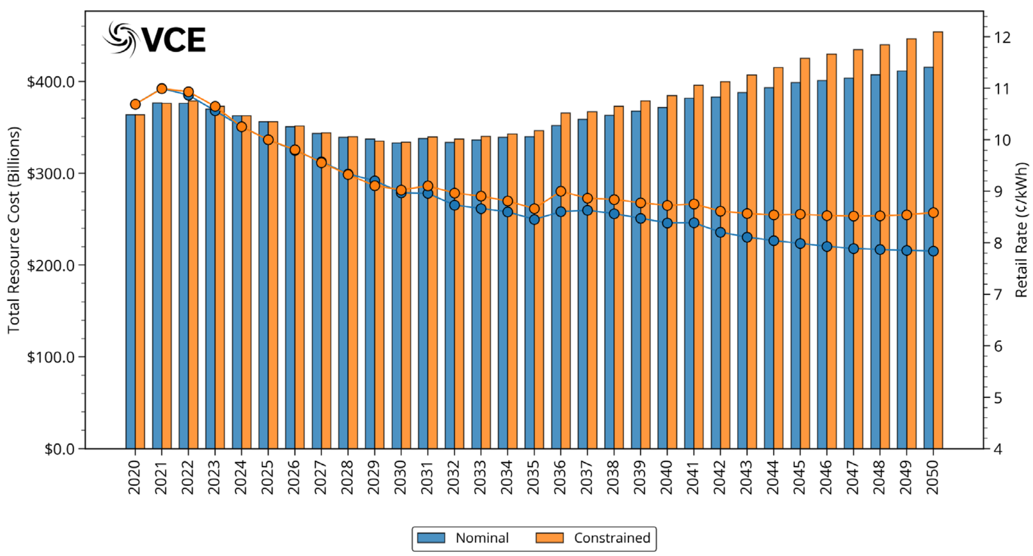


Figure 3.7: Total system costs and retail rates over the CONUS for the two scenarios modeled.

The additional system costs in the "Constrained" scenario continue to increase over the years and by 2050, the "Constrained" scenario has an additional annual cost of $38 billion compared to the "Nominal" scenario. These additional costs come from more than doubling the utility-scale solar and storage installed on the grid as well as the significantly more wind generation installed. The additional annual costs in the "Constrained" scenario add up to $346 billion cumulatively by 2050. Therefore, slower deployment of clean dispatchable generation such as advanced nuclear can significantly add to the cumulative spending on energy.

While the total system costs increase after 2030, the retail rates continue to decrease as the additional costs are spread over a larger load, resulting in approximately 26% reduction in retail rates by 2050 compared to 2020 values. The retail rates are calculated by taking into account utility overheads, revenue requirements and expenses and revenues from imports or exports in each region.

The retail rates in the "Constrained" scenario are roughly similar to the "Nominal" scenario until 2030. After 2030, the retail rates in the "Nominal" scenario show larger reductions driven by the lower total system costs. By 2050, the retail rates in the "Constrained" scenario are approximately 10% higher compared to the "Nominal" scenario. This small increase in retail rate is significant due to the economy-wide electrification which increases the energy burden for customers in the "Constrained" scenario. Cumulatively by 2050, the additional retail spending in the "Constrained" scenario is $449 billion. It should be noted that a moderate electrification scenario is being modeled in this study. If the economy undergoes more aggressive electrification efforts, the impact of the higher retail rates would be even further magnified which would severely hinder electrification and decarbonization efforts.

The breakdown of the cost per kWh of energy delivered by its source is shown in Fig. 3.8. In the early years, the largest contributors to the cost of energy are the fossil fuel generators and the distribution system costs. Retirement of the fossil fuel generators results in steady reduction in cost of energy and thus retail rates. After 2035, the contribution from advanced nuclear to the cost of energy steadily increases in the "Nominal" scenario, while in the "Constrained" scenario, wind and solar start to show increased contributions to the cost of energy. By 2050, in the "Nominal" scenario, advanced nuclear makes the largest contribution to the cost of energy after distribution system costs as it generates the largest fraction of energy. In the "Constrained" scenario, renewables (wind and solar) make up the largest contribution to the cost of energy since they are the largest generators of energy in that scenario.

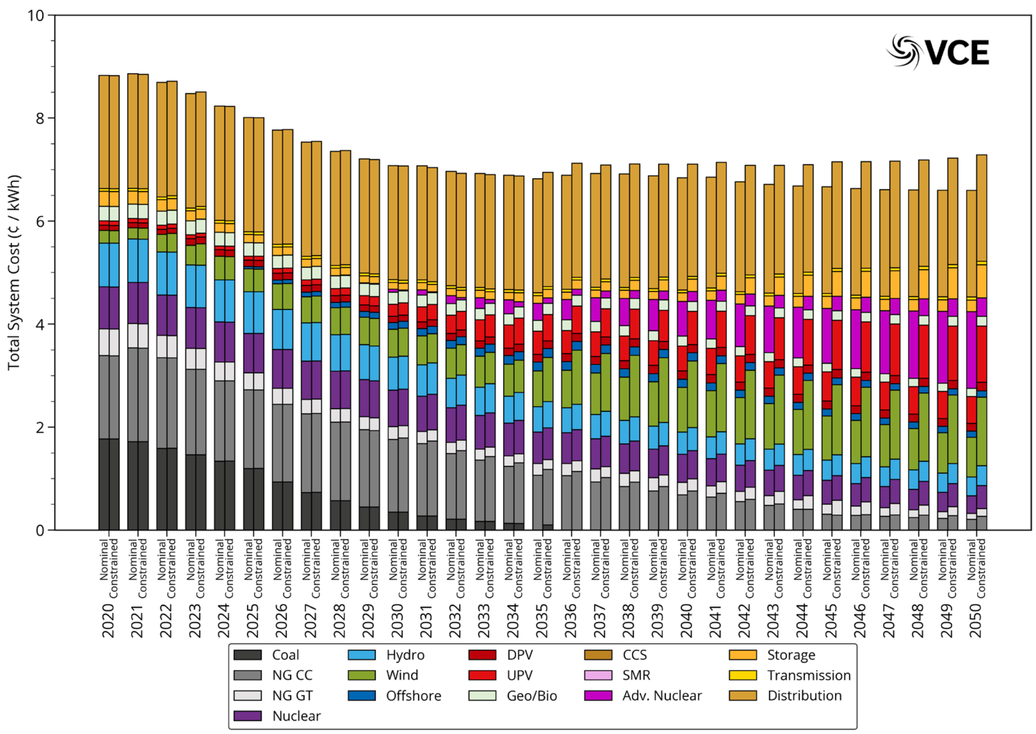


Figure 3.8: Cost per kWh of delivered energy broken out by source for the two scenarios modeled.

The average annual full-time equivalent jobs created in the nuclear energy sector in the two scenarios modeled is shown in Fig. 3.9. In the "Nominal" scenario, nuclear energy sector jobs grow from approximately 56,000 in 2020 to 234,000 in 2050 driven by the expansion of advanced nuclear deployed to the grid and the supporting industries needed to enable that expansion. The roughly 177,000 additional jobs supported by the nuclear industry in the "Nominal" scenario is only slightly less than the 200,000 job losses that occur in the coal and gas industry due to retirement of the fossil fuel generation. Given that almost all of the advanced nuclear deployed by the model is sited at decommissioned coal and gas sites (see Section 3.4), these jobs will continue to support the communities that depended on jobs created by fossil fuel generation. Therefore, a timely deployment of advanced nuclear technologies will not only save spending in the electricity sector, but also stem the job losses occurring due to retirement of fossil fuel generation and ensuring a just transition in those communities.

By contrast, in the "Constrained" scenario, the annual average jobs only increase to 83,000 in 2050. However, in this scenario retirement of coal and gas generation still result in about 187,000 job losses. Therefore, delays in deployment of advanced nuclear not only increases total system costs, but will cause net job losses in communities that relied on fossil fuel generators as the main source of employment.

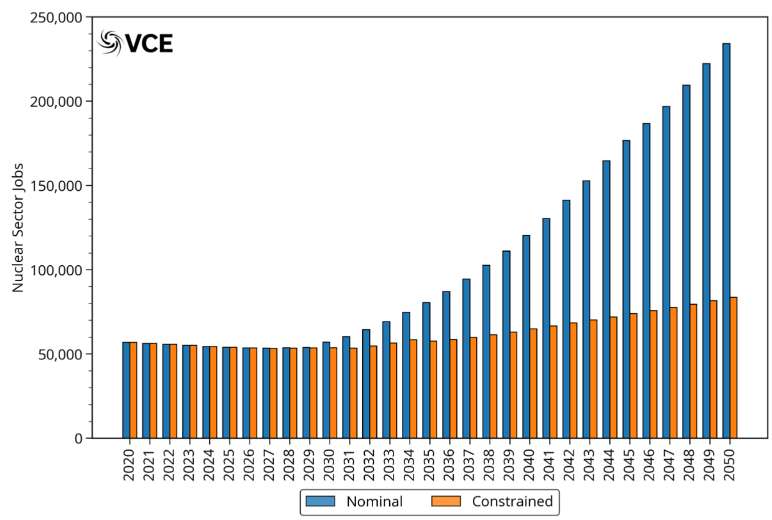


Figure 3.9: Average annual full-time equivalent jobs created in the nuclear energy sector for the two scenarios modeled.

3.3 CO_2 Emissions & Pollutants

In both the scenarios modeled, the electricity sector is required to decarbonize by at least 95% by 2050 while undergoing economy-wide electrification following the "Medium Electrification" scenario in the NREL Electrification Futures Study. Figure 3.10 shows the annual carbon dioxide emission reductions in the electricity sector and economy-wide as a result of electrification and decarbonization. The two scenarios follow very similar emission reduction paths and hence the emissions from the "Nominal" scenario are presented here. The annual electric sector emissions, after a slight increase in 2021, steadily reduce over the years reaching 95.75% reduction from 2020 levels by 2050. Since the rest of the economy follows the "Medium Electrification" pathway, the annual economy-wide emissions only reduce by 61% by 2050.

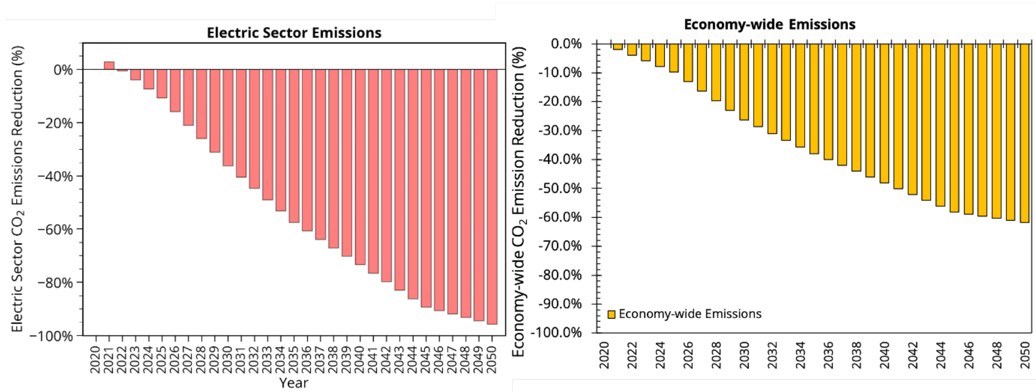


Figure 3.10: Annual electric sector emission reductions (left) and economy-wide emission reductions (right) in the two scenarios modeled.

Figure 3.11 shows the contributions from electrification and decarbonization in the cumulative emission reductions achieved in the two scenarios modeled. As a result of the rest-of-the-economy following the "Medium Electrification" pathway, the economy-wide emissions reduce by 23,318 million metric tons (mmT) cumulatively by 2050. However, since the electricity sector undergoes decarbonization as well, this results in a further cumulative emission reduction of 32,248 mmT by 2050. Therefore, the combined effect of electrification and decarbonization is a cumulative reduction of 55,566 mmT of carbon dioxide emissions from 2020 to 2050. This emission reduction is more than 1.5 times the annual global emissions in 2020. Therefore, even with moderate electrification efforts and 95% decarbonization of the electricity sector, the US can make significant reductions to global greenhouse gas emissions.

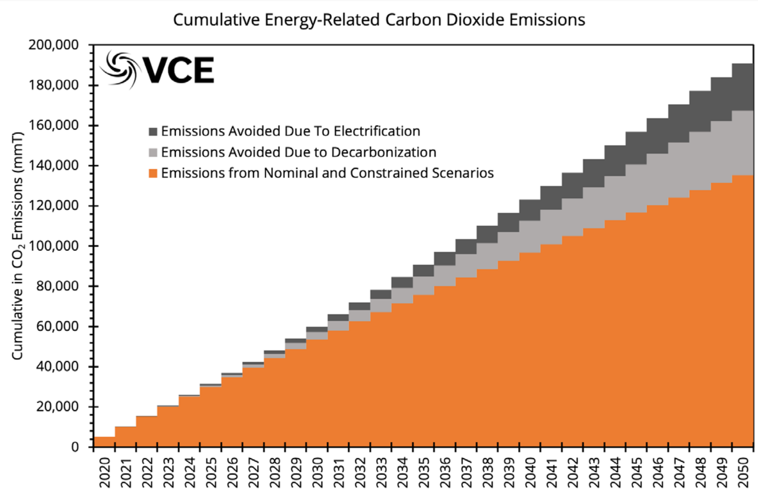


Figure 3.11: Cumulative economy-wide carbon dioxide emissions

In addition to reducing carbon dioxide, decarbonization of the electricity sector results in significant improvement to air quality through reduction in emissions of criteria air pollutants. Figure 3.12 shows the change in emissions of criteria pollutants tracked by WIS:dom-P over the modeling period in the two scenarios modeled. Emissions of SO_2, PM_{10}, $PM_{2.5}$ and VOC are seen to drop to almost zero by 2035 coinciding with full retirement of the coal generation. In addition, emissions of NO_x, CH_4, and N_2O steadily decrease and are reduced by more than 99% by 2050 due to significantly reduced usage of fossil fuel generation. These reductions in emissions of pollutants bring about significant health benefits to populations close to these power plants. Therefore, decarbonization of the electricity sector not only reduces the impact on climate change, but also brings about immediate health benefits to large sections of the population exposed to pollutants emitted by fossil fuel generators.

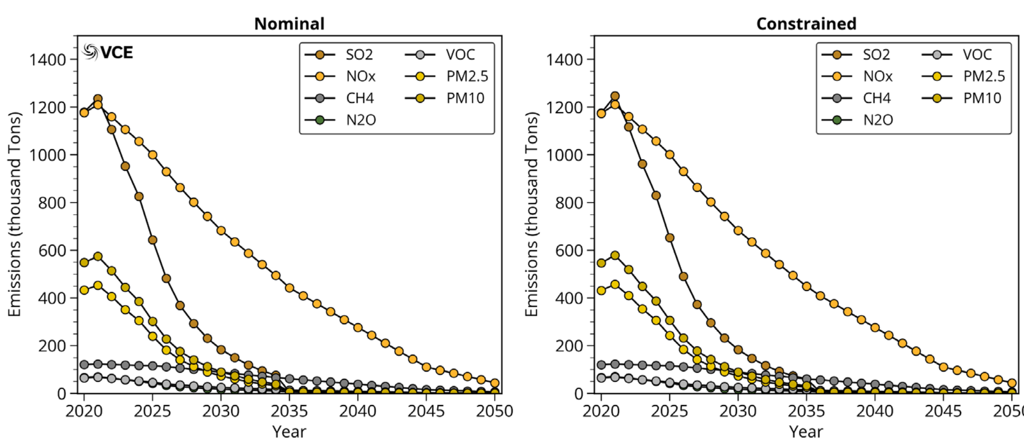


Figure 3.12: Change in emissions of criteria air pollutants from the electricity sector in the two scenarios modeled.

3.4 Siting of Generators (3-km)

WIS:dom-P uses weather datasets spanning multiple years at 3-km spatial resolution and 5-minute temporal intervals over the contiguous United States. WIS:dom-P performs an optimal siting of generators on the 3-km HRRR model grid. The existing generator layout reduced to a 3-km resolution along with the transmission paths above 115 kV is shown in Fig. 3.13. The grid is largely composed of fossil fuel generation in 2020. More nuclear exists in the eastern half of the country while more renewables exist in the western and central portion of the country.

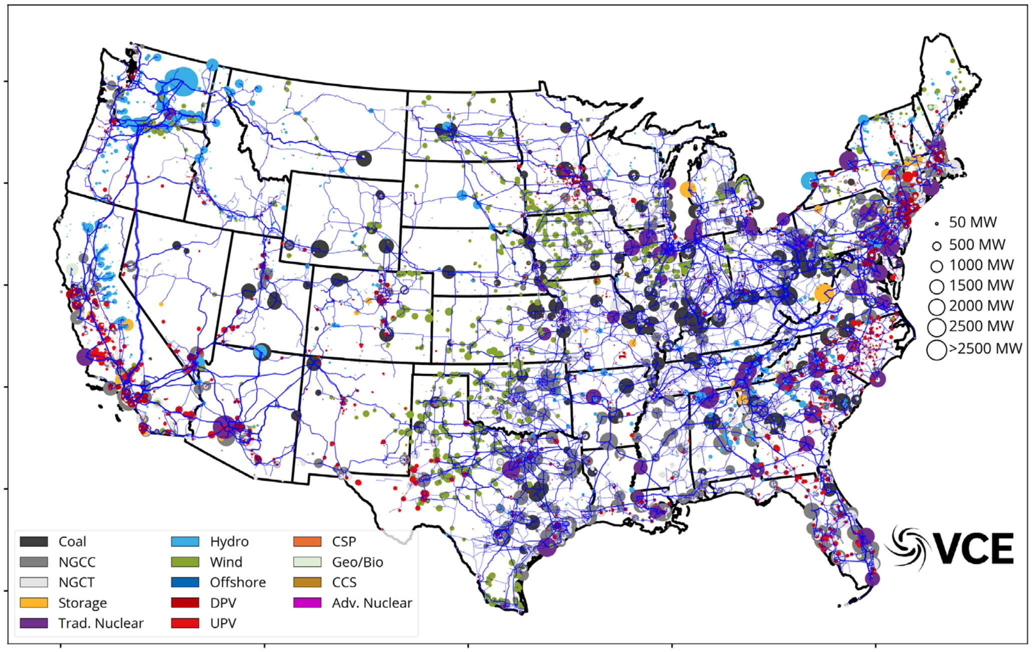


Figure 3.13: WIS:dom-P existing generators with transmission in 2020.

Figure 3.14 shows the 3-km siting of the capacity in 2050 across the US for the "Nominal" (top) and "Constrained" (bottom) scenarios. In both scenarios, the grid is transformed from being fossil fuel dominant to Variable Renewable Energy (VRE) dominant. Wind generation is spread throughout the central states, upper Midwest and even along the Mississippi river Valley and the northern Appalachian Mountains to take advantage of the geographic diversity, which results in more complementary generation profiles in addition to generating more energy near the load centers. Further, significant installations of UPV and DPV are deployed nearer to population centers. The deployment of DPV generation especially helps alleviate transmission congestion that routinely occurs in moving energy to densely populated regions.

It is apparent that in the "Constrained", where less advanced nuclear is built, storage helps fill the gap of having clean, firm support for VREs. Advanced nuclear technologies are sited near sources of water and available transmission (for example, where a coal plant is retired). It is assumed that the brownfield sites have sufficient space to create a containment region around the advanced nuclear plants. In both scenarios, advanced nuclear more prominently shows up in the eastern half of the US, but it plays its part in the western half of the country alongside Hydro and other VREs.

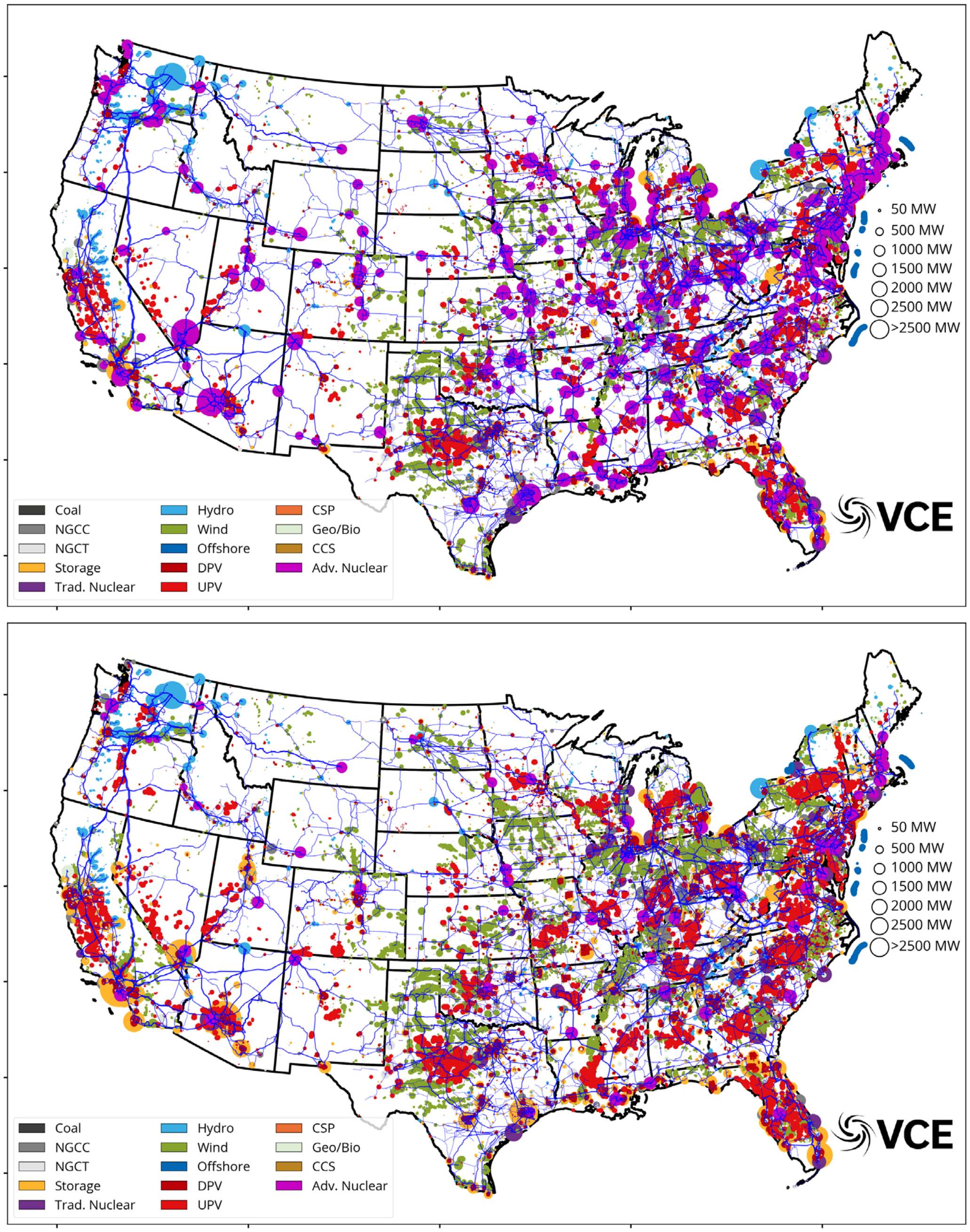


Figure 3.14: WIS:dom-P grid layout in 2050 for the "Nominal" (top) and the "Constrained" scenario (bottom).

Figure 3.15 shows the retired fossil fuel sites that were converted to advanced nuclear facilities in the two scenarios modeled. In the "Nominal" scenario, a majority of brownfield sites selected for conversion to advanced nuclear facilities are retired coal generation sites such as long the Ohio River, Comanche in Colorado and Colstrip in Montana. Coal generation sites are selected in greater numbers as these generators were retired the earliest and have access to water and unused transmission capacity. In the later years as gas and nuclear generators are retired, those sites are also selected by the model to build advanced nuclear facilities. In the "Constrained" scenario, only a handful of states deploy advanced nuclear facilities. In almost all cases the model expands the advanced nuclear facilities added in the early years by adding new reactors to existing advanced nuclear facilities. Therefore, in the "Constrained" scenario, only coal plants that were retired early in the modeling period are seen to be converted.

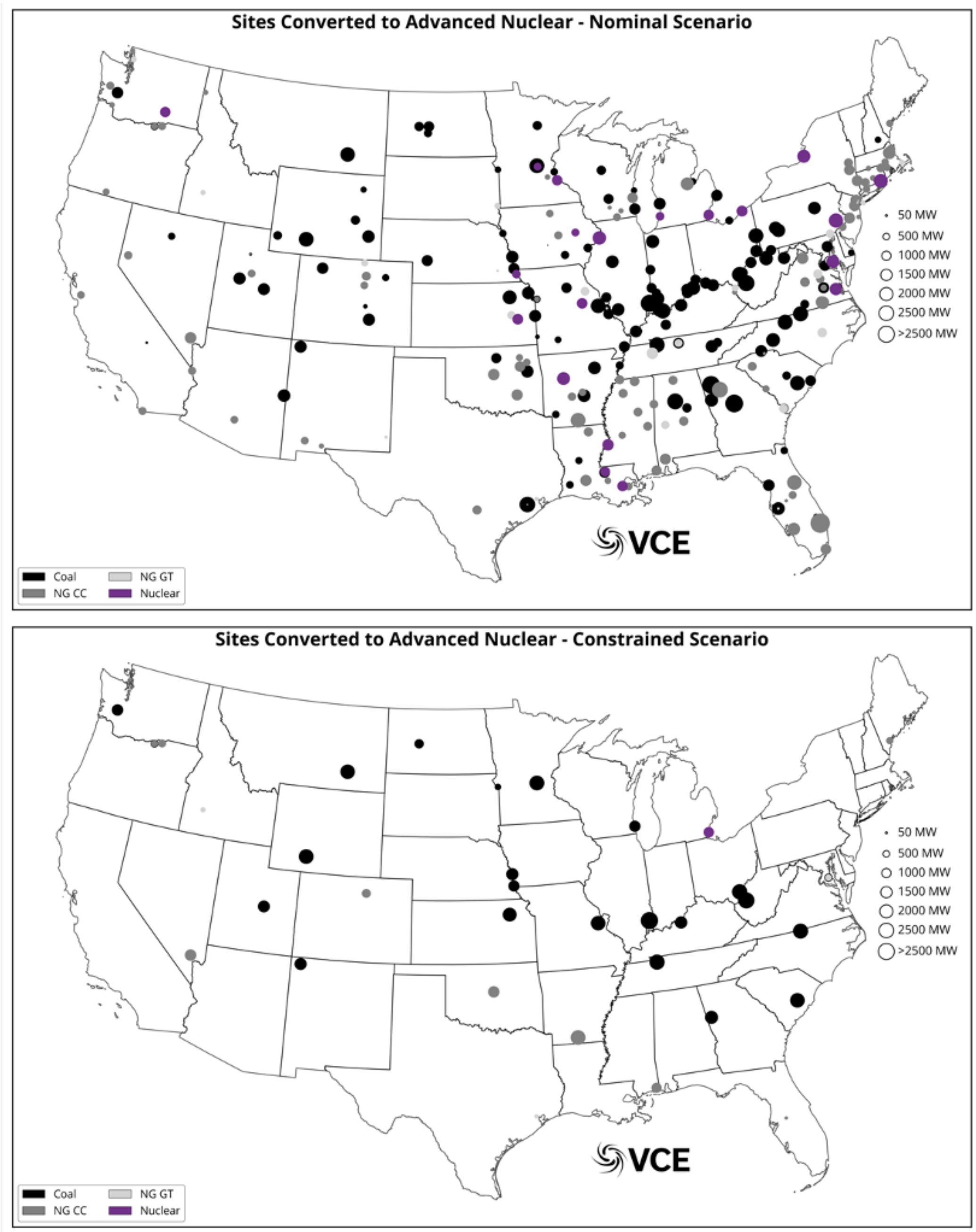


Figure 3.15: Retired fossil fuel sites that are converted to advanced nuclear facilities in the "Nominal" scenario (top) and "Constrained" scenario (bottom).

When making the siting decisions, the model takes into account several criteria to determine the optimal siting for generators. In addition to accounting for expected generation and distance from the load (for transmission considerations), the model ensures that generation is not sited in unsuitable locations. The model also ensures that the technical potential of each grid 3-km grid cell is not exceeded. The technical potential for the various VRE technologies in each grid cell is determined according to factors such as population, land cover, terrain slope, and others. In addition, each technology is limited by a maximum packing density to ensure that generators do not hamper performance of other generators in the grid cell, such as through wakes for wind turbines and excessive shading for solar panels. More information about these criteria and the WIS:dom-P model can be found in the technical documentation.[8]

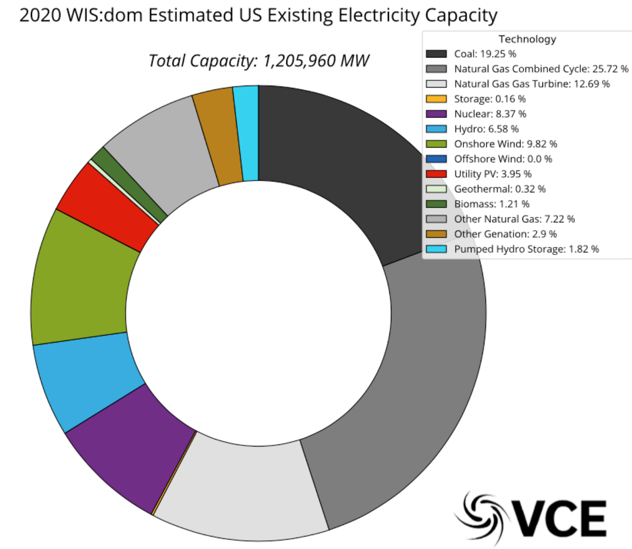
[8] https://vibrantcleanenergy.com/wp-content/uploads/2020/08/WISdomP-Model_Description(August2020).pdf

4 Datasets & WIS:dom-P Inputs

4.1 Generator Input Dataset

VCE processed the Energy Information Administration (EIA) annual data from 2020 to create the baseline input generator dataset for this study. From this dataset, information for the contiguous US was obtained. The mainland US includes 1206 GW of installed capacity. WIS:dom has the ability to solve over such scales at 5-minute resolution for several years chronologically.

The WIS:dom-P generator input datasets are built upon the publicly available EIA 860 and EIA 923 data. VCE carried out several steps to align and aggregate technology types to the 3-km model grid space that matches the National Oceanic and Atmospheric Administration (NOAA) High-Resolution Rapid Refresh (HRRR) model. In the process, year-on-year changes are analyzed. Across the United States, general trends show (for fossil fuels) coal capacities falling with natural gas combined cycle growing. Wind, solar and storage plants are on the rise as well. Nuclear is generally steady with only a few retirements. The trend continues in the data throughout 2021 based upon the recently released EIA 860 monthly data for that year.



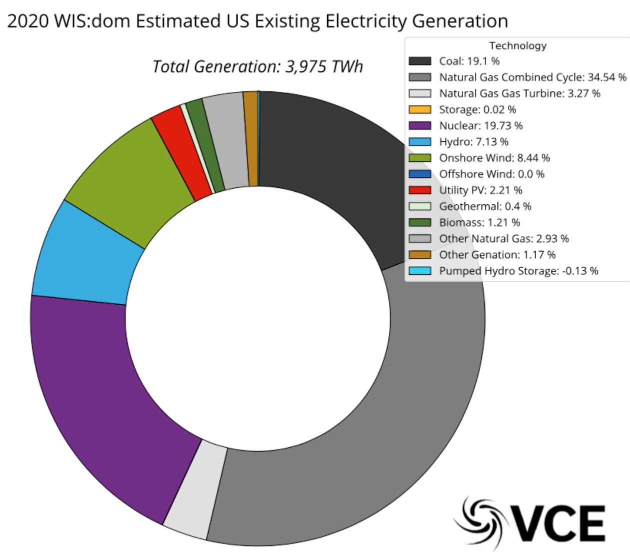


Figure 4.1: WIS:dom estimated installed capacity for the contiguous US (top). The total capacity modeled for this region is 1,206 GW. This also shows WIS:dom estimated generation by technology for the contiguous US (bottom).

The top panel of Fig. 4.1 shows the installed technology capacities over the contiguous US footprint for 2020. Natural gas is the dominant technology across the country. Traditional nuclear technologies make up just under 10% of the installed capacity across the US. Wind and solar (Variable Renewable Energy, or, VREs) make up just under 15% of the installed capacity. Coal is around 20%. The bottom panel of Fig. 4.1 shows the generation by technology over the contiguous US for 2020. In this view natural gas also dominates the US generation. As coal has retired, natural gas and renewable generation has stepped in. In 2020, the generation from coal was in parity with nuclear production, which, even five years ago, was not the case.

4.2 Renewable Siting Potential Dataset

VCE performs an extensive screening procedure to determine the siting potential of new generators across the contiguous US. This ensures that the WIS:dom model has constraints on where it can build new generation. First, USGS land cover information is utilized as a base within each 3 km grid cell to determine what is there (Fig. 4.2 top left panel). The siting constraint information for onshore wind, offshore wind, utility-scale solar PV and distributed solar PV is displayed in the remaining three panels of Fig. 4.2.

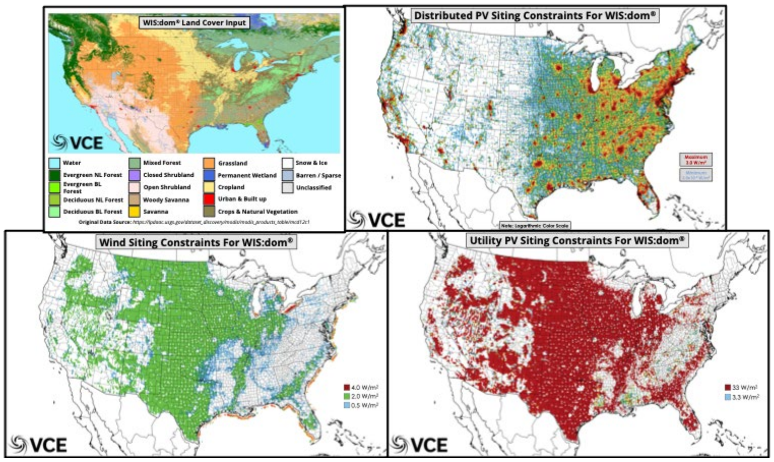


Figure 4.2: WIS:dom land cover (top left), distributed solar PV siting bounds (top right), utility-scale wind bounds (bottom right) and utility-scale solar PV (bottom right).

The first screening algorithm follows these steps:
(1) Remove all sites that are not on appropriate land-use categories.
(2) Remove all sites that have protected species.
(3) Remove all protected lands; such as national parks, forests, etc.
(4) Compute the slope, direction and soil type to determine its applicability to VRE installations.
(5) Determine the land cost multipliers based on ownership type.
(6) Remove military and other government regions that are prohibited.
(7) Avoid radar zones and shipping lanes.
(8) Avoid migration pathways of birds and other species.

The above, along with the knowledge of what is already built within a HRRR cell from the Generator Input data provides WIS:dom with a view of where it can technically build certain generators as well as certain technologies. Figure 4.2 also shows the siting constraints for wind, utility-scale solar PV and distributed solar PV.

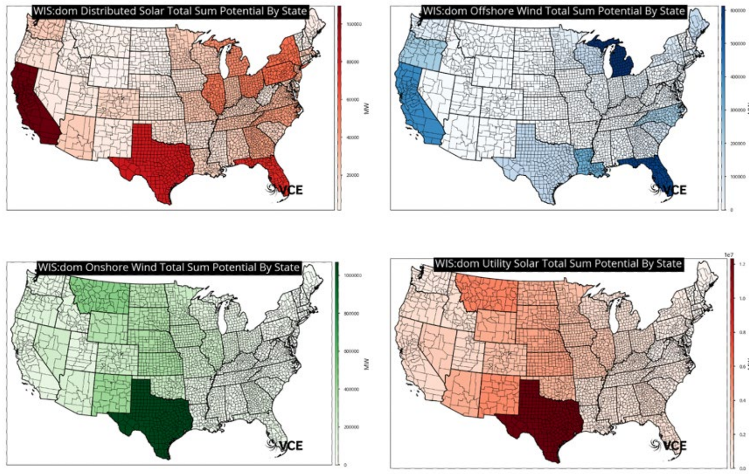


Figure 4.3: WIS:dom Total Sum Potential by state for Rooftop (top left), Offshore Wind (top right), Utility-scale Solar (bottom right) and Onshore Wind (bottom right) in MW.

For wind, utility-scale solar PV, distributed solar PV, and electric storage the available space use converted into capacity (MW & MWh) by assuming a density of the technologies. The above (Fig. 4.3) shows the state capacity total potential for each variable resource across the United States. For onshore wind, Texas, the Central Plains, the Front Range states and the Upper Midwest offer the most potential. Utility solar shows the same trend generally. Distributed solar potential is highest in the states with the largest populations and building infrastructures. Offshore wind potential is available along all coastal states. VCE also considers the Great Lakes with potential in the Upper Midwest. Floating offshore technologies would be needed along the West Coast.

4.3 Standard Inputs

There is a standard suite of input data for the WIS:dom-P model that sets the stage for several base assumptions about the energy grid and generator technologies. This includes items such as generator costs (capital, fixed, variable, fuel), generator lifetimes, heat rates, transmission/substation costs, legislative mandates, etc. The list of standard files is extensive and is continuously growing as the industry evolves. Additional inputs can be easily incorporated into WIS:dom-P. NEI provided customization to several inputs as well which were discussed in Section 2.1.

The Moderate NREL ATB values from 2021 were used for capital, fixed and variables costs of all generator technologies.

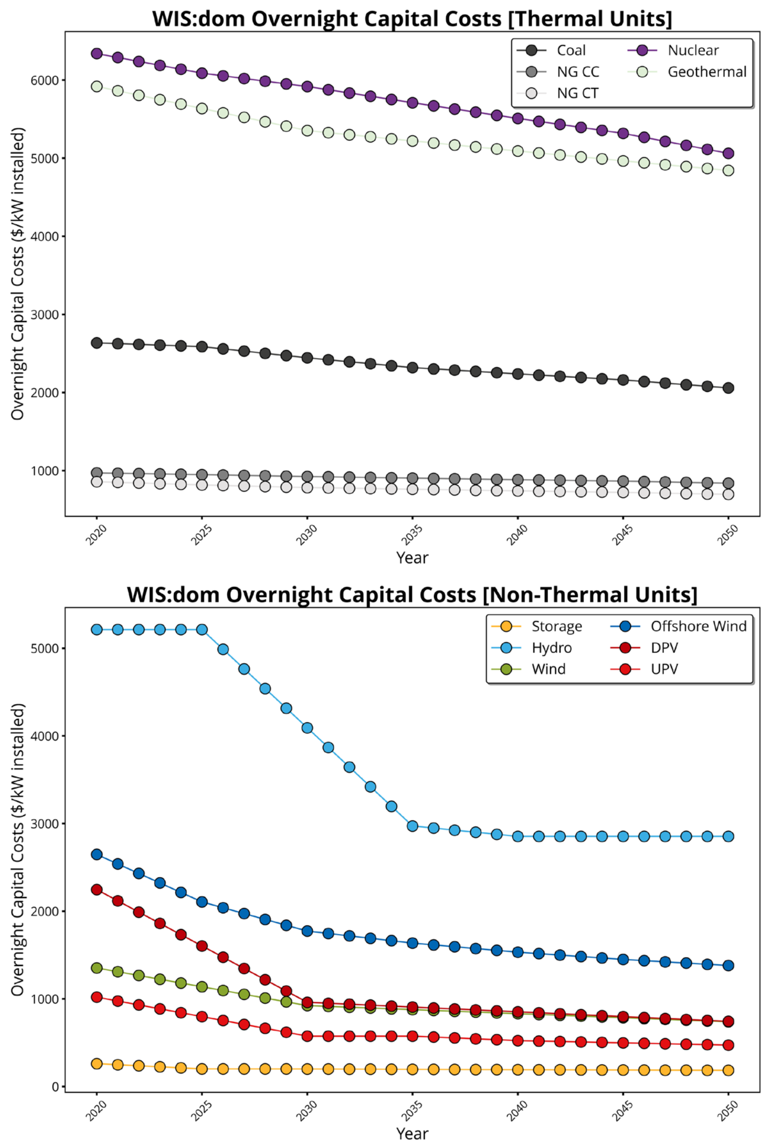


Figure 4.4: The overnight capital costs in real $/kW-installed for thermal (top) and non-thermal power plants (bottom) in WIS:dom-P. All costs are from NREL Moderate ATB 2021.

Figure 4.5 shows the fuel costs of thermal technologies. These costs started from the 2022 EIA Annual Energy Outlook (AEO) model High Oil and Gas Supply Scenario. With the high supply scenario, natural gas costs are generally lower in the later investment years than other AEO scenarios. Given the recent environment around natural gas supply, the years before 2025 are higher in cost for that fuel. In general, nuclear buildout can be sensitive to the costs of natural gas technologies and fuel. Higher gas fuel costs can direct WISdom-P towards nuclear.

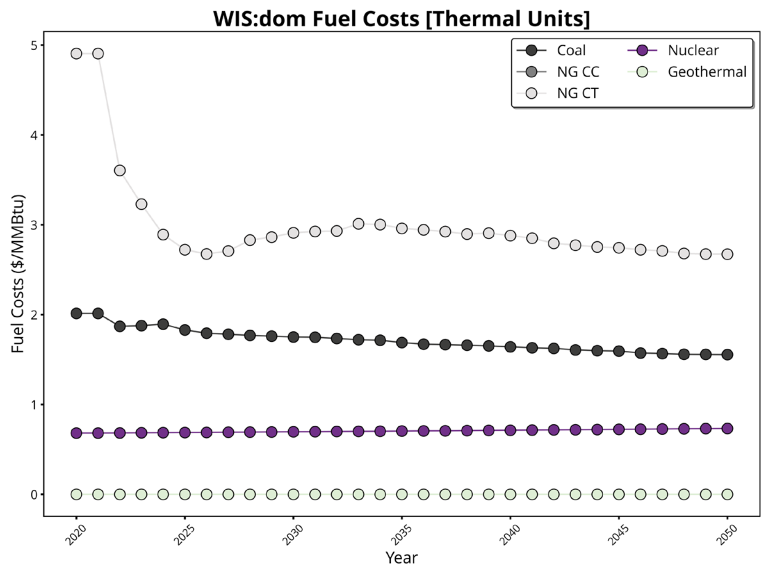


Figure 4.5: The fuel costs for thermal generators in WIS:dom-P in real $/MMBtu. All costs are from the 2022 EIA Annual Energy Outlook (High Oil and Gas Supply Scenario).

Storage is one of the most discussed inputs. Storage can have highly variable cost input values depending on sources. It also is a heavy driver as to how the model handles renewables, transmission and future baseload. It provides a firm, clean source of energy which can be used heavily by the model in decarbonized scenarios. The following Fig. 4.6 shows the cost per kW ($/kw) versus the battery pack capital cost ($/kWh) from the 2021 NREL Moderate ATB costs for storage used in all the scenarios.

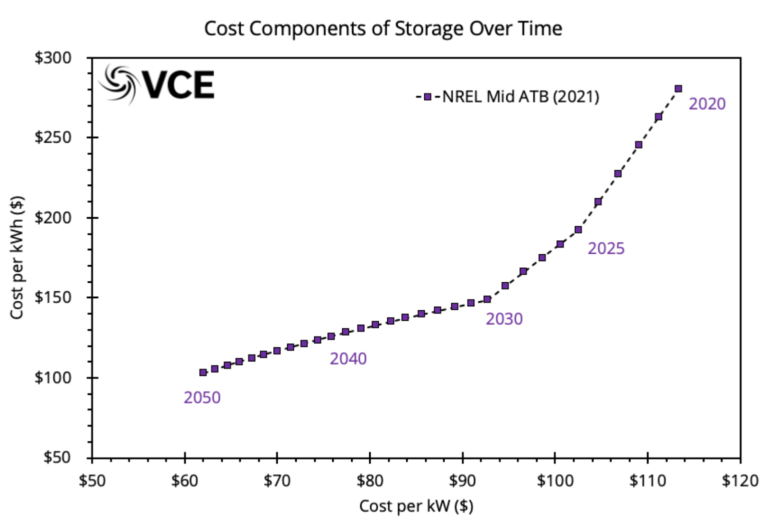


Figure 4.6: The Balance of System Capital Cost ($/kw) versus the Battery Pack Capital Cost ($/kWh). This is shown for the 2021 Moderate NREL ATB values in purple.

For these scenarios we modeled a generic advanced nuclear reactor technology. The advanced nuclear capital costs were adjusted between various scenarios to observe the impact of costs on buildout. The generic advanced nuclear standard inputs metrics were also created as an average between Small Modular Reactor and Molten Salt Reactor technologies that VCE has information on. This is discussed in greater detail in Section 2.1.

VCE uses the same ***real*** discount rate for all generator technologies including the Advanced and Novel technologies in the WIS:dom-P model. This value is 5.87%, which is applied with the book life of the technologies to provide the model with the amortized capital costs. The lifetime of the various technologies also impacts what/when the model optimally deploys generation as well as when it can retire units. The following Fig. 4.7 shows the standard economic lifetimes for the various technologies used within WIS:dom-P.

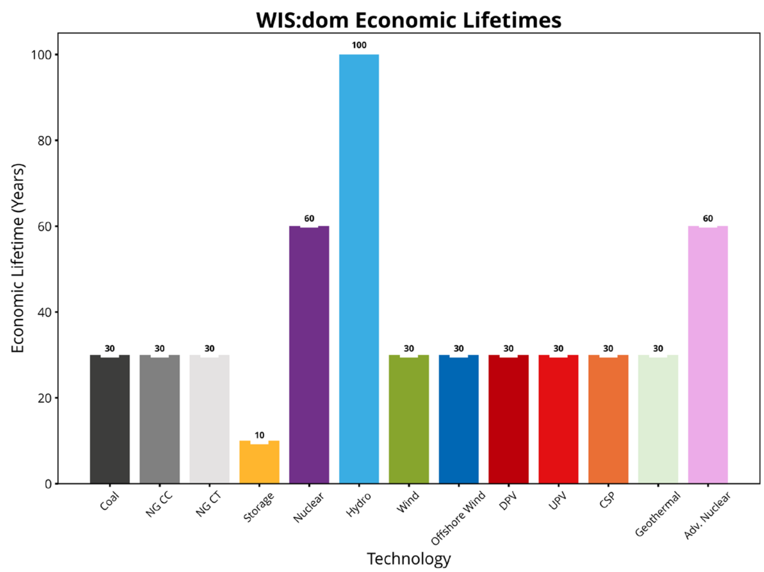


Figure 4.7: The economic lifetime for each generator type within WIS:dom-P in years. The economic lifetime means the time that the debt must be cleared from the units. The advanced nuclear technology has the same lifetime as traditional nuclear.

Transmission plays a large part in the optimized decisions that the WIS:dom-P model executes. The decision to build renewable technologies can be affected by the standard inputs around transmission aspects. The AC (includes substations) and DC costs are plotted for multiple years over various distances in Fig. 4.8.

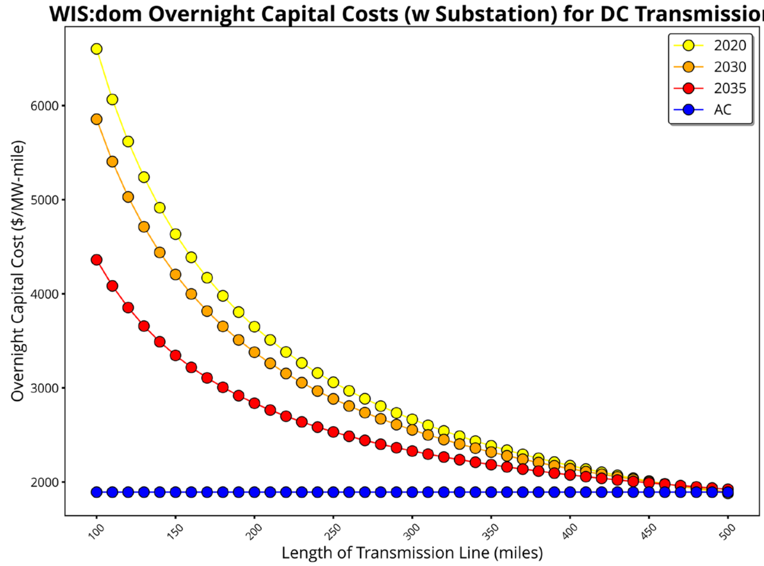


Figure 4.8: Shows the overnight capital cost of DC transmission in WIS:dom-P in real $/MW-mile installed over various distances. Costs are shown for 2020, 2030 and 2050. The overnight capital cost of AC transmission (including substations) is also shown in blue. This is the same cost no matter the investment period.

The economic lifetime, or rather, length of amortization, of the transmission assets in the model are 60 years for all investment periods with a 5.87% real discount rate.

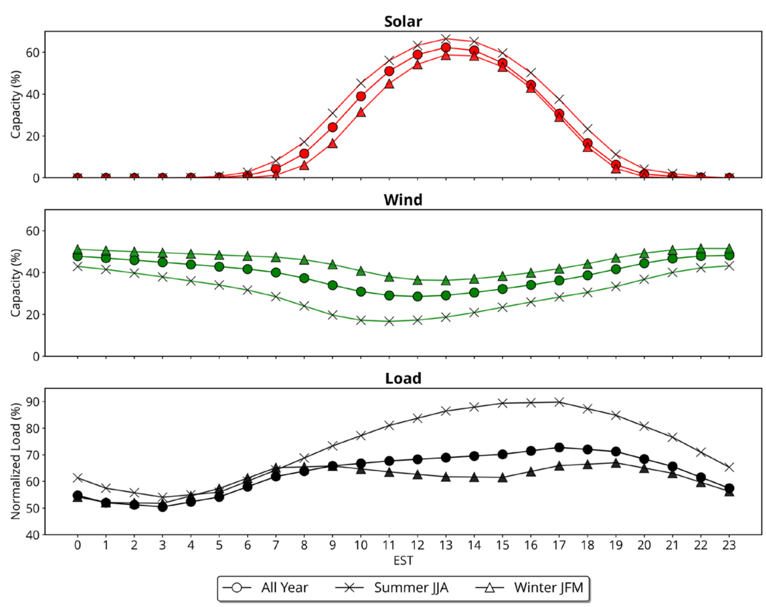
VCE documents and researches the various state legislature and renewable energy goals by tracking Renewable Portfolio Standards, Clean Energy Mandates, Offshore Wind Mandates, Storage Mandates and GHG Emission Reduction Mandates. These are utilized to inform the WIS:dom-P model of what is expected and what requirements are in place. Over 30 states have a renewable portfolio standard in place. Just over 10 states currently have a clean energy mandate. The northeast has become increasingly aggressive in setting offshore wind energy targets. The Production Tax Credit and the Investment Tax Credit for renewables is used in WIS:dom-P. The 45Q is also applied with the CCS technology. Both policies affect the baseline costs of these technologies.

4.4 United States Weather Analysis

The present section will analyze the weather data specific to the contiguous US for this study. This section will provide insight into why certain renewable sources are selected by the model. Even with the renewable resources available in the US, firm and clean energy sources will be in demand and necessary for a grid of the future.

Figure 4.9 displays the average wind and solar capacity across this region by hour of the day. The wind is for the 100-meter (above ground) level. The solar technology is single axis tracking pitched to latitude tilt. The NREL medium electrification load is also displayed for comparison. The series are shown for the average of the entire year and then the summer (June, July, August) and winter (January, February, March) seasons. The weather year for 2020 is used as the basis for this analysis. Figure 4.9 also shows a typical normalized load pattern for 2020 (top) and 2050 (bottom).

Figure 4.9 demonstrates the solar resource is both higher in peak and longer in duration during the summer, reaching over 60% capacity factor in those months for the US. For wind, the reverse occurs where this resource drops during the summer and increases during the winter. The stronger jet stream and weather patterns in winter are apparent. However, this seasonal discrepancy is not large in the nighttime hours for wind. Wind also exhibits a diurnal pattern where stronger resource is observed during the nighttime hours. This is a normal phenomenon for wind when the decoupling of the boundary layer near the surface at night allows for wind speeds to regularly increase due to less friction from the surface. Nighttime hours can see around 50% capacity factors from the wind resource on average for the whole year. It is easy to see the complementary temporal patterns in the wind and solar resource. The summer load dwarfs the winter months. The loads by 2050, with increased electrification, flatten out across the day compared to a standard 2020 load pattern. The typical nighttime load lulls in 2020 generally increase by 2050. This does match well with the average wind patterns of higher speeds at night showing an increase value of that technology in an electrified economy. The solar resource peaks nearer the load peaks of 2020. The peak of the solar tends to occur on average a few hours in advance of the diurnal peak load (leading to large evening ramps, typically described in the "duck curve"). In winter, the shape of the wind resource is more correlated with the shape of the load. This observation along with the anti-correlated nature of wind and solar shows the viability of wind.



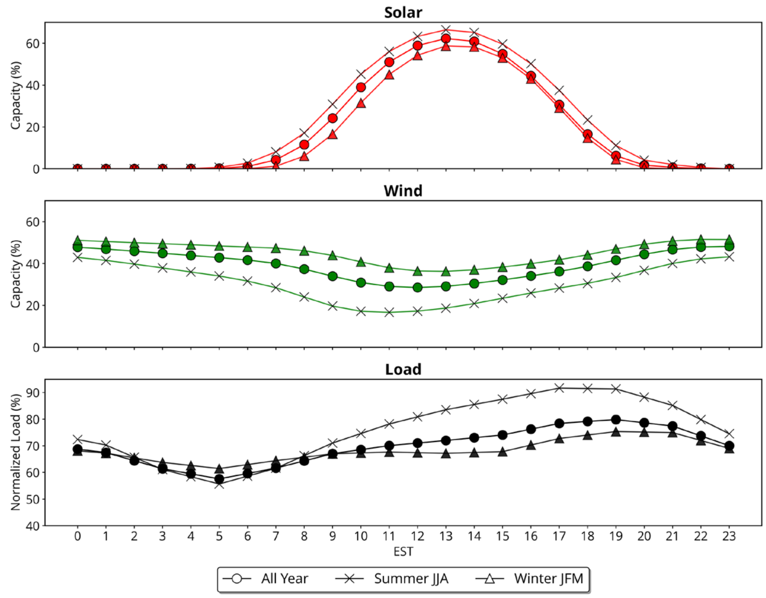


Figure 4.9: The average solar (red) and wind (green) resource shown for the US alongside the corresponding NREL load (black) by hour of the day (EST). The circles show the hourly averages for the entire 2020 year. The other two series look at the summer (JJA) and winter (JFM) months of 2020. This shows a 2020 (top) and 2050 (bottom) normalized standard load pattern.

VCE investigated the wind and solar resources at different spatial granularities as well for the present analysis. Figure 4.10 shows the average annual wind and solar resources throughout the day for the US contiguous states. Offshore potential sites are a part of these averages for wind. Figure 4.11 shows the average wind and solar resource for the 2020 weather year by state for the United States. These four images combined show the prominent wind and solar resources available across many states. Solar shows a clear delineation in afternoon peak resource in the southwestern states. However, even with that said, it is very ubiquitous throughout all states with average hourly resources peaking during the day above 40% capacity factors even for states with less resource. The peak phase shift going from western to eastern states is noticeable. Where possible, WISdom-P will work to take advantage of that offset. There is a much higher range in average resource across states regarding the wind resource. The Central Plains states boast continually high winds on average throughout the day. The southeast states as well as various intermountain west states have the lowest wind resource. This is a state-wide average; pockets of higher winds are possible. Tehachapi in California is an example.

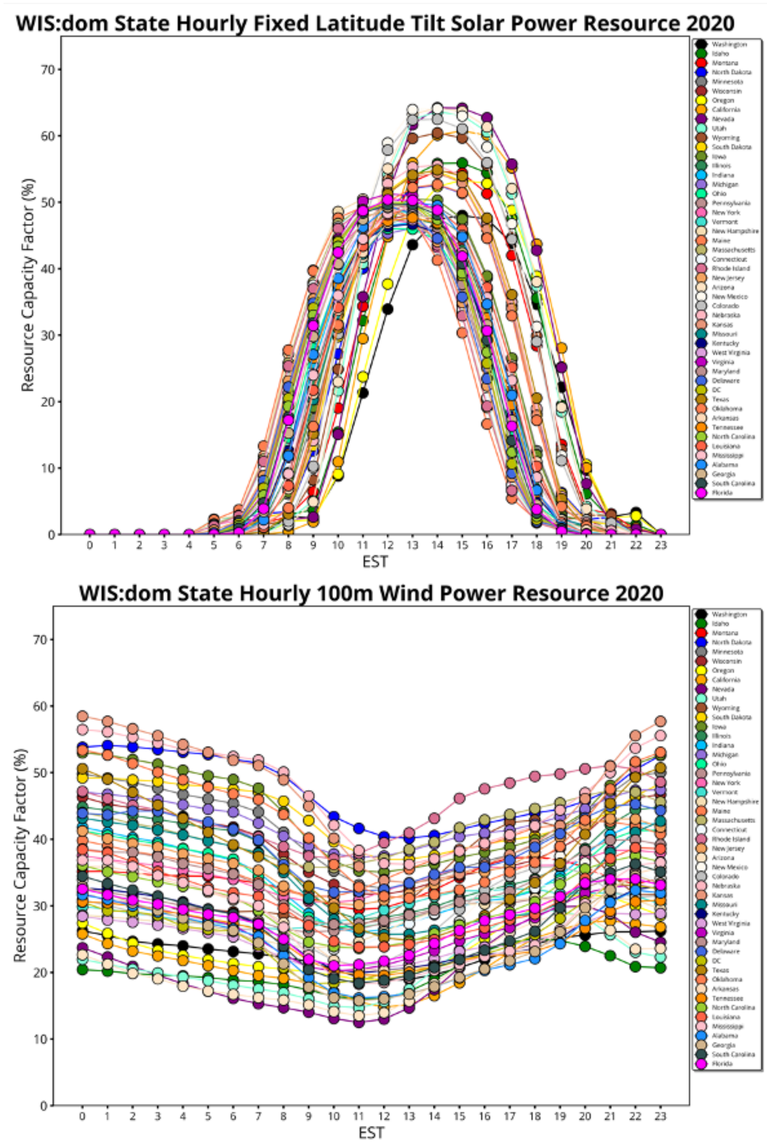
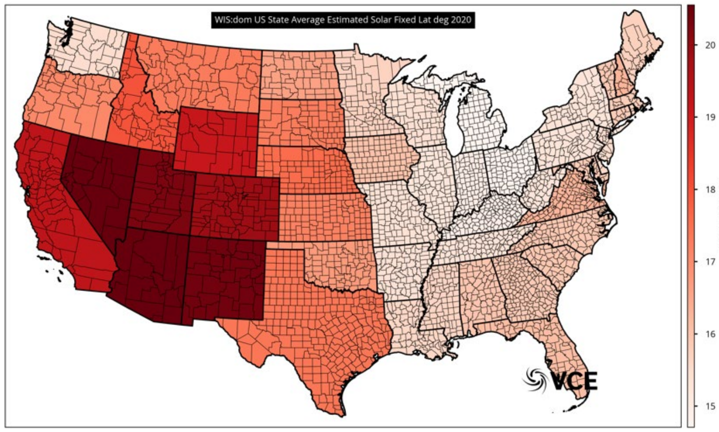


Figure 4.10: The 2020 average hourly solar resource capacity for all states (top). The 2020 average hourly wind resource capacity for all states (bottom)



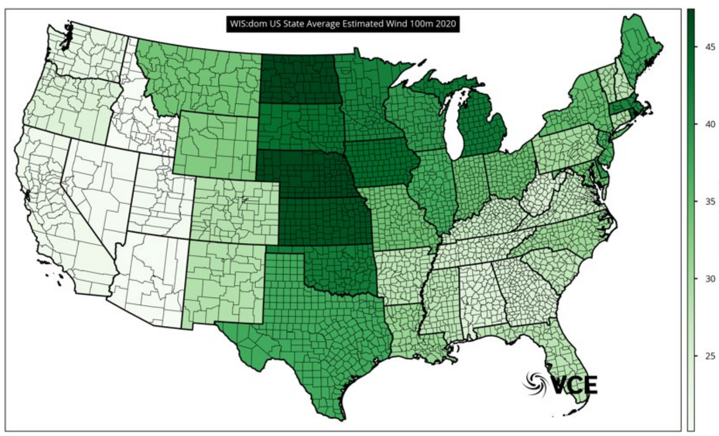


Figure 4.11: The average solar capacity factor (%) for 2020 by state in the US (top). The average wind capacity factor (%) for 2020 by state in the US (bottom)

VCE utilizes the 3-km NOAA HRRR weather model as the raw inputs for the weather and power datasets. Figure 4.12 looks at the wind capacity resources at this granularity across the US. The high resource in the center of the country is pronounced. Intermittent pockets of higher winds are observed in the western US and along the eastern seaboard into New England. The latter though will have space constraints the west will not have in the same way. Offshore wind will be a bigger driver of the layout along the eastern coast within the next decade. Floating offshore technologies necessary on the west coast are still in their infancy. It is clear from Fig. 4.12 that the wind resources are far more heterogenous than the solar resource across many states, but there is an abundance of both resources within the US.

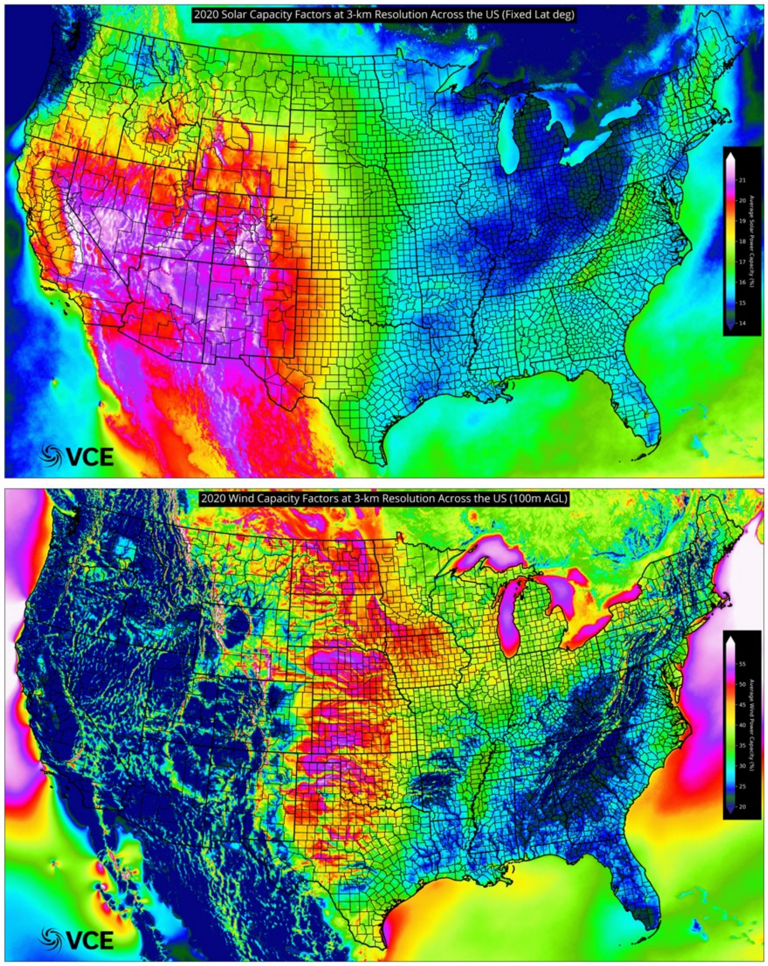


Figure 4.12: The 3-km latitude-tilted solar resource across the contiguous US in 2020 (top). The 3-km 100-meter wind resource across the contiguous US in 2020 (bottom).