Detailed Siting Enhancement of MISO High Penetration Wind, Solar and Storage:

Scenario Modeling Results

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Prepared For:
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Table of Contents

1. VCE® Background

Vibrant Clean Energy, LLC (VCE®) is a Colorado company that has positioned itself as a world-class provider of renewable energy assessment and energy optimization studies. VCE®, since its beginnings, has focused on providing the analytical underpinning for the energy transition underway across the world. The team at VCE® have provided support to the private and public sectors enabling more intelligent implementation of energy resources onto the electricity grid.

The primary mission of VCE® is to provide clients with the least-cost pathways to fulfill their particular needs. The least-cost pathways can be benchmarked against sensitivities to assess the impacts of alternative options. VCE® has expertise on Renewable Energy (RE), Energy Efficiency (EE), electric/thermal energy storage, system integration, Electric Vehicles (EVs), sector electrification, natural gas markets, economics, software development, policies and regulations, and big-data analytics.

VCE® is led by founder and CEO Dr Christopher T M Clack, who has a background in mathematics, statistics and renewable energy modeling. He has been building energy grid integration models for almost a decade with a strong interest in agnostic cost co-optimization. All the models that Dr Clack has created are constructed from the ground up to incorporate high-resolution weather and load data. In a nutshell, the models are designed to deal with big data.

The flagship model is known as WIS:dom® [Weather-Informed energy Systems: for design, operation, and market optimization]. It is the successor to the C-OEM suite. It is the first, and only, commercially available combined capacity expansion and production cost model that can solve for the entire North American grid, while considering variable generation, at 5-minute 3-km resolution, transmission power flow, generator physical limitations, retirements, and yearly investment periods. It, also, simultaneously solves for electricity storage, electric demand, sector electrification, and fuel markets and supply.

2. Purpose of Study

Study Objectives:

- The creation of a consecutive three-year weather and power dataset for wind and solar generators at 3-km, 5-minute resolution across the entire Eastern Interconnection (EIC) footprint;
- Description of the process and metrics surrounding the dataset creation;
- Perform detailed modeling of generator, storage and transmission siting using the WIS:dom® optimization tool for the MISO and EIC electricity grids as they transition to extremely high penetration levels of variable renewable energy (VRE), electric vehicles (EV), distributed solar (DPV) and electric storage;
- Compute the potential impacts of transmission and storage on the siting of the VREs;
- Address the issues with extremely high levels of VREs within MISO footprint;
- Calculate the fuel burns in each region of MISO under all scenarios.

Study Approach:

1. Create a high-resolution wind and solar dataset that covers the entire contiguous United States. The dataset will consist of three chronological calendar years and has a granularity of 3-km grid spacing with 5-minute time steps. The input data will be of the highest quality available and the power algorithms will contain state-of-the-science methods.
2. Provide the full dataset to MISO for use in all their future work.
3. Document the processes and methods for MISO and its stakeholders (the companion document to the present one).
4. Incorporate the high-resolution power datasets into WIS:dom® for production cost analysis at 5-minute frequency.
5. Perform WIS:dom® optimizations on twenty scenarios (each with ten investment cycles to reach their final target) to create portraits of the evolution of the MISO and EIC electricity grid under deep penetration levels of VREs.
6. Compose a summary of the modeling results to determine salient features and observations that the modeling displays (present document).
7. Feed the VRE siting decisions from the WIS:dom® scenarios into the MISO MTEP process.

3. High-level Modeling Results

3.1. WIS:dom® Model Scenarios Performed

The following subsections will explore the results from the WIS:dom® model runs for the present study. Scenarios 1-10 include results for the entire Eastern Interconnection (EIC) and Scenarios 11-19 include just MISO alone. For the sake of brevity, not all results and figures from each scenario are included in the result documentation, but all model outputs are available in the included model output spreadsheets (here).

Note that the investment periods used here for these model runs do not correspond to years (or sets of years) like traditional capacity expansion analyses usually do. Here, scenarios 1 and 2 (for the whole of EIC) and 11 (MISO-only) are optimal capacity expansion runs that are given ten investment periods, or iterations, to evolve the grid to a steady or "*optimal*" state. The model needs multiple investment periods because there are limitations to the amount of turn over to the resource mix that can happen in each iteration and the progress towards a target can provide insight into the challenges to be faced and their approximate timing with respect to the distance from the intended goal. Essentially, for optimal scenarios, after iteration 4, the solution should start to converge because the underlying technology costs changes as if time is evolving to 2030 and then remaining stable going forward.

Scenarios 3-10 (EIC) and 12-19 (MISO-only) are designed to test the grids for increasing levels of technology deployment and each investment period is designed to show a percentage of that deployment. For example, in Scenario 8 (Optimal pathway to 90% wind and solar in EIC with transmission expansion), investment period 7 would mean correspond to 70% towards the goal of 90% wind and solar. Thus, the model would require that the EIC be 63% (70%*90%) wind and solar in Scenario 8, investment period 7. Table 1 shows a summary of the 19 scenarios performed, each with ten investment periods (IPs).

Table 1: Minimum WIS:dom® Optimization Model Constraints (blank cell indicates no limit).

Purpose	Scenario	Trading	Tx. Exp.	Wind %	PV %	Storage %	DPV %	DSM %	EV %
Optimal Expansion (EIC)	1		Expand						
Optimal Expansion (EIC)	2	Current	Current						
Optimal Wind & Solar (EIC)	3-4	Current / Expand	Current / Expand	Combined 50%			10%	10%	10%
Optimal Wind & Solar (EIC)	5-6	Current / Expand	Current / Expand	Combined 75%			20%	20%	20%
Optimal Wind & Solar (EIC)	7-8	Current / Expand	Current / Expand	Combined 90%			30%	30%	30%
Optimal Wind & Solar (EIC)	9-10	Current / Expand	Current / Expand	Combined 100%			30%	30%	50%
Optimal Expansion (MISO)	11	None							
Optimal Wind (MISO)	12	None		100%					
Optimal Solar (MISO)	13	None			100%				
Optimal Storage (MISO)	14	None				2%			
Optimal DPV (MISO)	15	None					10%		
Optimal DSM (MISO)	16	None						10%	
Optimal EV (MISO)	17	None							10%
50/50 Wind Solar (MISO)	18	None		50%	50%				
100% Wind and Solar (MISO)	19	None		Combined 100%					

3.2. General Features from EIC Scenarios (1 - 10)

- The economically optimal deployment of wind and solar for the EIC converges to between 25-30% of annual generation.

- Paths to very high levels of VREs have the lowest system costs when renewable generation is between 40 - 45% of annual generation after which the costs can rise dramatically.

- The ability to expand transmission facilitates much more renewables integration at lower costs, while requiring less planning reserve capacity.

- Transmission expansion on average resulted in larger ramps of the thermal and storage fleets (more efficient use of capital) by the latter investment periods, but the system was less reliant on energy storage to meet peak demand.

- High levels of renewables, up to about 80% of annual electricity generation, can be incorporated for approximately the same as 2017 electricity costs, but reaching the last 10-20% towards 100% renewables can increase prices substantially (up to 3x).

Across the scenarios that assessed the impact of differing levels of renewables (Scenarios 3-10), transmission played a key role in resource deployment levels. In general, scenarios that included allowing transmission expansion to non-MISO regions (Scenarios 4, 6, 8, and 10) resulted in more wind and less solar deployment. However, differences in deployment varied across LRZs, with transmission expansion scenarios generally deploying more wind in LRZs 1-5 (the locations with the better wind resource) and, with the exception of the 100% wind and solar scenario, less wind in LRZs 6-10. Up to 75% renewables, including transmission expansion resulted in more solar PV deployment in LRZs 5 and 6, but the trend was reversed in the 90% and 100% renewables scenarios as more transmission expansion resulted in less PV deployment in LRZs 5 and 6.

Allowing for transmission allowed more power to flow to non-MISO regions and reduced curtailment per unit capacity installed, so the model choose to deploy resources (wind in LRZs 1-5) that might have been further away from MISO load, but had better capacity factors (and correlation to load) resulting in lower overall system costs.

3.3. General Features from MISO Scenarios (11 - 19)

For ease of comparison, Figure 1 through Figure 4 show differences for final installed capacity, energy generation by technology, Levelized Cost of Electricity (LCOE), and carbon dioxide (CO_2) emissions for each of the nine MISO-only scenarios (Scenarios 11-19). In general, scenarios that mandated certain percentages of energy to come from wind and solar resulted in higher amounts of capacity, total energy generated (and curtailed), higher LCOE values, but the lowest emissions. Higher renewables scenarios also saw higher ramps (>10x) in the altered load (load + energy storage charging + exports) than in the optimal case. However, even in the optimal case, load ramps increased by about 36% between investment period 1 and 10.

Locational deployment of renewables across the MISO footprint varied based on the scenario, but in the optimal case (Scenario 11) wind tended to be deployed across LRZs 1-7, with the most in LRZ 1 and 3, and little to no deployment in LRZs 8-10, which makes sense given the wind resource availability in each region. Solar PV (utility and rooftop) was most concentrated in LRZs 6 and 9 with little deployed in LRZs 3, 4, and 7. Scenario 15 (10% distributed PV) followed similar trends, except there was also more deployment in LRZ 5, 8, and 10. Storage deployments were most concentrated in LRZs 5 and 6. Scenarios 14, 16, and 17 followed similar trends as Scenario 11.

In Scenario 12 (100% wind), each LRZ received a significant wind build out by investment period 10, with all, save LRZ10, deploying over 60 GW each, with the largest deployment of almost 100 GW in LRZ 4. The second most wind deployment was almost 90 GW (including 366 MW offshore wind in the Gulf of Mexico) in LRZ 9, which received none in the optimal scenario (Scenario 11). All regions experienced large energy storage deployments with LRZ 9 receiving the most (~48 GW), but LRZs 1 and 5-8 all deployed over 10 GW of storage.

In Scenario 13 (100% solar), about 2/3 of the solar capacity (utility and rooftop) was deployed in LRZs 1, 9, and 10 – locations with typically better solar resources. Each LRZ received energy storage, with over 80% deployed in LRZs 1, 3, 6, 8, and 9.

The final two high renewables scenarios (18 and 19) deployed solar, wind, and storage in similar patterns. Wind was more favorably deployed in LRZs 1, 3, 5, and 9, while solar was generally more built in LRZs 2, 4, 7, and 9, and energy storage was more favored in LRZs 4, 6, 7, and 9.

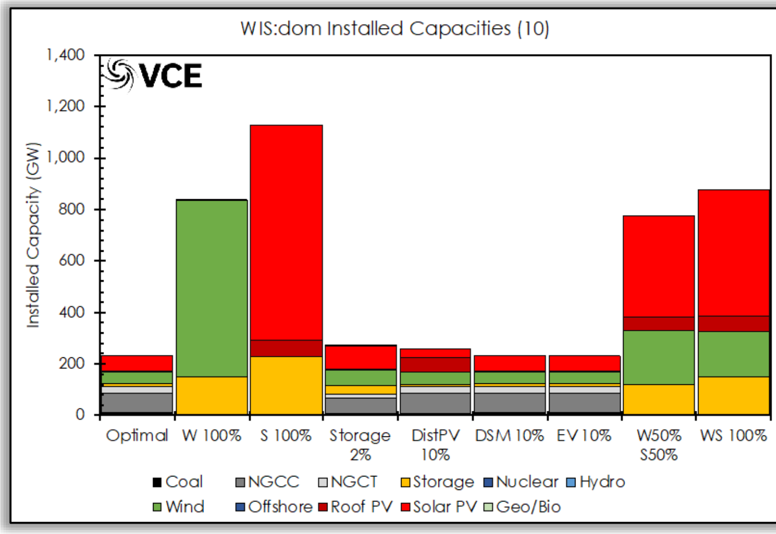


Figure 1: A comparison of the final installed capacities (investment period 10) for each of the MISO-only scenarios.

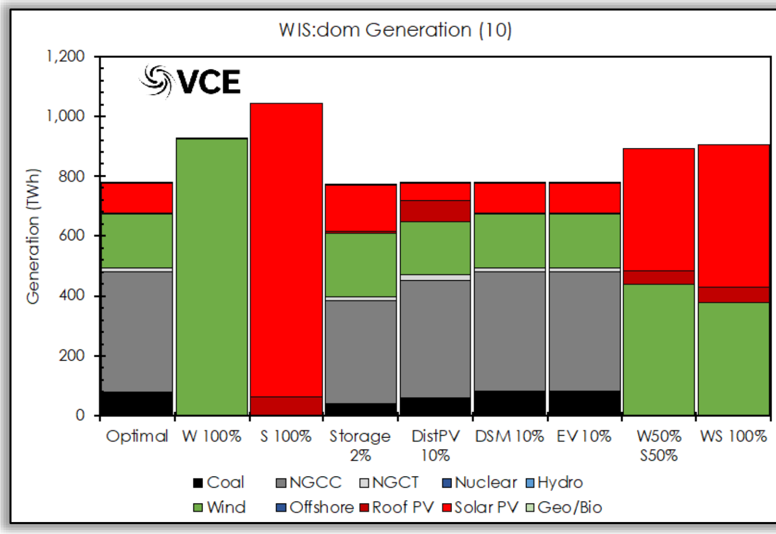


Figure 2: A comparison of the final amount of generation by technology type for each MISO-only scenario.

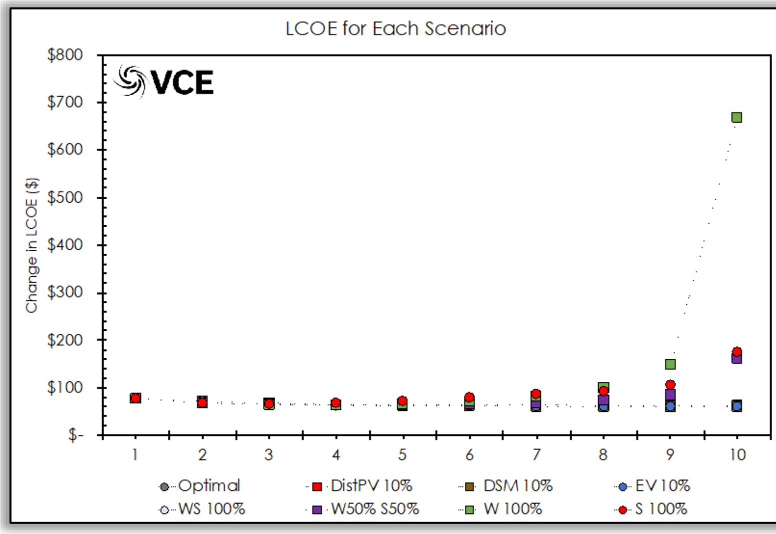


Figure 3: A comparison of the LCOE of each MISO-only scenario by investment period.

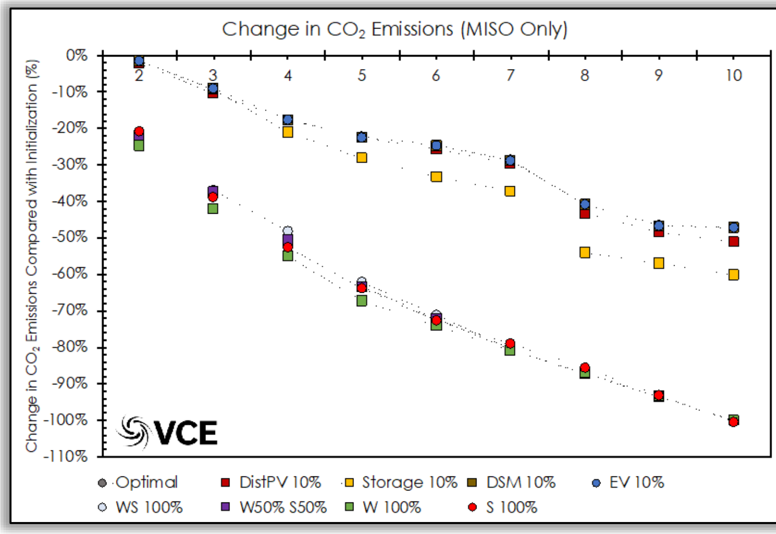


Figure 4: A comparison of the emissions (CO_2 only) impacts of each MISO-only scenario by investment period.

4. Details of the EIC Modeling Scenarios

4.1. Optimal Expansion (EIC) with Transmission Expansion (Scenario 1)

The first scenario considered here is an optimal expansion of the Eastern Interconnect (EIC) where both transmission and energy trading are allowed to expand. In this scenario, the WIS:dom® optimization model was allowed to choose the location and amount of each type of generation resource available to it with the objective to least-cost optimize the matching of electricity supply and demand for every five-minute interval of each investment period.

Figure 5 shows the evolution of installed capacity by power plant type for Scenario 1. In general, coal, NGCT (natural gas combustion turbines), and nuclear capacities fall while NGCC (natural gas combined cycle), energy storage and renewable capacities rise. By investment period 10, over 928 GW of power plants, of all types exist in the EIC, up from about 790 GW in the first investment period. Between investment period 1 and 10, coal decreases by about 68%, NGCC increases by about 31%, NGCT decreases by about 53%, storage increases by about 227%, all nuclear retires, about half of the hydro fleet retires, wind increases by almost 280%, offshore wind increases by almost 100%, and solar increases by over 4,000%. Economic dispatch of the fleet causes the capacity factors of the remaining thermal plants to generally rise over the investment periods as the fleet transitions.

Between steps 6 and 7 we also see the maximum system load exceeding firm generation supply (coal, gas, nuclear, hydro and storage). This does not mean that the model was not able to match supply and demand, but that, on peak, the system is able to rely on some renewables to be online.

By investment period 10, wind (on and offshore) and solar (utility and rooftop) account for about 32% of the total amount of electricity generated in the EIC compared with just over 5% in the first investment period. These final values align with previous studies that have looked at EIC-wide potential renewable deployments. Storage levels approach almost 50 GW of power capacity and about 225 GWh of energy capacity, resulting in about 4.5 hours of storage duration, which aligns with many current energy storage projects being constructed at 4-hour durations. On peak (total EIC), storage is called on to meet about 3.3% of demand, but is required to meet almost 16% of demand at other times of the year.

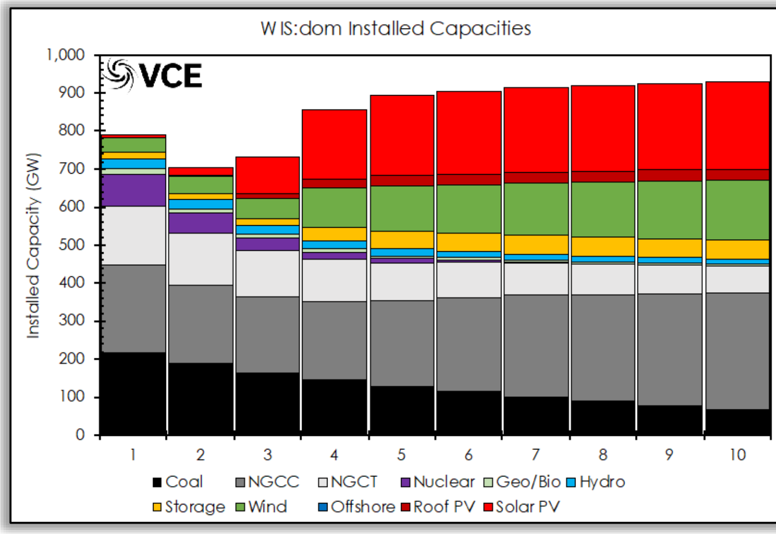


Figure 5: Power plant capacities by type in the EIC over each of the investment periods in Scenario 1. State and county level data are available in the included spreadsheets of the results.

Figure 6 and Figure 7 show the difference in where WIS:dom® constructs power plants between the first and last investment period. Note that, to keep the maps legible, only power plants larger than 50 MW are shown. As such, it can appear as though there are less diffuse types of power plants, such as Rooftop PV and some smaller wind farms, thus capacity totals for each type are included in the map legend. Also note that power plants larger than 2,500 MW were all assigned the same size circle to again make the maps easier to read. All county-level capacity data are available in the included results spreadsheets.

The most noticeable difference between the two figures is the replacement of the large coal and nuclear units with large NGCC and storage units along with the deployment of large amounts of solar PV across the EIC's footprint.

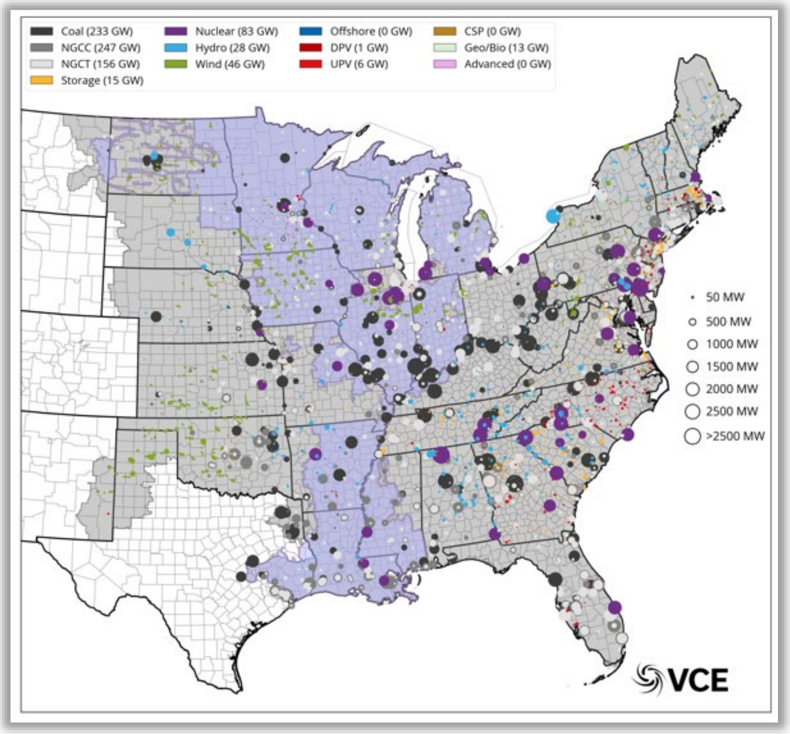


Figure 6: Location, type and size of powerplants in the EIC for Scenario 1, investment period 1. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

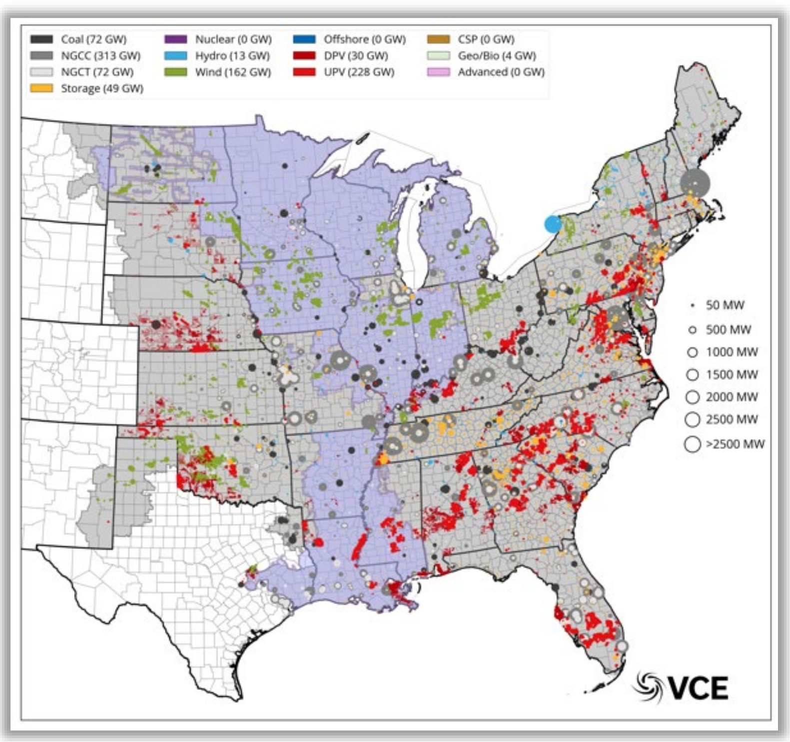


Figure 7: Location, type and size of powerplants in the EIC for Scenario 1, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 8 shows example seasonal hourly dispatch patterns for the first and last iterations of the entire EIC system. Coal and nuclear generation substantially decline between the first and last iteration, while NGCC generation and energy storage dispatch increase to compensate for ramps in demand and renewable output. Wind and solar become integral parts of the resource mix by the tenth investment period.

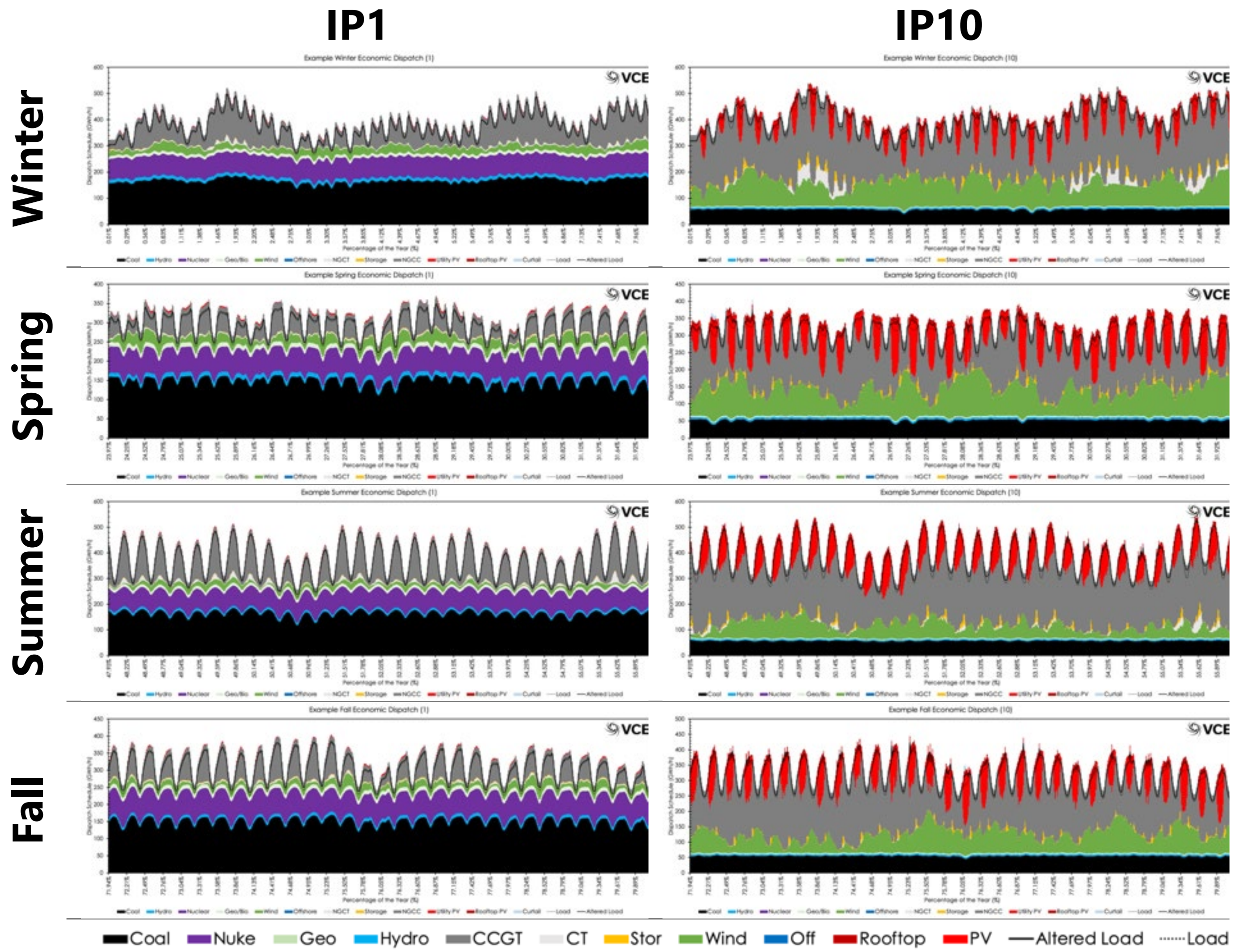


Figure 8: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 1.

In investment period 1, the EIC-wide NGCC fleet ramps (up and down, absolute value per hour), about 3.4%, with a max ramp of about 14.4% over the entire simulation year, NGCT plants ramp less, about 0.5% per hour, with a max ramp of 6.1%, and storage ramps, on average less than 1% per hour, but has a max ramp of almost 62%. However, by investment period 10, average hourly fleet wide ramps have increased to 3.9%, 1.5%, and 7.7% for NGCC, NGCT, and storage, respectfully, and maximum ramps increased more so, to 16.4%, 70.8%, and 96.4% for the three technologies. Coal generally ramped less often in investment period 10, but did have slightly higher maximum ramps.

Figure 9 shows the percent breakdown of generation from each technology for all investment periods in Scenario 1. The percentage of generation from coal and gas plants combined stays relatively constant over all the iterations, whereas nuclear is largely replaced by additions of wind and solar PV. Even though the total nameplate capacities of fossil fuel plants decline overall (see Figure 5), increased capacity factors for the remaining fleet keep the percentage of total amount of electricity generated by fossil fuels relatively flat, although coal's share falls in every investment period. Note that total electricity consumption is assumed to grow about 5% from the first to the tenth iteration.

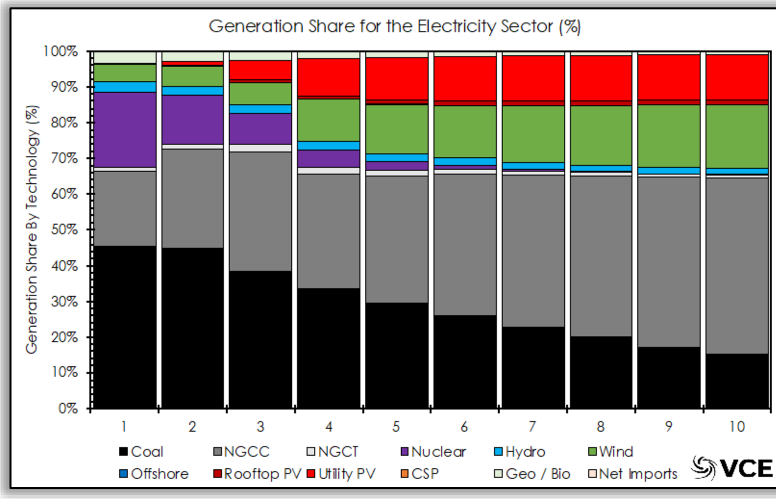


Figure 9: Percentage generation share for the electricity sector by technology and iteration number for Scenario 1.

Figure 10 shows the change in emissions, relative to the first iteration, for iterations 2-9. After initial increases, due to retiring nuclear plant's generation being replaced mostly with natural gas, emissions decline across the board due to coal-to-gas switching and increasing renewable generation. Some emissions fall faster than others, such as SO_2, because coal plants generally emit much larger quantities than gas plants. Carbon emissions fall modestly due to the fact that the share of gas generation increases and gas plants emit carbon, albeit less than coal plants.

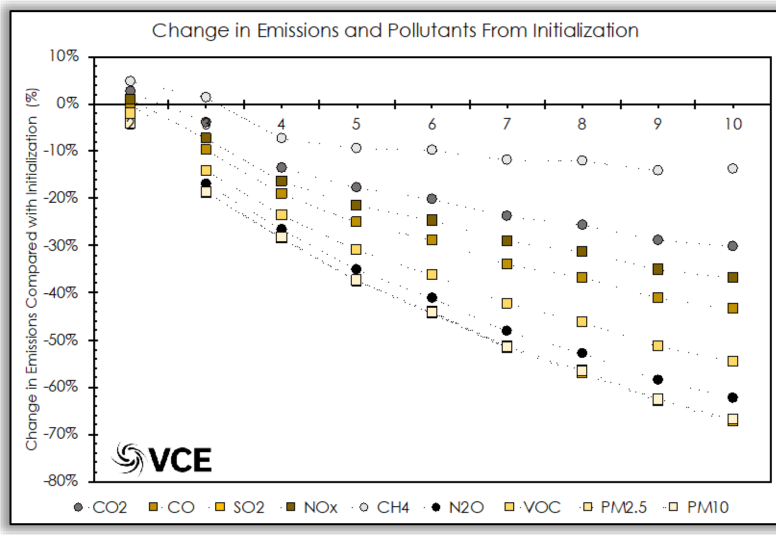


Figure 10: Emissions impacts given the changes in electricity generation for all investment periods of Scenario 1.

Figure 11 shows the change in employment in the electricity sector for each iteration, relative to the first iteration – between the first and tenth iteration, electricity sector employment increases by about 116%. However, the jobs created are in different sectors. Coal jobs decrease by about 68%, nuclear jobs decrease almost 100% and natural gas jobs remain almost flat. On the other hand, wind jobs increase by over 280%, transmission jobs increase by over 200%, and solar jobs increase the most, by almost 4,200%, relative to the first iteration.

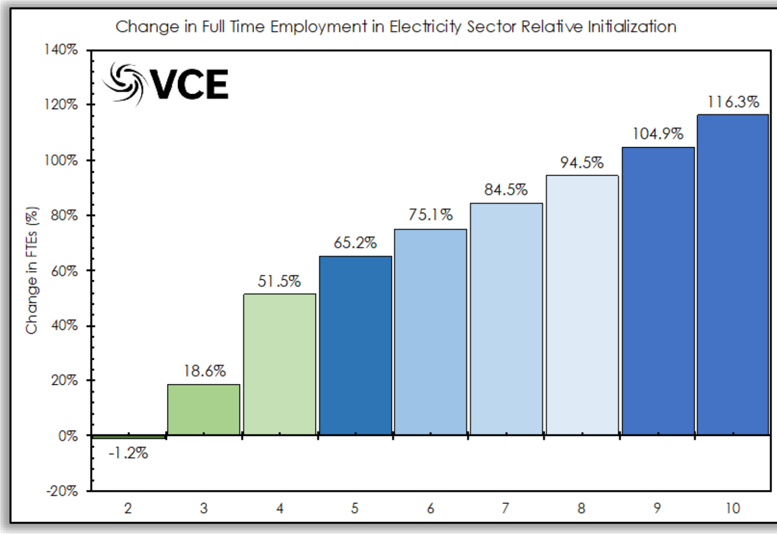


Figure 11: Employment (full-time equivalent) impacts given the changes in the EIC's electricity sector for Scenario 1.

Figure 12 shows the change in delivered electricity costs for each investment period, relative to the first investment period, or initialization. As this analysis is an optimal capacity expansion, the model chooses the least-cost suite of technologies to deploy each iteration and, thus, we see costs decline over all investment periods. Costs decline quickly at first as the model retires the least economical units and then costs declines slow as the system approaches the optimal grid mix.

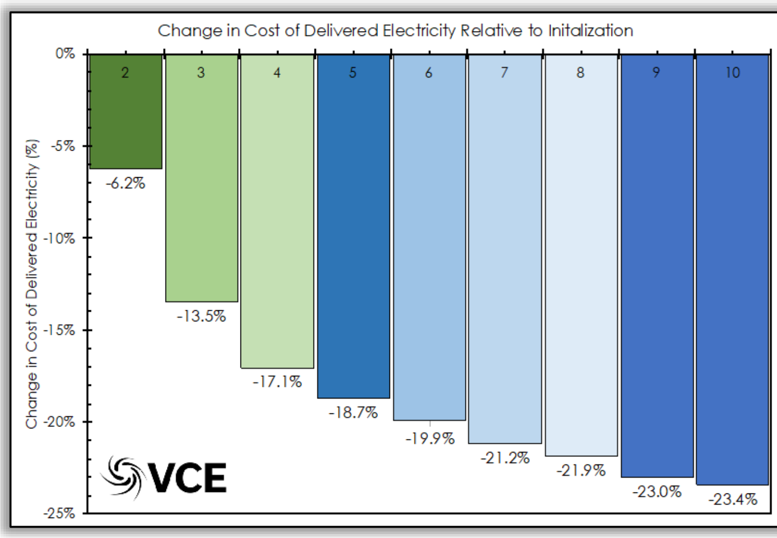


Figure 12: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 1.

Figure 13 shows the deployment of transmission between each state in the EIC as well as to and from the MISO LRZs. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. In general, it is optimal to build transmission in most areas and over most investment periods as a more connected grid makes it easier to deploy least-cost technologies to match supply and demand.

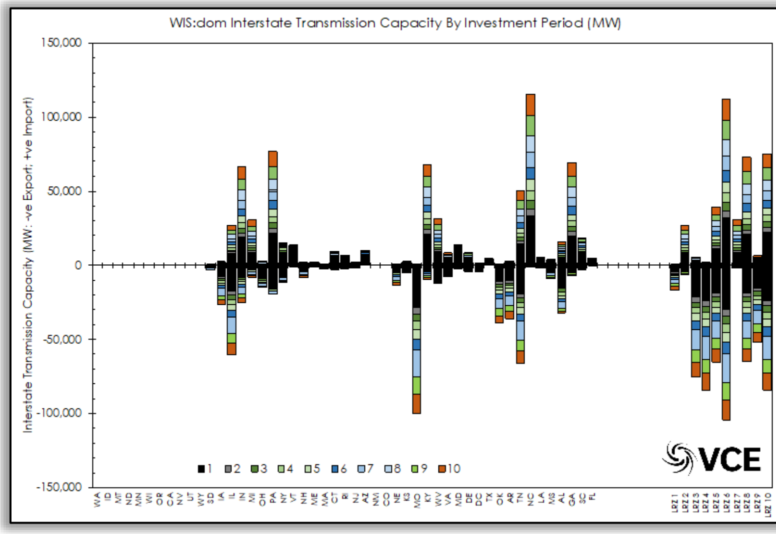


Figure 13: Interstate and inter-MISO region transmission capacity (MW) by investment period for Scenario 1. Negative values indicate capacity to export and positive values indicate capacity to import into that state/MISO region.

Figure 14 through Figure 16 show the coal, natural gas, and uranium fuel burns in billion mmBtu (Quads) for each investment period, respectfully. Coal fuel burn declines across the board in every region because other generation types are deployed and dispatched. Natural gas fuel burn trends upward over the investment periods except for a temporary decline between investment period 3 and 4 due to a large deployment of renewables in that investment step. However, by investment period 5, the upward trend in natural gas fuel burn resumes. Uranium fuel burn declines rapidly until investment period 8 where it essentially goes to zero, there is some residual nuclear generation in the latter investment periods, but the vast majority of nuclear capacity retires over the entire EIC.

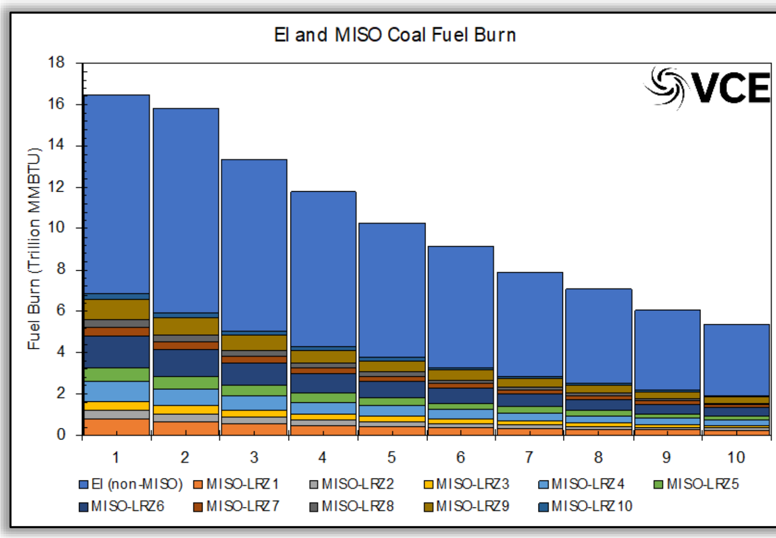


Figure 14: Coal fuel burn (billion mmBtu or Quads) for each MISO LRZ and the rest of EIC for Scenario 1.

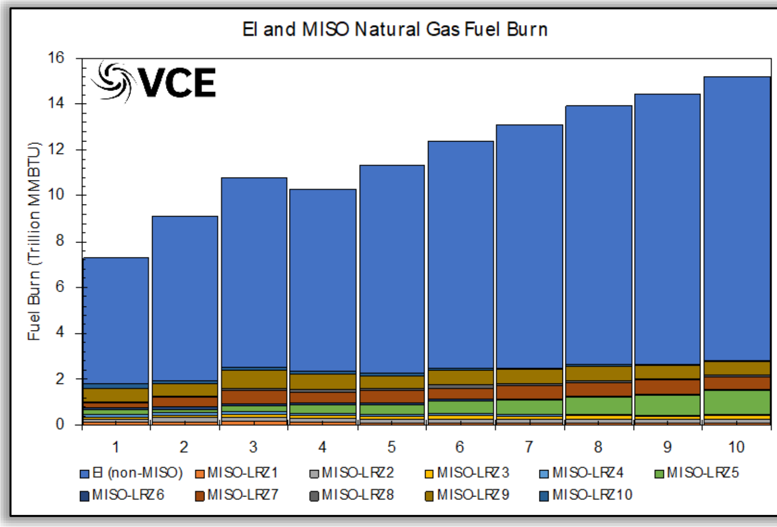


Figure 15: Natural gas fuel burn (billion mmBtu or Quads) for each MISO LRZ and the rest of EIC for Scenario 1.

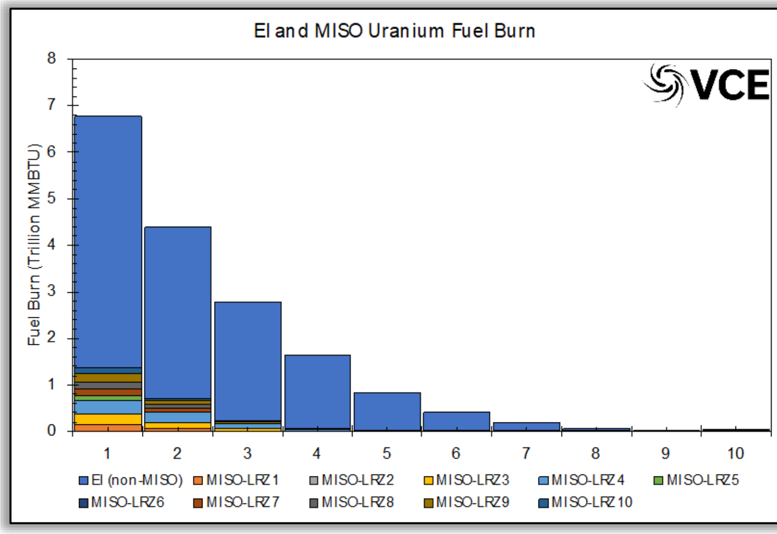


Figure 16: Uranium fuel burn (billion mmBtu or Quads) for each MISO LRZ and the rest of EIC for Scenario 1.

4.2. Optimal Expansion (EIC) without Transmission Expansion (Scenario 2)

This scenario has the same objective and input assumptions as the first scenario, except that the WIS:dom® model is not allowed to expand transmission or energy trading between MISO and non-MISO regions of EIC. However, economical expansion of both are allowed between MISO LRZs. For the sake of brevity, only a selection of the Figures shown for Scenario 1 will be shown for the other EIC-wide scenarios, but all figures are available in the spreadsheets and data files that are included with the present report.

Figure 17 shows the evolution of installed capacity by power plant type for Scenario 2. In general, coal, NGCT, and nuclear capacities fall while NGCC, energy storage and renewable capacities rise. By investment period 10, over 888 GW (40 GW less than Scenario 1) of power plants, of all types exist in the EIC, up from about 790 GW in the first investment period. Between investment period 1 and 10, coal decreases by about 68%, NGCC increases by about 30%, NGCT decreases by about half, storage increases by about 227%, nuclear decreases by almost 70%, about half of the hydro fleet retires, wind increases by almost 170%, offshore wind increases by almost 120%, and solar increases by over 3,700%. Economic dispatch of the fleet causes the capacity factors of the remaining thermal plants to generally rise over the investment periods as the fleet transitions.

Unlike in Scenario 1, maximum system load does not exceed firm generation supply (coal, gas, nuclear, hydro and storage). This indicates how a more connected grid can access more and cheaper resources and remain stable at higher levels of renewables. Also, unlike Scenario 1, some nuclear capacity is retained in the EIC, including in MISO territory.

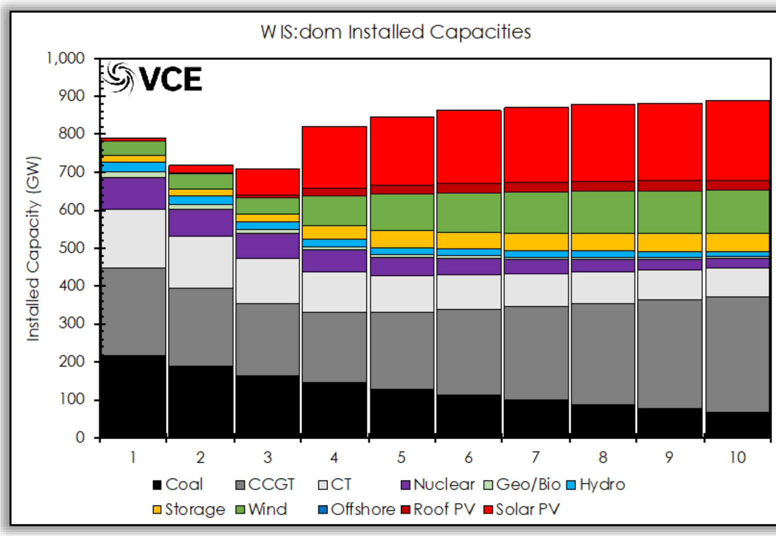


Figure 17: Power plant capacities by type in the EIC over each of the investment periods in Scenario 2. State and county level data are available in the included spreadsheets of the results.

By investment period 10, wind (on and offshore) and solar (utility and rooftop) account for about 26% of the total amount of electricity generated in the EIC compared with just over 5% in the first investment period. Similar to Scenario 1, storage levels approach almost 50 GW of power capacity and about 225 GWh of energy capacity, resulting in about 4.5 hours of storage duration. On peak (total EIC), storage is called on to meet about 7.8% of demand, but is required to meet up to 13.8% of demand at other times of the year.

Thus, without transmission expansion, the system is more reliant on storage on-peak, but less reliant on average.

Figure 18 shows the siting of power plants in the last investment period for Scenario 2. This Figure can be directly compared to Figure 6 as that is the same starting point for Scenarios 1-10. Note that, to keep the maps legible, only power plants larger than 50 MW are shown. As such, it can appear as though there are less diffuse types of power plants (such as rooftop PV and some smaller wind farms), thus capacity totals for each type are included in the map legend. Also note that power plants larger than 2,500 MW were all assigned the same size circle to again make the maps easier to read. All county-level capacity data are available in the included results spreadsheets.

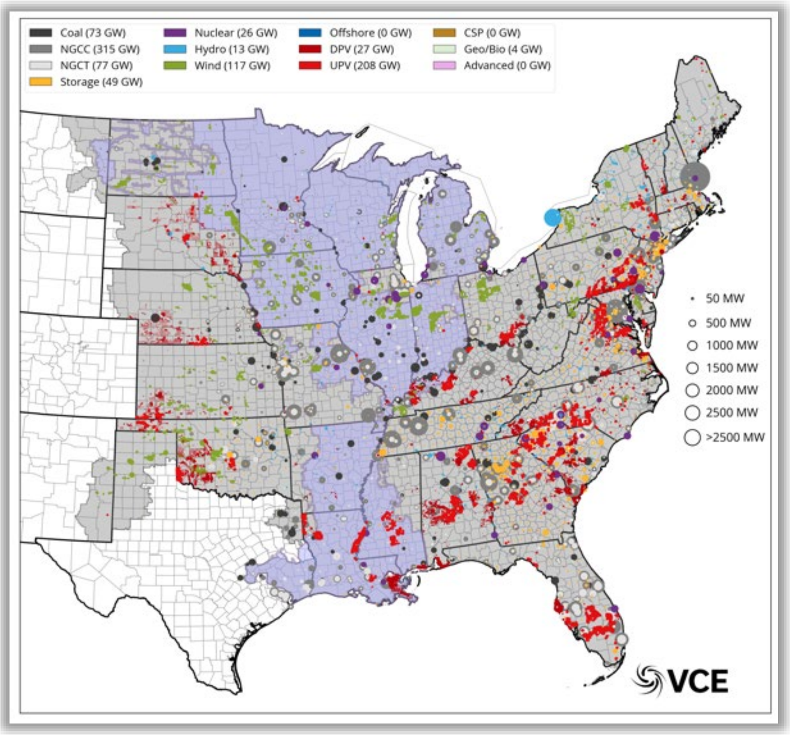


Figure 18: Location, type and size of powerplants in the EIC for Scenario 2, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 19 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire EIC system. Coal and nuclear generation substantially decline between the first and last iteration, while NGCC generation and energy storage dispatch increase to compensate for ramps in demand and increased renewables output. Similar to Scenario 1, the wind and solar (by IP 10) are substantial fractions of the electricity mix.

IP1 **IP10**

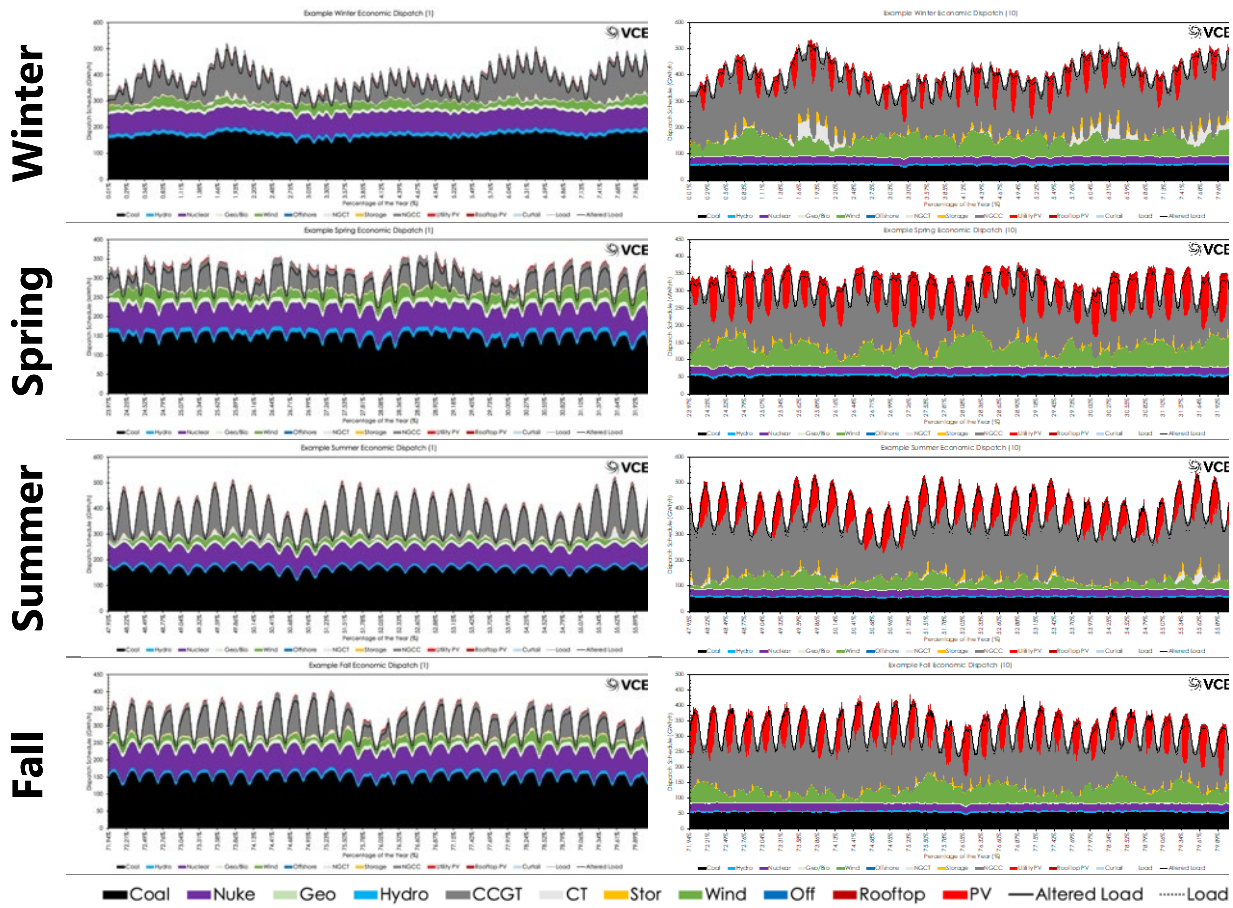


Figure 19: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 2. Hourly dispatch values are available in the accompanying results spreadsheets.

In investment period 1 (the results of which are the same as Scenario 1), the EIC-wide NGCC fleet ramps (up and down, absolute value per hour), about 3.4%, with a max ramp of about 14.4% over the entire simulation year, NGCT plants ramp less, about 0.5% per hour, with a max ramp of 6.1%, and storage ramps, on average less than 1% per hour, but has a max ramp of almost 62%. However, by investment period 10 in Scenario 2, average ramps have increased to 3.9%, 1.3%, and 6.7% for NGCC, NGCT, and storage, respectfully, and maximum ramps increased more so, to 15%, 61%, and about 85% for each of the technologies. Coal ramps did not change much. Maximum ramps are lower in Scenario 2 because less renewables have been deployed and more firm generation is still online.

Figure 20 shows the percent breakdown of generation from each technology for all investment periods in Scenario 2. The percentage of generation from coal and gas plants combined stays relatively constant over all the iterations whereas nuclear is largely replaced by additions of wind and solar PV. Even though the total nameplate capacities of fossil fuel plants decline overall (see Figure 17), increased capacity factors for the remaining fleet keep the percentage of total amount of electricity generated by fossil fuels relatively flat, although coal's share falls in every investment period. Note that total electricity consumption is assumed to grow about 5% from the first to the tenth iteration.

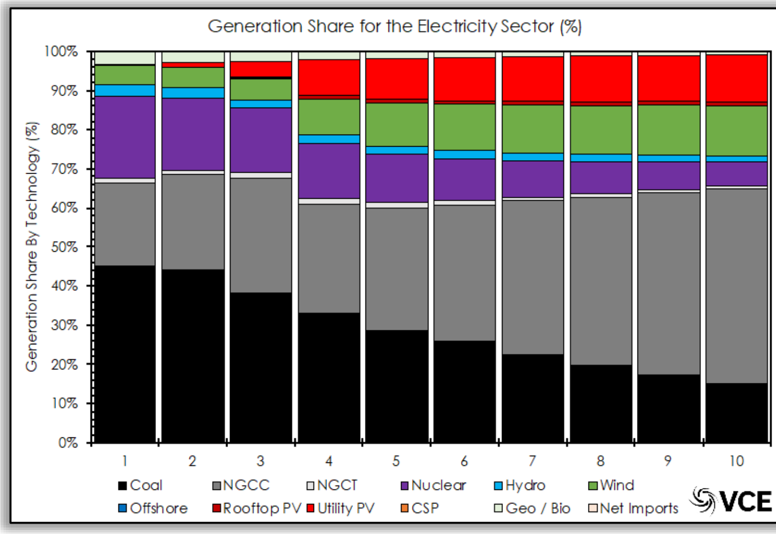


Figure 20: Percentage generation share for the electricity sector by technology and iteration number for Scenario 2.

Figure 21 shows the change in delivered electricity costs for each investment period, relative to the first investment period, or initialization. As this analysis is an optimal capacity expansion, the model chooses the least-cost suite of technologies to deploy each iteration, thus we see costs decline over all investment periods. Costs decline quickly at first as the model retires the least economical units and then costs declines slow as the system approaches the optimal grid mix. While costs fall substantially for each investment period, they do not fall as much as Scenario 1; declining about 22% in compared with 23.5% in Scenario 1 (See Figure 12).

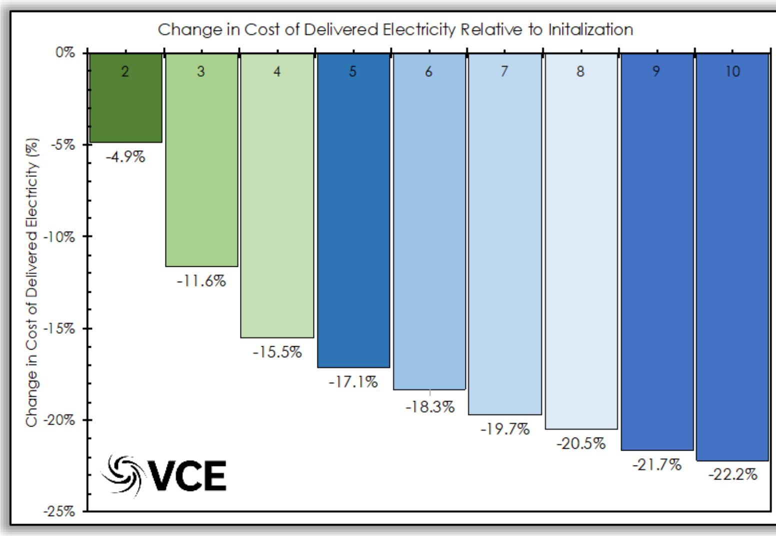


Figure 21: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 2.

Figure 22 shows the deployment of transmission in each state in EIC as well as to and from the MISO LRZs for Scenario 2. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. Note that in this scenario, transmission expansion between MISO and non-MISO regions was not allowed, but transmission expansion between MISO LRZs and expansion between non-MISO regions in EIC was allowed. This restriction resulted in quite a bit less transmission expansion in Scenario 2 relative to Scenario 1 (see Figure 13).

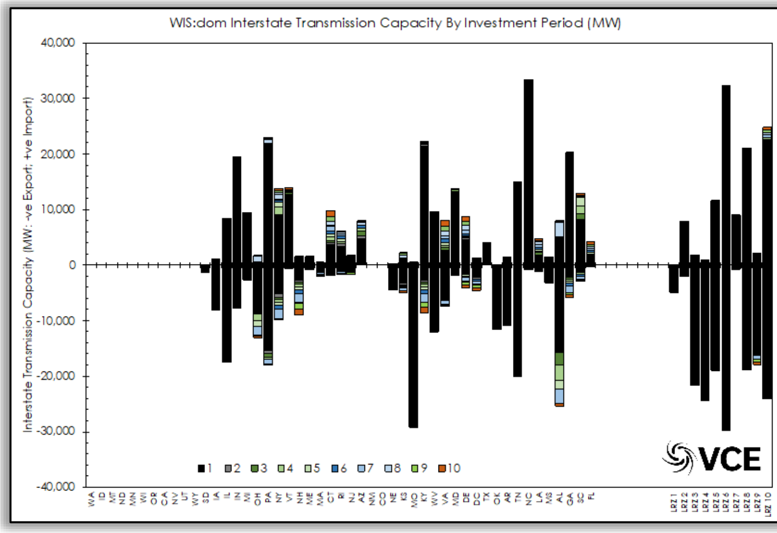


Figure 22: Interstate and inter-MISO region transmission capacity (MW) by investment period for Scenario 2. Negative values indicate capacity to export and positive values indicate capacity to import into that state/MISO region.

By investment period 10, while, in general, the effect of less transmission expansion led to lower levels of renewable deployment, the effects were different across the MISO LRZ regions. Wind deployments fell (between Scenario 1 and 2) in every LRZ except LRZ5, which saw about 2 GW more deployment. LRZs 1 and 3 saw the most contraction in wind deployments, each having about 4 GW less in Scenario 2. LRZs 9 and 10 saw less solar (utility and rooftop) deployment in Scenario 2 relative to Scenario 1, while LRZs saw more solar deployments. Solar capacity factors are generally more spatially uniform than they are for wind, so, given restrictions in building transmission from MISO to non-MISO regions, the model opted for renewables that were better matched to local demand.

In Scenario 2, emissions fall across all categories with CO_2 emissions falling by about 31% by investment period 10, which is slightly more than in Scenario 1 (30% CO_2 reductions). This difference is likely due to more nuclear plants staying online and still generating about 6% of total energy in the EIC. Full emissions details and accounting are available in the results spreadsheets.

Full time employment in the electricity sector by investment period 10 increases by about 52% relative to today in Scenario 2 vs. a 116% increase in Scenario 1. This difference is largely do the reduction in the number of transmission associated jobs given the reduced ability of the model to build transmission between MISO and non-MISO regions.

Fuel burn data and figures are available in the results spreadsheets, but similar patterns are seen as in Scenario 1. In Scenario 2, natural gas fuel burned more than doubles to almost 15 Quads, coal fuel burn decreases from about 16.5 to 5.3 Quads and uranium fuel burn decreases from 6.8 to 2.1 Quads, but does not disappear as in Scenario 1.

4.3. Path to 50% Wind & Solar (EIC) without Transmission Expansion (Scenario 3)

This scenario charts the optimal pathway for the entire EIC to generate half of its power from wind and solar by the 10th investment period. In this scenario, the model is not allowed to expand transmission or energy trading between MISO and non-MISO regions of EIC. However, economical expansion of both are allowed between MISO LRZs.

Figure 23 shows the evolution of installed capacity by power plant type for Scenario 3. In general, coal, NGCT, and nuclear capacities fall while NGCC, energy storage and renewable capacities rise. By investment period 10, over 1,308 GW of power plants, of all types exist in the EIC, up from about 790 GW in the first investment period. Between investment period 1 and 10, all coal retires, NGCC increases by about 48%, NGCT decreases by about half, storage increases by about 334%, all nuclear retires, almost all of the hydro fleet retires, wind increases by almost 540%, and solar increases by over 8,900%.

Economic dispatch of the fleet causes the capacity factors of the remaining thermal plants to generally rise over the investment periods as the fleet transitions. Also, storage is called upon to meet as much as 20% of demand during certain periods.

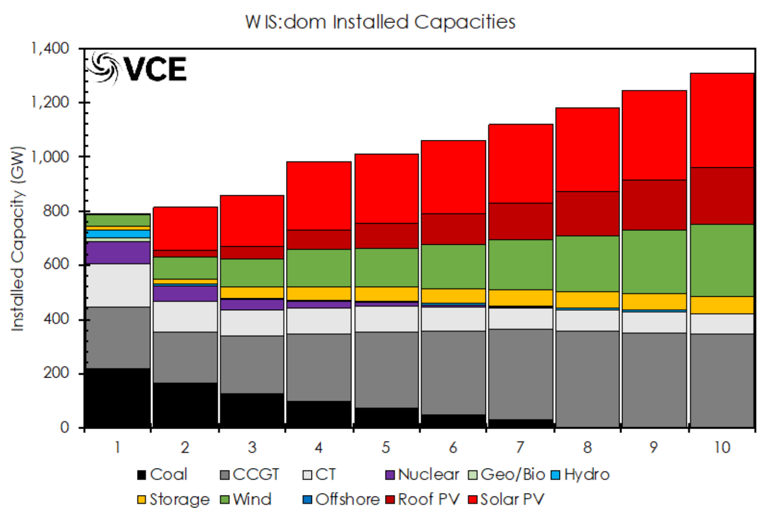


Figure 23: Power plant capacities by type in the EIC over each of the investment periods in Scenario 3. State and county level data are available in the included spreadsheets of the results.

Figure 24 shows the siting of power plants in the last investment period for Scenario 3. This Figure can be directly compared to Figure 6 as that is the same starting point for Scenarios 1-10. All county-level capacity data are available in the included results spreadsheets.

The model is forced to site more wind and solar than is economically optimal, and thus must make the best decisions given the tradeoffs of local load, transmission availability, and renewable resource. In general, the model tries to site solar as far west and south as possible, but also close to load centers on the eastern seaboard. Wind, having more heterogeneous resource is more constrained to parts of the EIC where the wind resource is best.

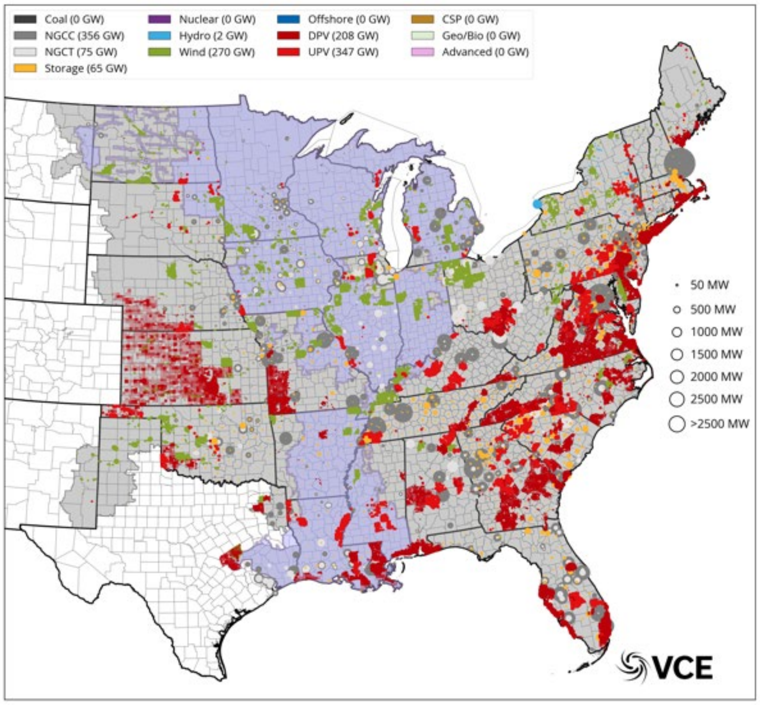
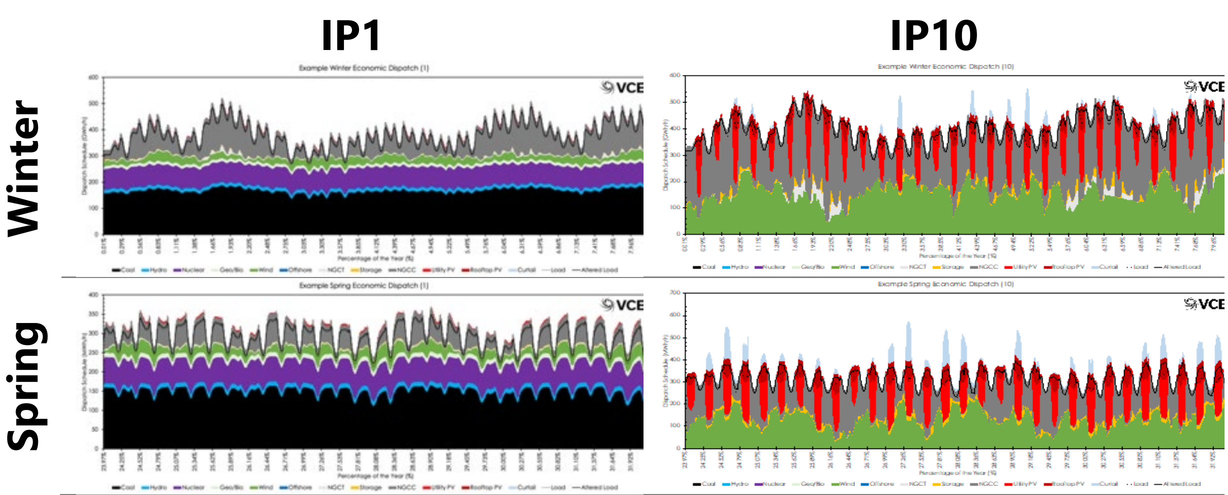


Figure 24: Location, type and size of powerplants in the EIC for Scenario 3, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 25 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire EIC system. Coal and nuclear generation disappear between the first and last investment periods while NGCC generation and energy storage dispatch increase significantly to compensate for ramps in demand and increased renewables output. We also start to see large amounts of curtailment on days that have both strong solar and wind resource availability. In all, about 3% of total wind and solar generation is curtained across the system by the last investment period.



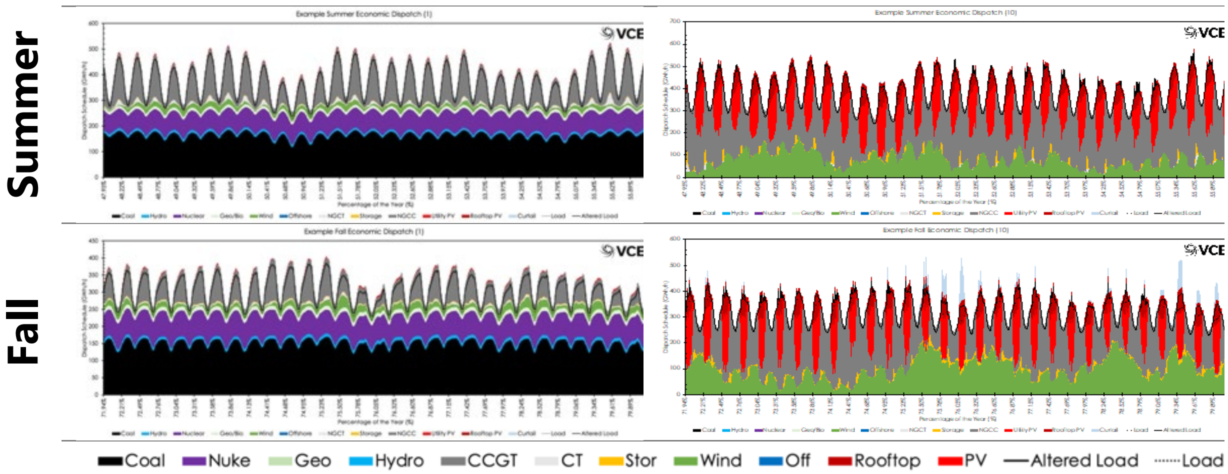


Figure 25: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 3.

In investment period 1 (the results of which are the same as Scenario 1), the EIC-wide NGCC fleet ramps about 3.4%, with a max ramp of about 14.4% over the entire simulation year, NGCT plants ramp less, about 0.5% per hour, with a max ramp of 6.1%, and storage ramps, on average less than 1% per hour, but has a max ramp of almost 62%. However, by investment period 10 in Scenario 3, average ramps have increased to 5.9%, 1.0%, and 7.2% for NGCC, NGCT, and storage, respectfully, and maximum ramps increased more so, to 34%, 65%, and about 95% for each of the technologies.

Figure 26 shows the percent breakdown of generation from each technology for all investment periods in Scenario 3. The percentage of generation from coal and nuclear plants declines rapidly as the share of natural gas fired generation increases to accommodate also increasing solar and wind generation.

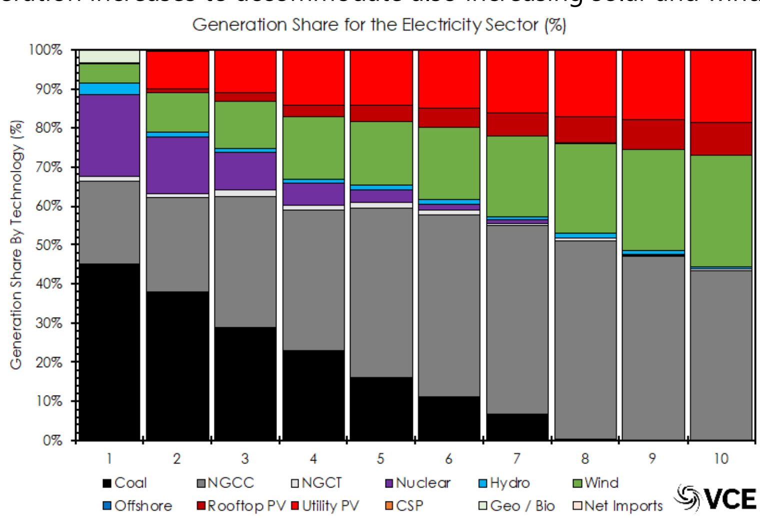


Figure 26: Percentage generation share for the electricity sector by technology and iteration number for Scenario 3.

Figure 27 shows the change in delivered electricity costs for each investment period, relative to the first investment period, or initialization. Costs decline quickly at first as the model retires the least economical units and then costs declines slow as the system deploys large amounts of renewables. While costs for all investment periods are lower than the first, the lowest costs are in investment period 9, which corresponds to the grid getting about 45% of its electricity from wind and solar. These levels of cost declines are not much different, in percentage terms, than the optimal capacity expansion cost reductions seen in Scenario 1 (about 23.5% reductions, See Figure 12).

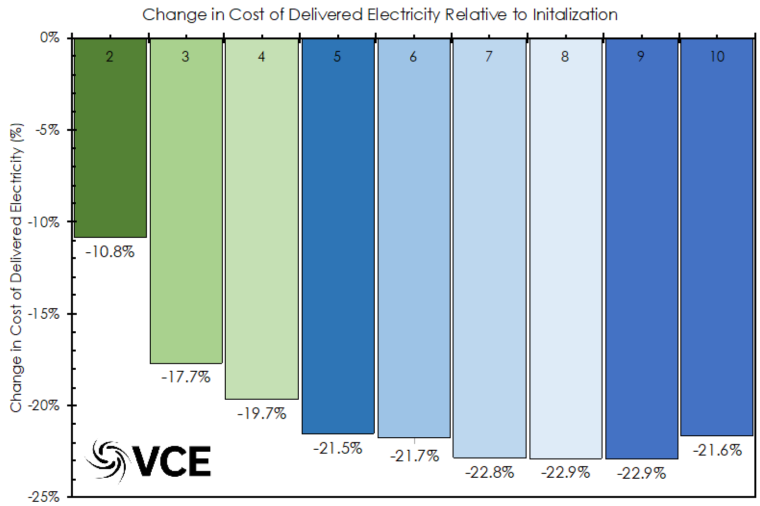


Figure 27: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 3.

Figure 28 shows the deployment of transmission in each state in EIC as well as to and from the MISO LRZs for Scenario 3. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. Note that in this scenario, transmission expansion between MISO and non-MISO regions was not allowed, but transmission expansion between MISO LRZs and expansion between non-MISO regions in EIC was allowed. Within MISO, the most transmission deployment was between LRZ 9 and 10.

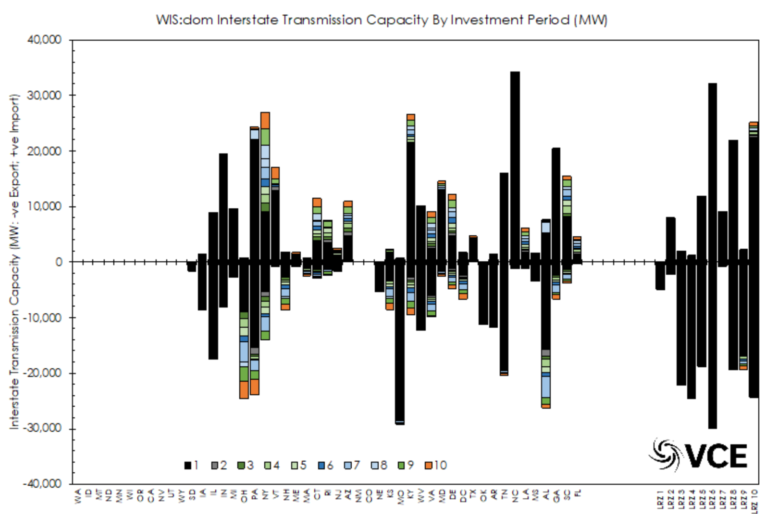


Figure 28: Interstate and inter-MISO region transmission capacity (MW) by investment period for Scenario 3. Negative values indicate capacity to export and positive values indicate capacity to import into that state/MISO region.

In Scenario 3, emissions fall across all categories with CO_2 emissions falling by about 61% by investment period 10, which is slightly more than in Scenario 1 (30% CO_2 reductions). The decline is due largely to the deployment of large levels of renewables and all coal retiring. Full emissions details and accounting are available in the results spreadsheets.

Full time employment in the electricity sector in investment period 10 increases by about 150% relative to initialization in Scenario 3. While large numbers of coal and nuclear related jobs are reduced, there is explosive growth in the number of solar and wind jobs needed for this scenario.

In Scenario 3, natural gas fuel burn increases to about 15.7 Quads in investment period 7 before falling to 13.2 Quads in investment period 10 as more solar and wind come online, coal fuel burn decreases from about 16.5 Quads to zero by investment period 8 and uranium fuel burn also declines to zero by investment period 8. Full fuel burn details and accounting are available in the results spreadsheets.

4.4. Path to 50% Wind & Solar (EIC) with Transmission Expansion (Scenario 4)

This scenario charts the optimal pathway for the entire EIC to generate half of its power from wind and solar by the 10th investment period. This scenario is similar to Scenario 3 except that transmission expansion is allowed between MISO and non-MISO regions.

Figure 29 shows the evolution of installed capacity by power plant type for Scenario 4. In general, coal, NGCT, and nuclear capacities fall while NGCC, energy storage and renewable capacities rise. By investment period 10, over 1,262 GW of power plants, of all types exist in the EIC, up from about 790 GW in the first investment period, but about 46 GW less than Scenario 3. Between investment period 1 and 10, all coal retires, NGCC increases by about 39%, NGCT decreases by about half, storage increases by about 338%, all nuclear retires, about 80% of the hydro fleet retires, wind increases by almost 590%, and solar increases by over 8,200%. Economic dispatch of the fleet causes the capacity factors of the remaining thermal plants to generally rise over the investment periods as the fleet transitions.

Relative to Scenario 3, Scenario 4 sees more wind deployment and less solar deployment, which makes sense given that transmission is allowed to expand and the model can tap areas of the country that were before unavailable.

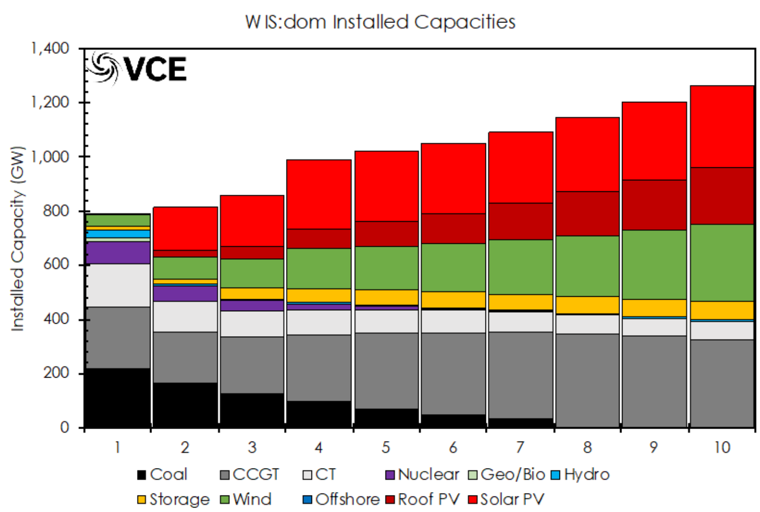


Figure 29: Power plant capacities by type in the EIC over each of the investment periods in Scenario 4. State and county level data are available in the included spreadsheets of the results.

Figure 30 shows the siting of power plants in the last investment period for Scenario 4. This Figure can be directly compared to Figure 6 as that is the same starting point for Scenarios 1-10. All county-level capacity data are available in the included results spreadsheets. As the results from Scenario 4 are similar to Scenario 3, the deployment maps also look similar. More wind is deployed, but similar amounts of gas and storage are also placed in the system to firm up generation.

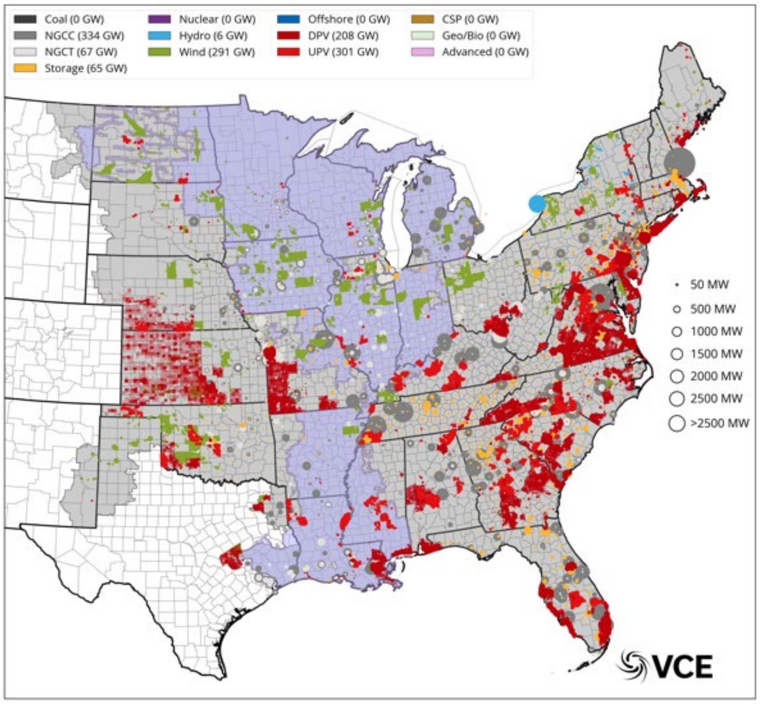
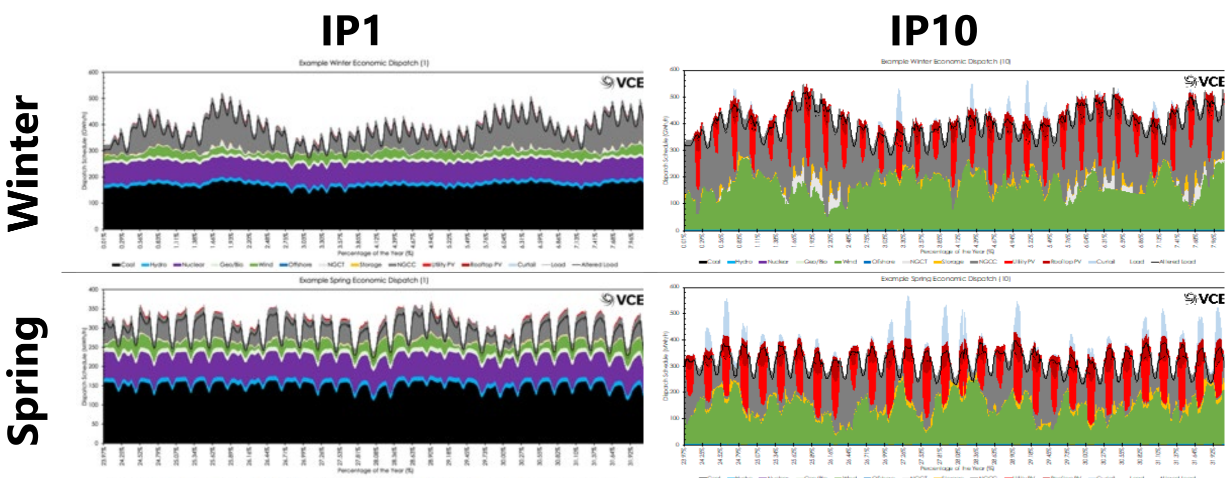


Figure 30: Location, type and size of powerplants in the EIC for Scenario 4, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 31 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire EIC system. Coal and nuclear generation disappear between the first and last investment periods while NGCC generation and energy storage dispatch increase significantly to compensate for ramps in demand and increased renewables output. We also see large amounts of curtailment on days that have both strong solar and wind resource availability. In all, about 2% of total wind and solar generation is curtained across the system by the last investment period (vs. about 3% curtailment in the transmission-constrained Scenario 3).



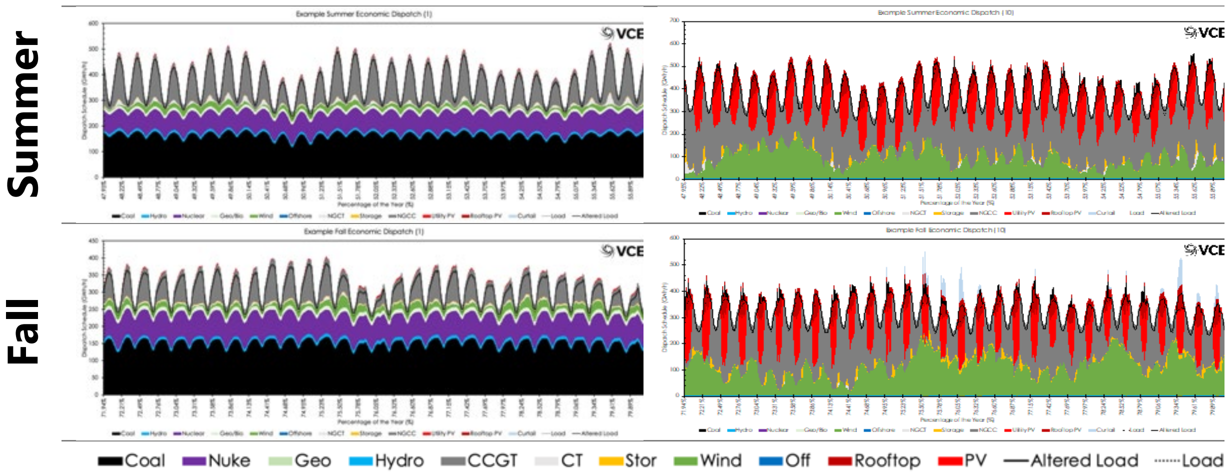


Figure 31: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 4.

By investment period 10 in Scenario 4, average ramps for NGCC, NGCT, and storage are 5.5%, 1.4%, and 7.4%, respectfully, and maximum ramps were 35%, 68%, and about 91% for each of the technologies. Also, storage is called upon to provide as much as 21% of the entire EIC load for some hours, but less than 1% on-peak.

Figure 32 shows the percent breakdown of generation from each technology for all investment periods in Scenario 4. Similar to Scenario 3, the percentage of generation from coal and nuclear plants declines rapidly as the share of natural gas fired generation increases to accommodate also increasing solar and wind generation.

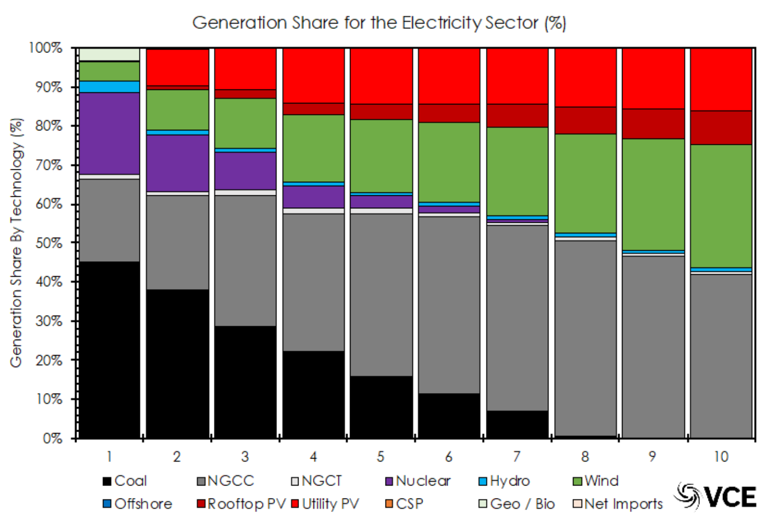


Figure 32: Percentage generation share for the electricity sector by technology and iteration number for Scenario 4.

Figure 33 shows the change in delivered electricity costs for each investment period, relative to the first investment period, or initialization. Costs decline quickly at first as the model retires the least economical units and then costs declines slow as the system deploys large amounts of renewables. While costs for all investment periods are lower than the first, the lowest costs are in investment period 9, which, like Scenario 3 results, corresponds to the grid getting about 45% of its electricity from wind and solar. Compared to Scenario 3, costs are lower given the ability of the model to build more transmission capacity.

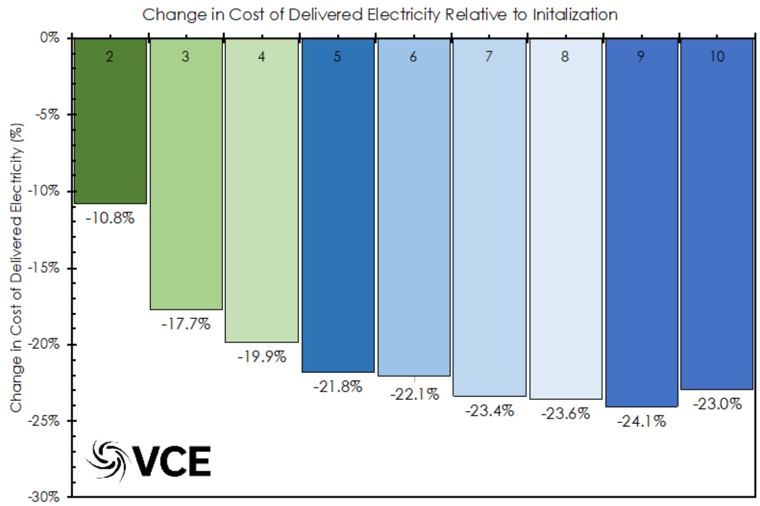


Figure 33: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 4.

Figure 34 shows the deployment of transmission in each state in EIC as well as to and from the MISO LRZs for Scenario 4. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. As transmission was allowed to expand between MISO and non-MISO regions in this scenario, we see much more transmission expansion relative to Scenario 3. Note that the y-axis has changed scale and is about three times larger than in Scenario 3.

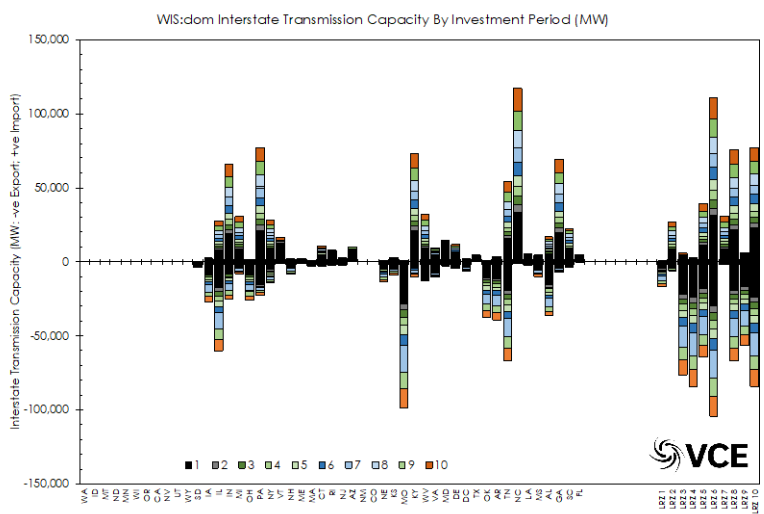


Figure 34: Interstate and inter-MISO region transmission capacity (MW) by investment period for Scenario 4. Negative values indicate capacity to export and positive values indicate capacity to import into that state/MISO region.

In Scenario 4, emissions fall across all categories with CO_2 emissions falling by about 62% by investment period 10, which is slightly more than in Scenario 3 (61% CO_2 reductions). The decline is due largely to the deployment of large levels of renewables and all coal retiring. Full emissions details and accounting are available in the results spreadsheets.

Full time employment in the electricity sector in Scenario 4, by investment period 10 increases by about 194%, relative to today. While large numbers of coal and nuclear related jobs are reduced, there is explosive growth in the number of solar, wind and transmission jobs needed for this scenario.

In Scenario 4, natural gas fuel burn increases to about 15.7 Quads in investment period 7 before falling to 13 Quads in investment period 10 as more solar and wind come online, coal fuel burn decreases from about 16.5 Quads to zero by investment period 9 and uranium fuel burn declines to zero by investment period 8. Full fuel burn details and accounting are available in the results spreadsheets.

4.5. Path to 75% Wind & Solar (EIC) without Transmission Expansion (Scenario 5)

This scenario charts the optimal pathway for the entire EIC to generate 75% of its power from wind and solar by the 10th investment period. In this scenario, the model is not allowed to expand transmission or energy trading between MISO and non-MISO regions of EIC. However, economical expansion of both are allowed between MISO LRZs.

Figure 35 shows the evolution of installed capacity by power plant type for Scenario 5. In general, coal, NGCT, and nuclear capacities fall while NGCC, energy storage and renewable capacities rise. By investment period 10, over 1,753 GW of power plants, of all types exist in the EIC, up from about 790 GW in the first investment period. Between investment period 1 and 10, all coal retires, NGCC increases by about 9%, NGCT decreases by about half, storage increases by about 790%, all nuclear retires, all of the hydro fleet retires, wind increases by almost 840%, offshore wind increases by almost 74,000% (starting from 30 MW), and solar increases by over 14,000%.

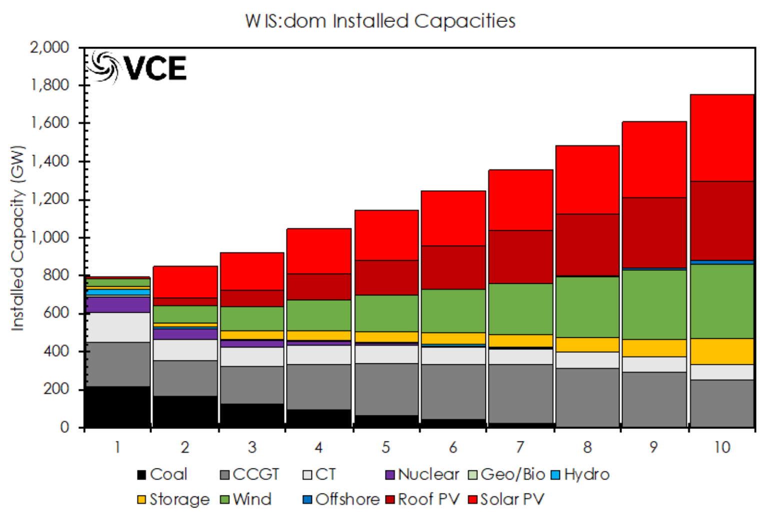


Figure 35: Power plant capacities by type in the EIC over each of the investment periods in Scenario 5. State and county level data are available in the included spreadsheets of the results.

Figure 36 shows the siting of power plants in the last investment period for Scenario 5. This Figure can be directly compared to Figure 6 as that is the same starting point for Scenarios 1-10. All county-level capacity data are available in the included results spreadsheets. In this scenario, we see large amounts of wind and solar in similar places to precious scenarios, as well as the deployment of offshore wind on the east coast.

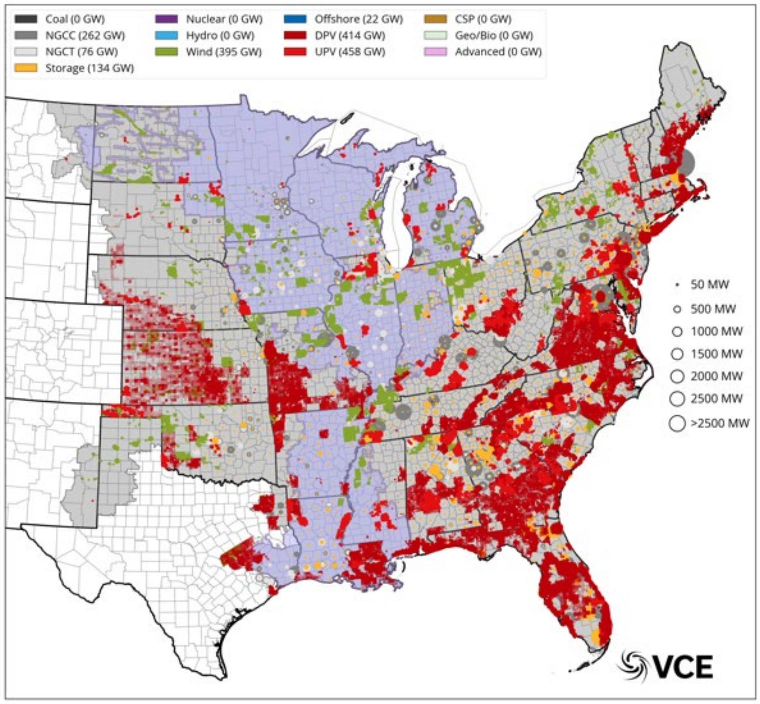
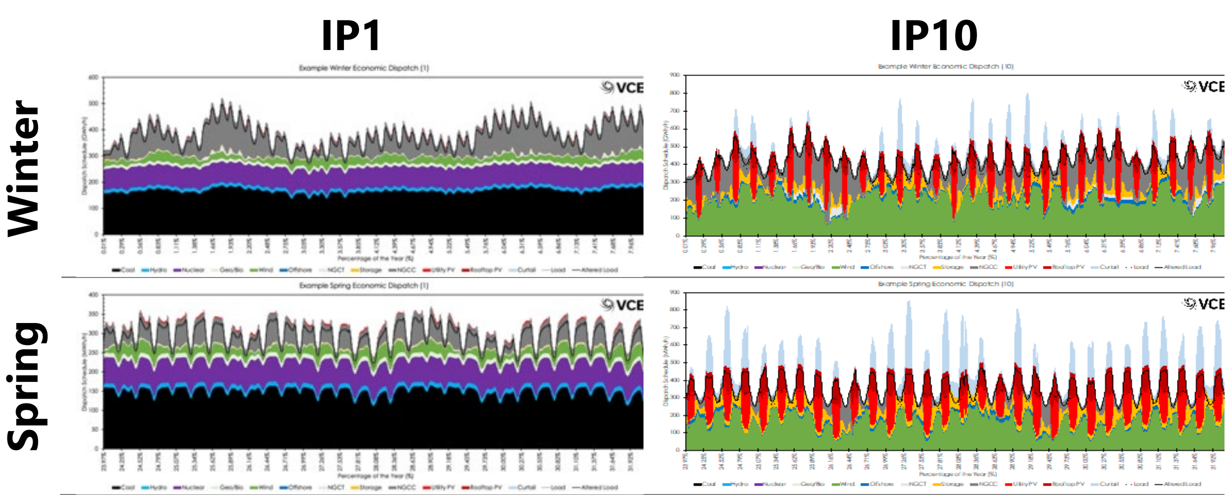


Figure 36: Location, type and size of powerplants in the EIC for Scenario 5, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 37 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire EIC system. Coal and nuclear generation disappear between the first and last investment periods while energy storage increasingly dispatches to compensate for ramps in demand and increased renewables output. NGCC output increased in the middle investment periods, but by investment period 10 has been reduced to allow for 75% of generation to be met by wind and solar. We also see curtailment on most days by investment period 10. In all, about 10% of total wind and solar generation (8% of total generation) is curtailed across the system by the last investment period.



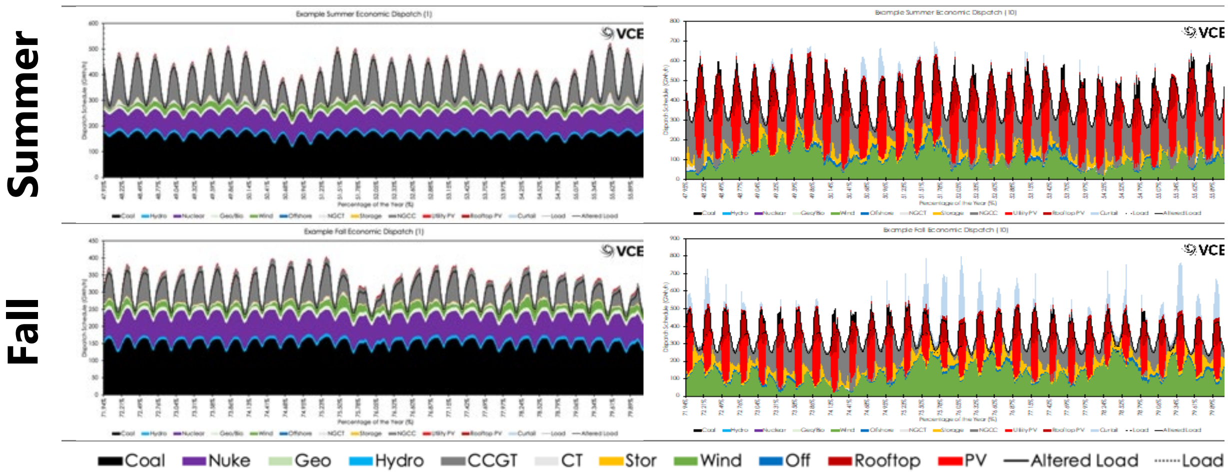


Figure 37: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 5.

By investment period 10 in Scenario 5, average ramps for NGCC, NGCT, and storage are 5.0%, 0.8%, and 8.6%, respectfully, and maximum ramps are 48%, 55%, and about 90% for each of the technologies. Also, storage is called upon to provide as much as 45% of the entire EIC altered load for some hours, but less than 3% on-peak.

Figure 38 shows the percent breakdown of generation from each technology for all investment periods in Scenario 5. Both fossil and nuclear generation decline rapidly throughout the investment periods to incorporate increasing amounts of solar and wind generation. In this scenario, we start to see more of a reliance on rooftop PV to provide generation to the system.

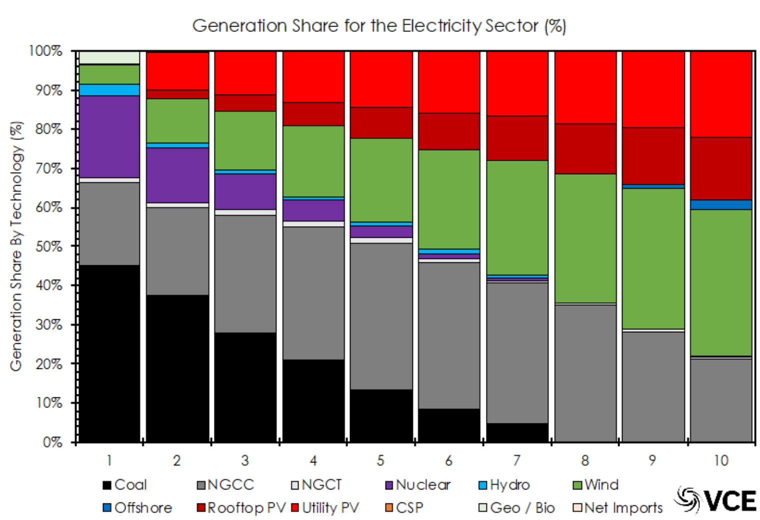


Figure 38: Percentage generation share for the electricity sector by technology and iteration number for Scenario 5.

Figure 39 shows the change in delivered electricity costs for each investment period, relative to the first investment period, or initialization. Costs decline quickly at first as the model retires the least economical units and then costs declines slow as the system deploys large amounts of renewables. While costs for all investment periods are lower than the initialization costs, the lowest costs are in investment period 5, which corresponds to the grid getting about 40% of its electricity from wind and solar. Relative to investment period 5, higher wind and solar levels are more expensive as the model is forced to curtail more energy and deploy more energy storage systems.

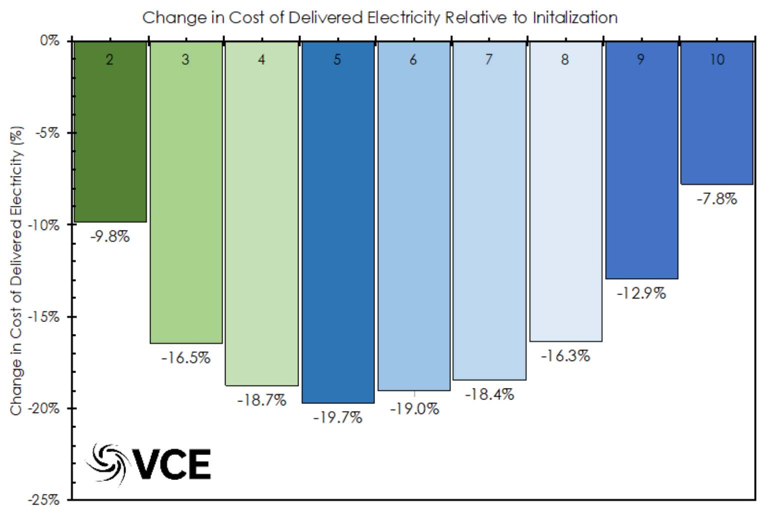


Figure 39: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 5.

Figure 40 shows the deployment of transmission in each state in EIC as well as to and from the MISO LRZs for Scenario 5. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. Note that in this scenario, transmission expansion between MISO and non-MISO regions was not allowed, but transmission expansion between MISO LRZs and expansion between non-MISO regions in EIC was allowed. However, more transmission capacity is built in this scenario and within MISO, the most transmission deployment was again between LRZ 9 and 10.

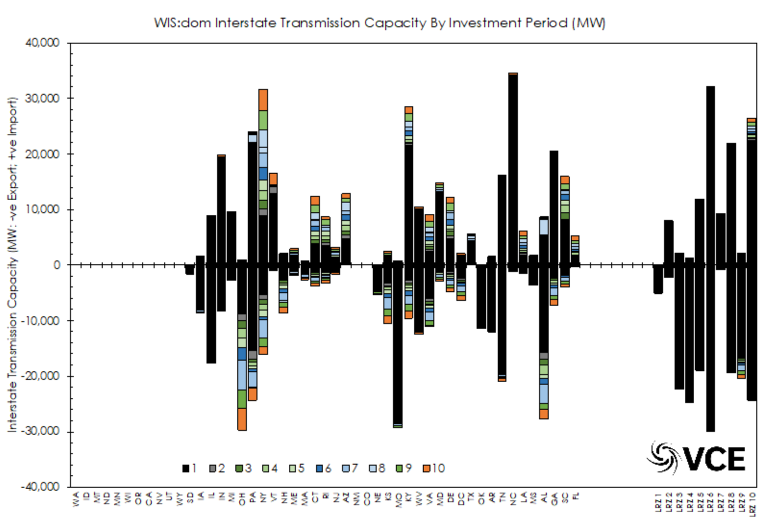


Figure 40: Interstate and inter-MISO region transmission capacity (MW) by investment period for Scenario 5. Negative values indicate capacity to export and positive values indicate capacity to import into that state/MISO region.

In Scenario 5, emissions fall across all categories with CO_2 emissions falling by about 81% by investment period 10. The decline is expected due to the deployment of high levels of renewables and all most fossil generation retiring. Full emissions details and accounting are available in the results spreadsheets.

Full time employment in the electricity sector in Scenario 5, by investment period 10 increases by about 240%, relative to today. While large numbers of coal and nuclear related jobs are reduced, there is explosive growth in the number of solar and wind jobs needed for this scenario.

In Scenario 5, natural gas fuel burn increases to about 11.9 Quads in investment period 5 before falling to 6.5 Quads in investment period 10 as more solar and wind come online, coal fuel burn decreases from about 16.5 Quads to zero by investment period 8 and uranium fuel burn declines to zero by investment period 8. Full fuel burn details and accounting are available in the results spreadsheets.

4.6. Path to 75% Wind & Solar (EIC) with Transmission Expansion (Scenario 6)

This scenario charts the optimal pathway for the entire EIC to generate 75% of its power from wind and solar by the 10th investment period. This scenario is similar to Scenario 5 except that transmission expansion is allowed between MISO and non-MISO regions.

Figure 41 shows the evolution of installed capacity by power plant type for Scenario 6. In general, coal, NGCT, and nuclear capacities fall while NGCC, energy storage and renewable capacities rise. By investment period 10, over 1,658 GW of power plants, of all types exist in the EIC, up from about 790 GW in the first investment period, but about 100 GW less than Scenario 5. Between investment period 1 and 10, all coal retires, NGCC increases by about 5%, NGCT decreases by about half, storage increases by about 533%, all nuclear retires, all of the hydro fleet retires, wind increases by almost 971%, offshore wind increases by almost 55,000% (starting from 30 MW), and solar increases by over 12,400%.

Relative to Scenario 5, Scenario 6 sees more wind deployment and less solar deployment which is expected given that transmission is allowed to expand and the model can tap areas of the country that were before unavailable. In this scenario, we see the deployment of rooftop PV exceeding that of utility-scale PV, again, largely due to transmission capacity allowing for more wind deployment.

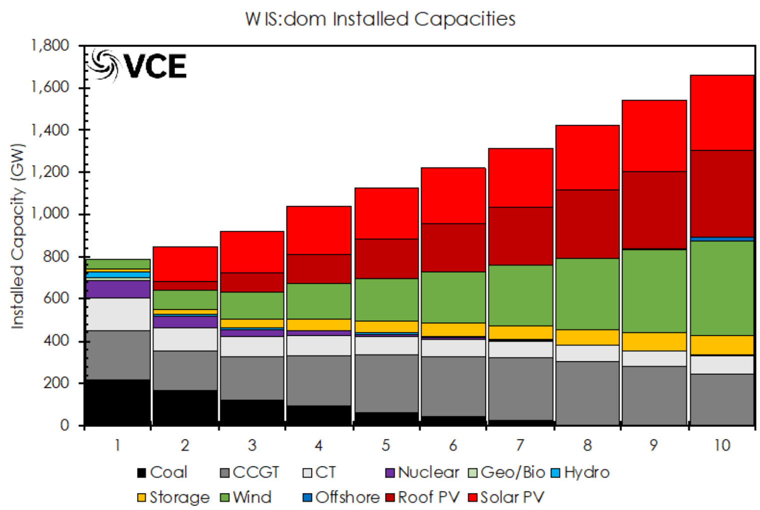


Figure 41: Power plant capacities by type in the EIC over each of the investment periods in Scenario 6. State and county level data are available in the included spreadsheets of the results.

Figure 42 shows the siting of power plants in the last investment period for Scenario 6. This Figure can be directly compared to Figure 6 as that is the same starting point for Scenarios 1-10. All county-level capacity data are available in the included results spreadsheets. In this scenario, we see large amounts of wind and solar in similar places to precious scenarios, as well as the deployment of about 17 GW offshore wind on the east coast, albeit lower levels than in Scenario 5 (22 GW), again due to the ability to build more transmission capacity.

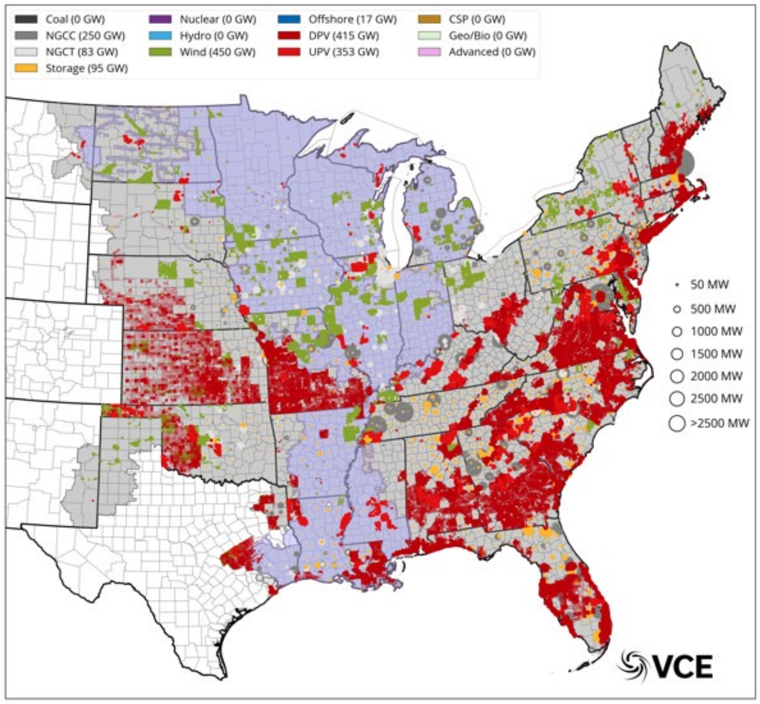
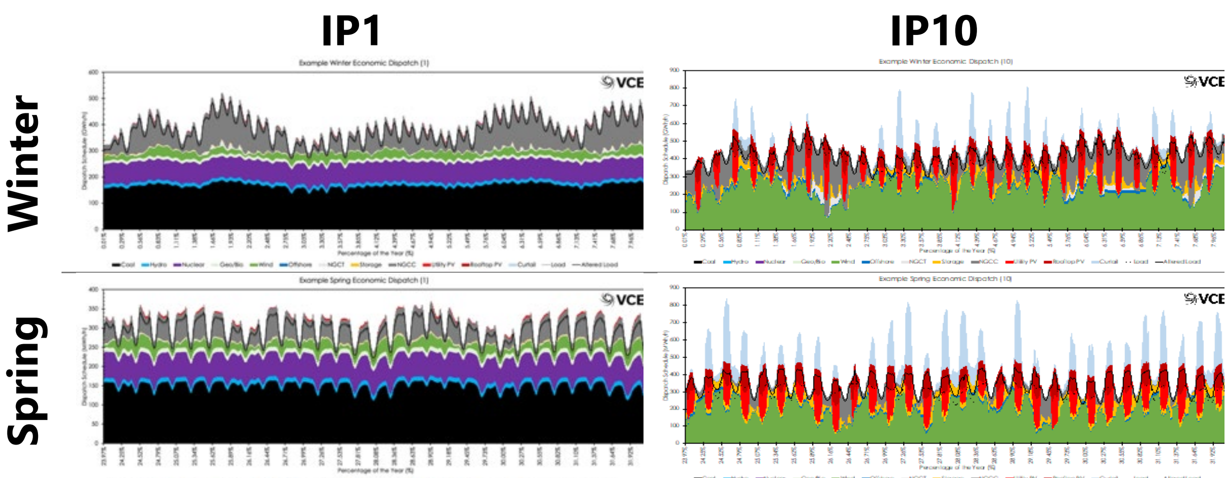


Figure 42: Location, type and size of powerplants in the EIC for Scenario 6, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 43 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire EIC system. Coal and nuclear generation disappear between the first and last investment periods while energy storage increasingly dispatches to compensate for ramps in demand and increased renewables output. NGCC output increased in the middle investment periods, but by investment period 10 has been reduced to allow for 75% of generation to be met by wind and solar. We also see curtailment on most days by investment period 10. In all, about 9.2% of total wind and solar generation (7.8% of total generation) is curtained across the system by the last investment period, less than in Scenario 5 (~10% / 8%).



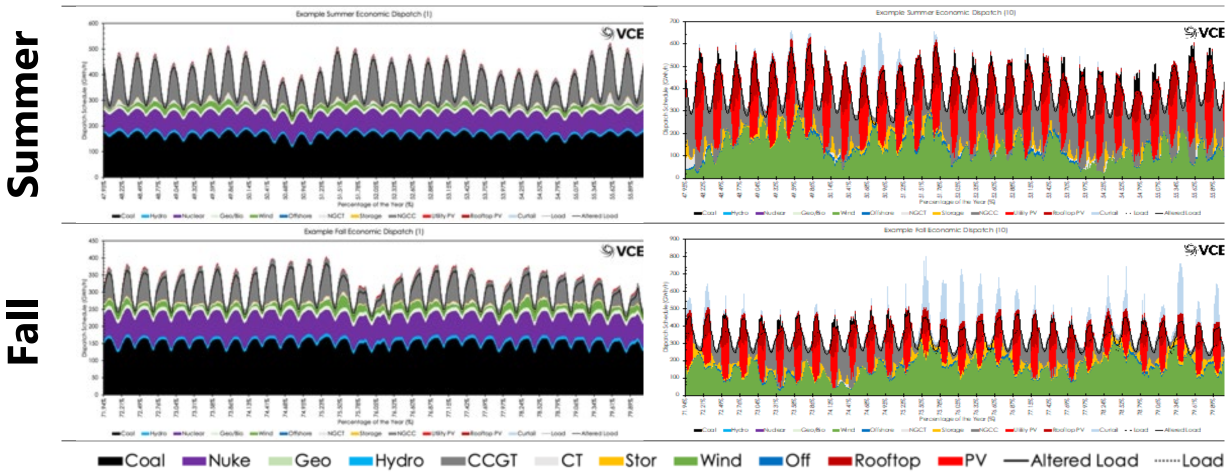


Figure 43: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 6.

By investment period 10 in Scenario 6, average ramps for NGCC, NGCT, and storage are 5.3%, 1.2%, and 9.8%, respectfully, and maximum ramps are 52%, 58%, and about 90% for each of the technologies. Also, storage is called upon to provide as much as 35% of the entire EIC altered load for some hours, but less than 5% on-peak. Compared to Scenario 5, which limited transmission expansion, energy storage in Scenario 6 is used less on average, but more during peak demand.

Figure 44 shows the percent breakdown of generation from each technology for all investment periods in Scenario 6. Both fossil and nuclear generation decline rapidly throughout the investment periods to incorporate increasing amounts of solar and wind generation.

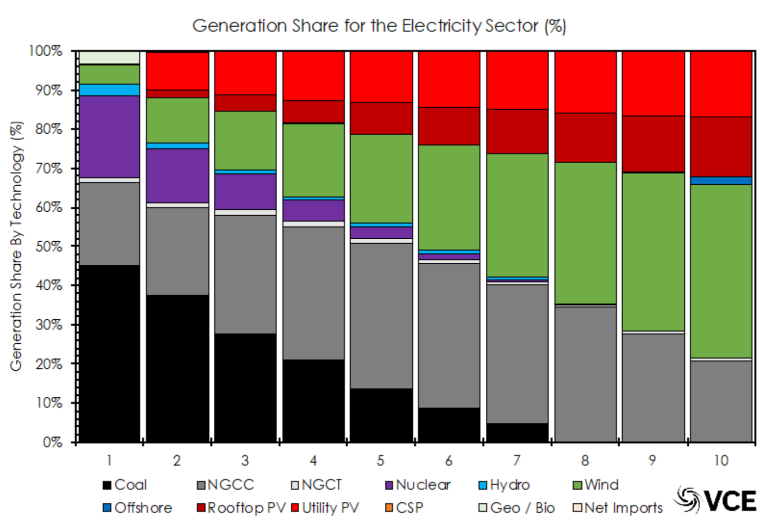


Figure 44: Percentage generation share for the electricity sector by technology and iteration number for Scenario 6.

Figure 45 shows the change in delivered electricity costs for each investment period, relative to the first investment period, or initialization. Costs decline quickly at first as the model retires the least economical units and then costs declines slow as the system deploys large amounts of renewables. While costs for all investment periods are lower than initialization costs, the lowest costs are in investment period 5, which corresponds to the grid getting about 40% of its electricity from wind and solar. Relative to investment period 5, higher wind and solar levels are more expensive as the model is forced to curtail more energy and deploy more energy storage systems.

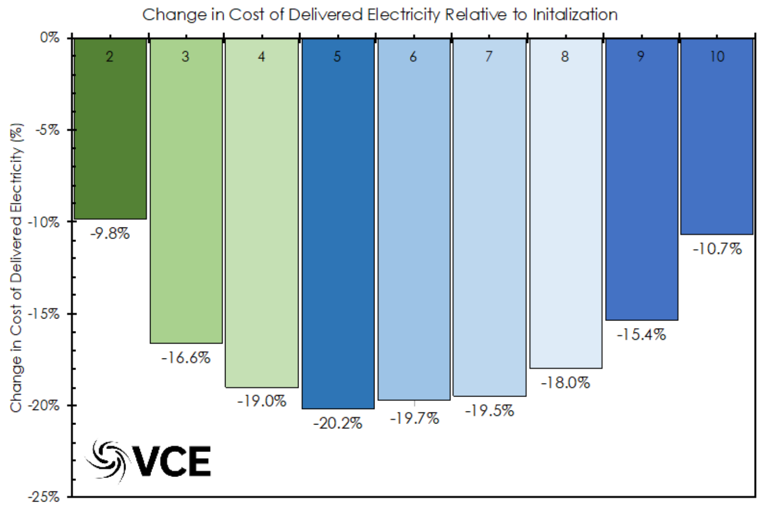


Figure 45: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 6.

Figure 46 shows the deployment of transmission in each state in EIC as well as to and from the MISO LRZs for Scenario 6. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. As transmission was allowed to expand between MISO and non-MISO regions in this scenario, we see much more transmission expansion relative to Scenario 5 and many states and LRZ regions more than doubled their transmission capacity. Note that the y-axis has changed scale and is about three times larger than in Scenario 5.

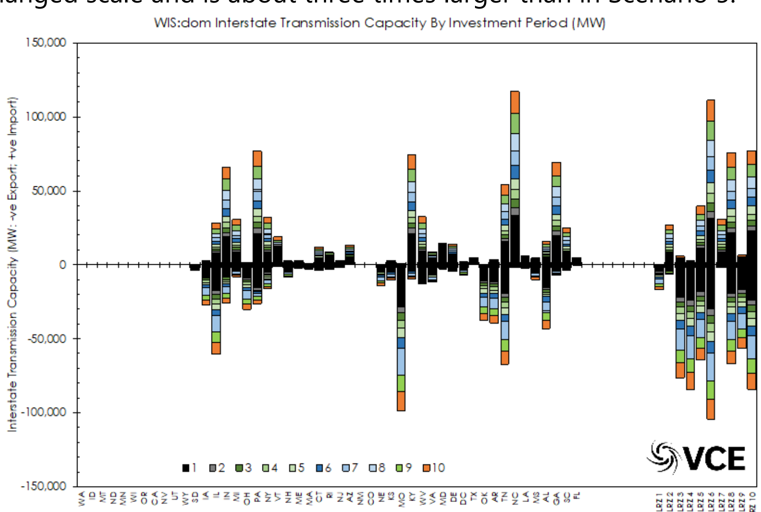


Figure 46: Interstate and inter-MISO region transmission capacity (MW) by investment period for Scenario 6. Negative values indicate capacity to export and positive values indicate capacity to import into that state/MISO region.

In Scenario 6, emissions fall across all categories with CO_2 emissions falling by about 81% by investment period 10. The decline is expected due to the deployment of high levels of renewables and all most fossil generation retiring. Full emissions details and accounting are available in the results spreadsheets.

Full time employment in the electricity sector in Scenario 6, by investment period 10 increases by about 278%, relative to today. While large numbers of coal and nuclear related jobs are reduced, there is explosive growth in the number of solar, wind, and transmission jobs needed for this scenario.

In Scenario 6, natural gas fuel burn increases to about 11.8 Quads in investment period 5 before falling to 6.5 Quads in investment period 10 as more solar and wind come online, coal fuel burn decreases from about 16.5 Quads to zero by investment period 8 and uranium fuel burn declines to zero by investment period 8. Full fuel burn details and accounting are available in the results spreadsheets.

4.7. Path to 90% Wind & Solar (EIC) without Transmission Expansion (Scenario 7)

This scenario charts the optimal pathway for the entire EIC to generate 90% of its power from wind and solar by the 10th investment period. In this scenario, the model is not allowed to expand transmission or energy trading between MISO and non-MISO regions of EIC. However, economical expansion of both are allowed between MISO LRZs.

Figure 47 shows the evolution of installed capacity by power plant type for Scenario 7. In general, all fossil and nuclear capacities fall while energy storage and renewable capacities rise. By investment period 10, over 2,195 GW of power plants, of all types exist in the EI, up from about 790 GW in the first investment period. Between investment period 1 and 10, all coal retires, NGCC decreases by about 30%, NGCT decreases by about half, storage increases by about 1,550%, all nuclear retires, all of the hydro fleet retires, wind increases by almost 950%, offshore wind increases by almost 130,000% (starting from 30 MW), and solar increases by almost 20,000%. Given the high levels of required renewables and reduced transmission expansion capacity, the model builds a larger amount of rooftop PV (625 GW) than to utility-scale PV (602 GW).

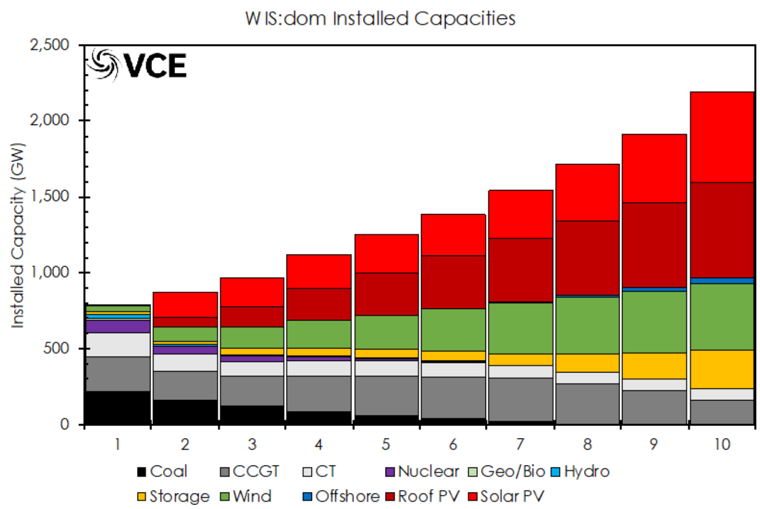


Figure 47: Power plant capacities by type in the EIC over each of the investment periods in Scenario 7. State and county level data are available in the included spreadsheets of the results.

Figure 48 shows the siting of power plants in the last investment period for Scenario 7. This Figure can be directly compared to Figure 6 as that is the same starting point for Scenarios 1-10. All county-level capacity data are available in the included results spreadsheets. In this scenario, we see large amounts of wind and solar in similar places to precious scenarios, as well as the deployment of offshore wind on the east coast.

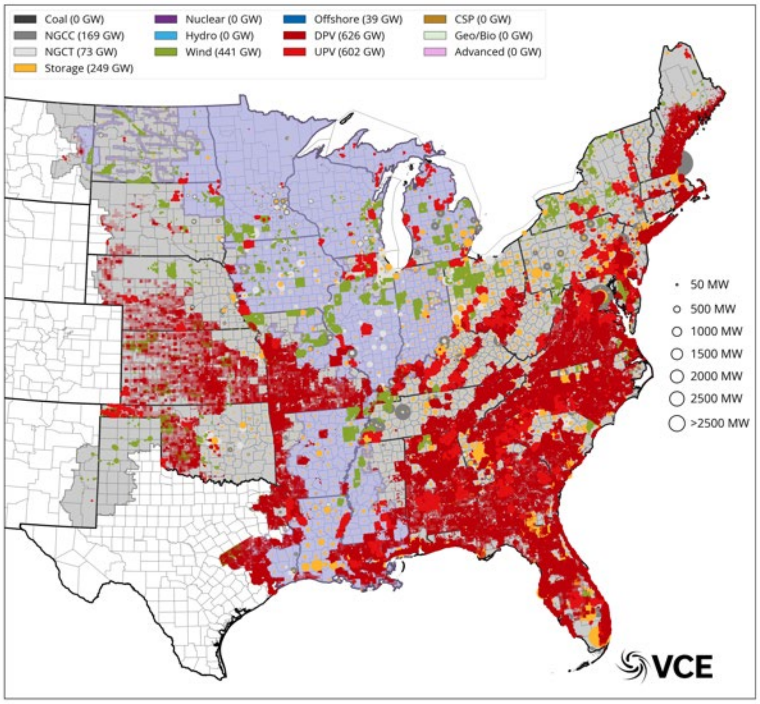
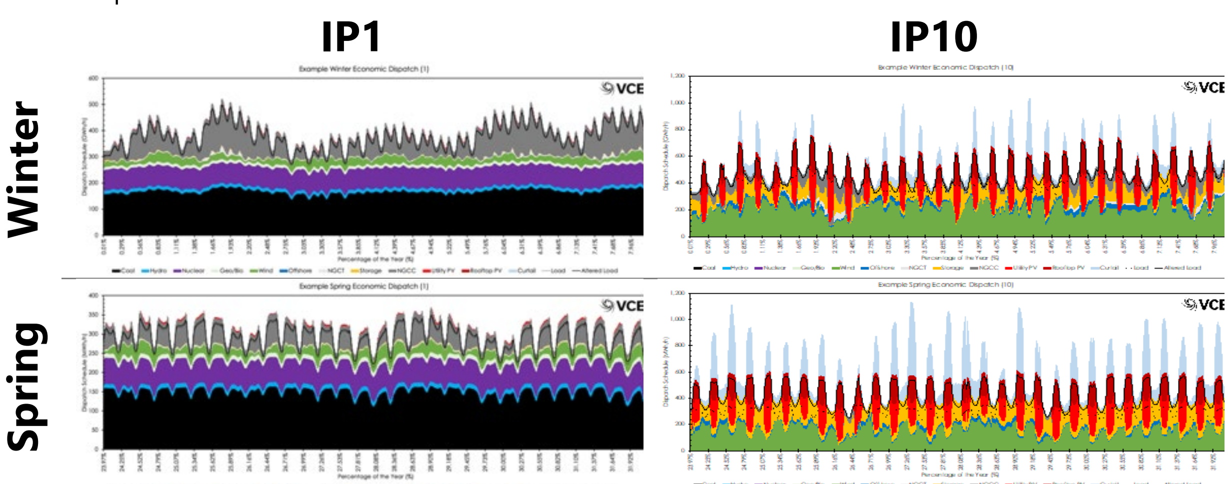


Figure 48: Location, type and size of powerplants in the EIC for Scenario 7, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 49 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire EIC system. Coal and nuclear generation disappear between the first and last investment periods while energy storage increasingly dispatches to compensate for ramps in demand and increased renewables output. NGCC output increased in the middle investment periods, but by investment period 10 has been reduced to allow for 90% of generation to be met by wind and solar. We also see curtailment on most days by investment period 10. In all, about 16% of total generation is curtained across the system by the last investment period.



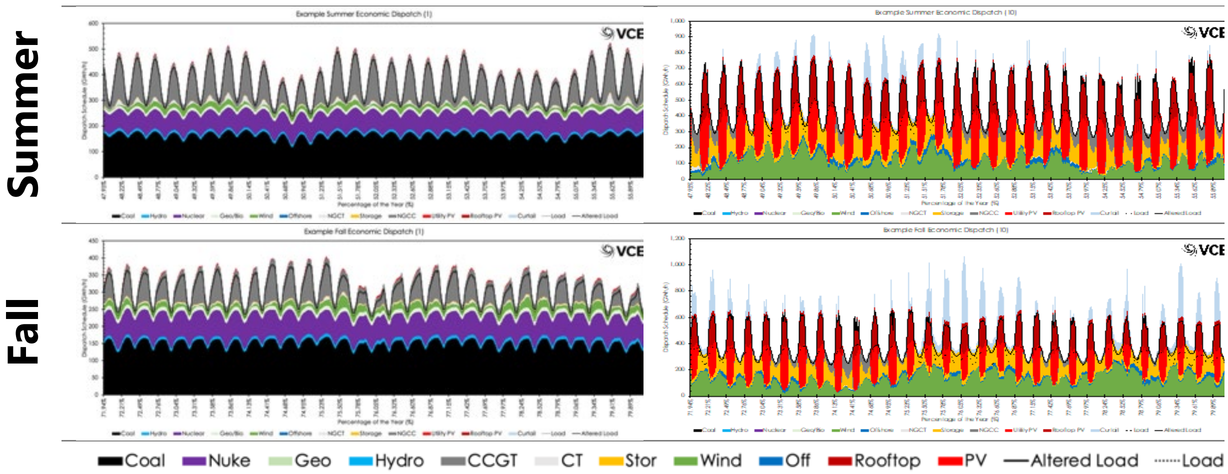


Figure 49: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 7.

By investment period 10 in Scenario 7, average ramps for NGCC, NGCT, and storage are 3%, 1%, and 7%, respectfully, and maximum ramps are 45%, 67%, and about 76% for each of the technologies. Also, storage is called upon to provide almost 80% of the entire EIC altered load for some hours, but less than 1% on-peak.

Figure 50 shows the percent breakdown of generation from each technology for all investment periods in Scenario 7. Both fossil and nuclear generation decline rapidly throughout the investment periods to incorporate increasing amounts of solar and wind generation.

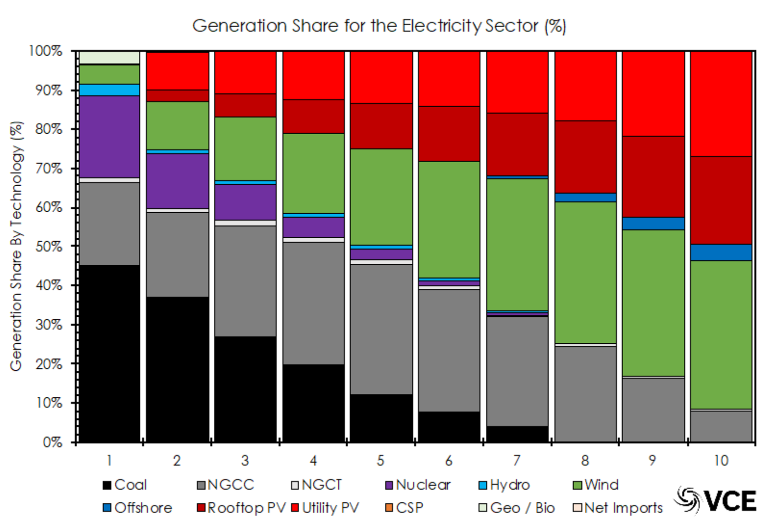


Figure 50: Percentage generation share for the electricity sector by technology and iteration number for Scenario 7.

Figure 51 shows the change in delivered electricity costs for each investment period, relative to the first investment period, or initialization. Costs decline quickly at first as the model retires the least economical units and then costs declines slow as the system deploys large amounts of renewables. While costs for all investment periods are lower than today's costs, the lowest costs are in investment period 5, which corresponds to the grid getting about 45% of its electricity from wind and solar. Relative to investment period 5, higher wind and solar levels are more expensive as the model is forced to curtail more energy and deploy more energy storage systems. By investment period 10, prices are higher than they are today due to the pushing of the system beyond economical deployments of wind and solar technologies.

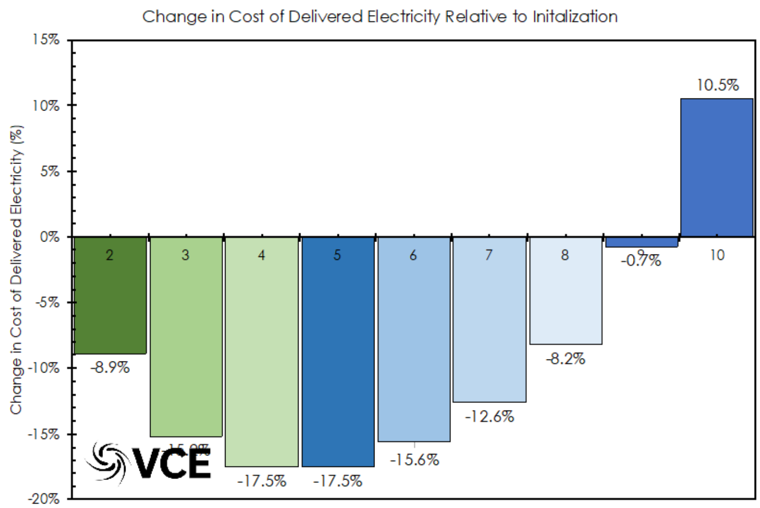


Figure 51: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 7.

Figure 52 shows the deployment of transmission in each state in EIC as well as to and from the MISO LRZs for Scenario 7. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. Note that in this scenario, transmission expansion between MISO and non-MISO regions was not allowed, but transmission expansion between MISO LRZs and expansion between non-MISO regions in EIC was allowed. However, more transmission capacity is built in this scenario and within MISO, the most transmission deployment was again between LRZ 9 and 10.

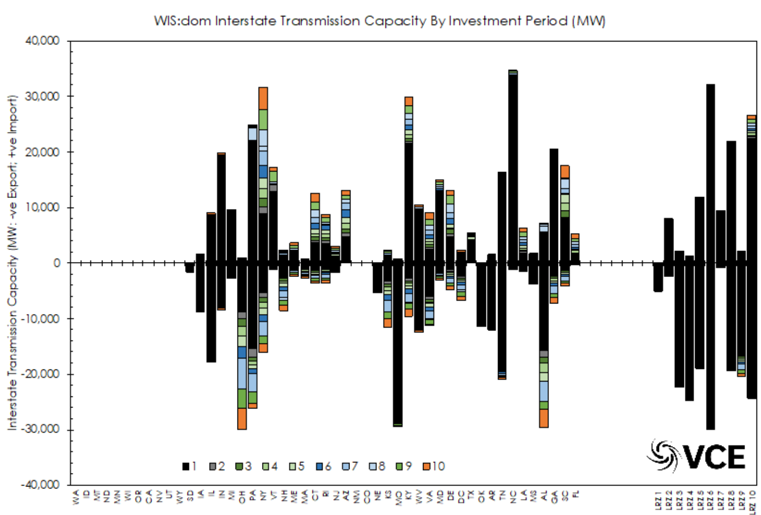


Figure 52: Interstate and inter-MISO region transmission capacity (MW) by investment period for Scenario 7. Negative values indicate capacity to export and positive values indicate capacity to import into that state/MISO region.

In Scenario 7, emissions fall across all categories with CO_2 emissions falling by about 92% by investment period 10. The decline is expected due to the deployment of high levels of renewables and all most fossil generation retiring. Full emissions details and accounting are available in the results spreadsheets.

Full time employment in the electricity sector in Scenario 7, by investment period 10 increases by about 320%, relative to today. While large numbers of coal and nuclear related jobs are reduced, there is explosive growth in the number of solar and wind jobs needed to deploy the renewables needed for this scenario.

Fuel burn data and figures are available in the results spreadsheets. In Scenario 7, natural gas fuel burn increases to about 10.6 Quads in investment period 5 before falling to 2.6 Quads in investment period 10 as more solar and wind come online, coal fuel burn decreases from about 16.5 Quads to zero by investment period 8 and uranium fuel burn declines to zero by investment period 8.

4.8. Path to 90% Wind & Solar (EIC) with Transmission Expansion (Scenario 8)

This scenario charts the optimal pathway for the entire EIC to generate 90% of its power from wind and solar by the 10th investment period. This scenario is similar to Scenario 7 except that transmission expansion is allowed between MISO and non-MISO regions.

Figure 53 shows the evolution of installed capacity by power plant type for Scenario 8. In general, all fossil and nuclear capacity falls while energy storage and renewable capacities rise. By investment period 10, over 2,080 GW of power plants, of all types exist in the EIC, up from about 790 GW in the first investment period. Between investment period 1 and 10, all coal retires, NGCC decreases by about 35%, NGCT decreases by about half, storage increases by about 1,260%, all nuclear retires, all of the hydro fleet retires, wind increases by about 1,080%, offshore wind increases by almost 129,000% (starting from 30 MW), and solar increases by almost 18,000%.

Relative to Scenario 7, Scenario 8 sees more wind deployment and less solar deployment, which is expected given that transmission is allowed to expand and the model can tap areas of the country that were before unavailable.

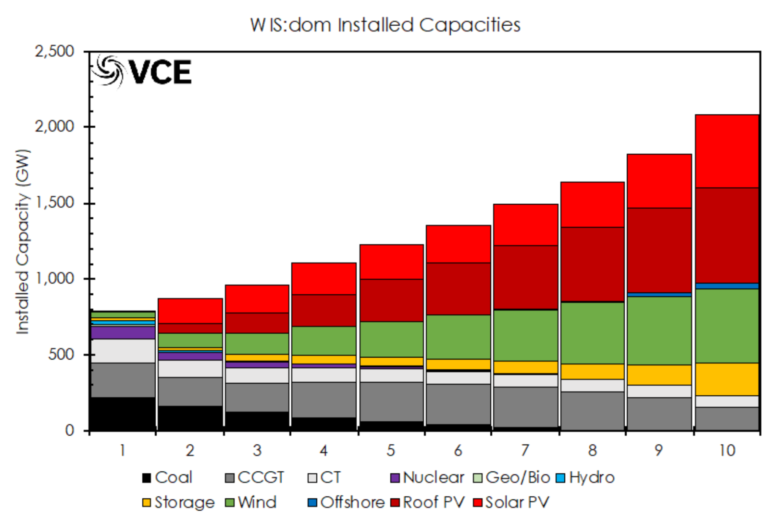


Figure 53: Power plant capacities by type in the EIC over each of the investment periods in Scenario 8. State and county level data are available in the included spreadsheets of the results.

Figure 54 shows the siting of power plants in the last investment period for Scenario 8. This Figure can be directly compared to Figure 2 as that is the same starting point for Scenarios 1-10. All county-level capacity data are available in the included results spreadsheets. In this scenario, we see large amounts of wind and solar in similar places to precious scenarios, as well as the deployment of almost 40 GW offshore wind on the east coast.

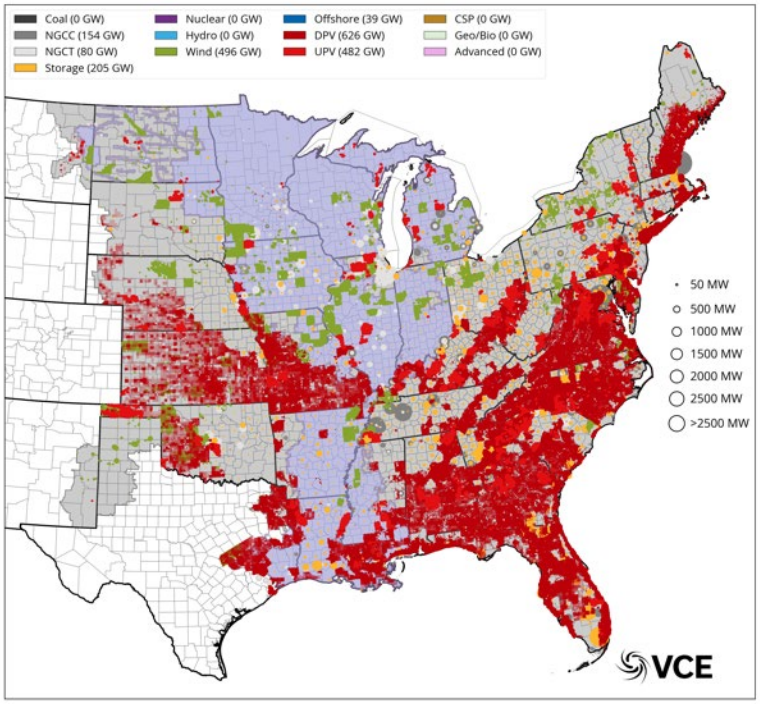
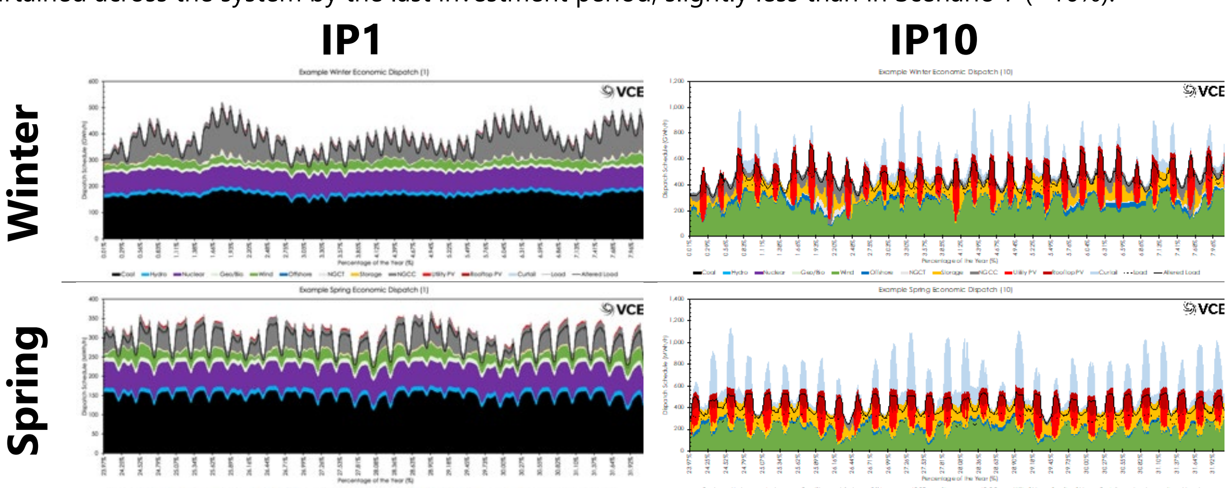


Figure 54: Location, type and size of powerplants in the EIC for Scenario 8, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 55 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire EIC system. Coal and nuclear generation disappear between the first and last investment periods while energy storage increasingly dispatches to compensate for ramps in demand and increased renewables output. NGCC output increased in the middle investment periods, but by investment period 10 has been reduced to allow for 90% of generation to be met by wind and solar. We also see curtailment on most days by investment period 10. In all, about 15% of total wind and solar generation (15.4% of total generation) is curtained across the system by the last investment period, slightly less than in Scenario 7 (~16%).



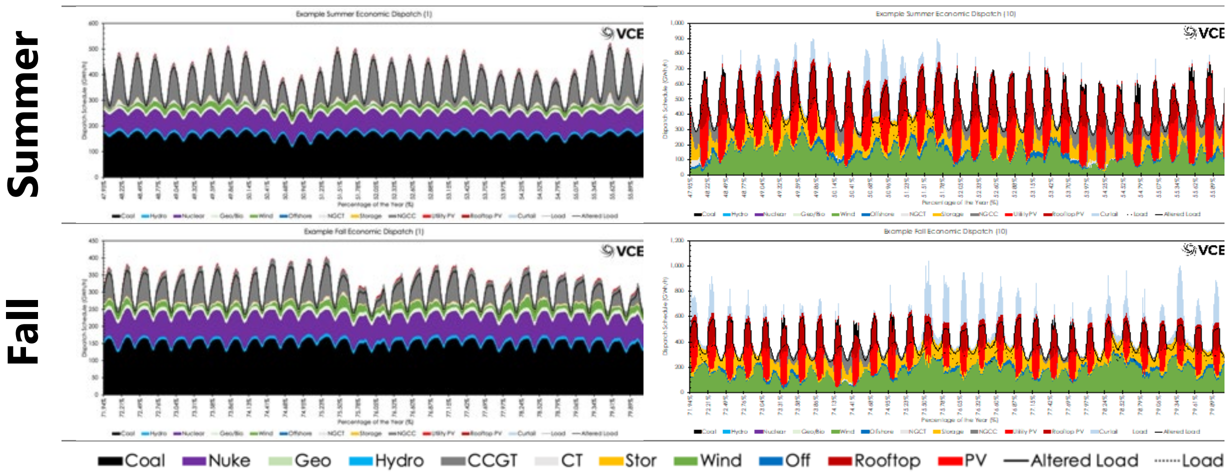


Figure 55: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 8.

By investment period 10 in Scenario 8, average ramps for NGCC, NGCT, and storage are 3%, 1%, and 8%, respectfully, and maximum ramps are 52%, 73%, and about 82% for each of the technologies. Also, storage is called upon to provide almost 65% of the entire EIC altered load for some hours, but less than 1% on-peak. Allowing transmission expansion in Scenario 8 leads towards larger ramps from the natural gas and storage fleets, but less of a reliance on storage to meet overall system demand, overall a more efficient use of capital.

Figure 56 shows the percent breakdown of generation from each technology for all investment periods in Scenario 8. Both fossil and nuclear generation decline rapidly throughout the investment periods to incorporate increasing amounts of solar and wind generation.

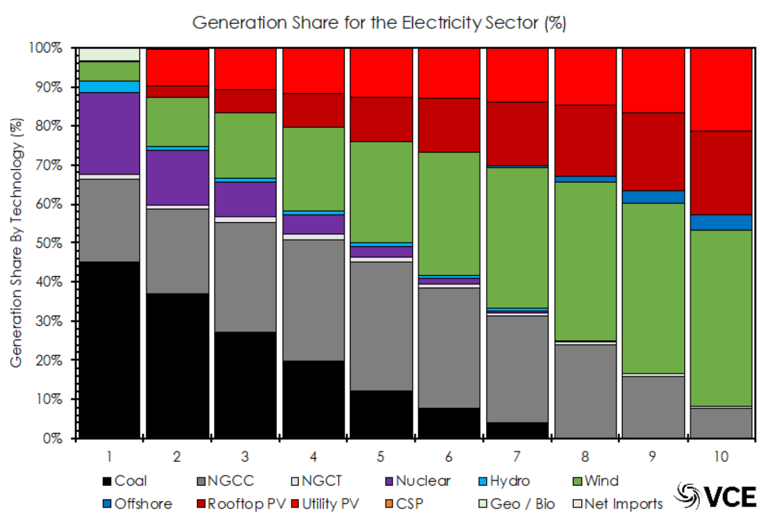


Figure 56: Percentage generation share for the electricity sector by technology and iteration number for Scenario 8.

Figure 57 shows the change in delivered electricity costs for each investment period, relative to the first investment period, or initialization. Costs decline quickly at first as the model retires the least economical units and then costs declines slow as the system deploys large amounts of renewables. While costs for all investment periods are lower than the initialization costs, the lowest costs are in investment period 5, which corresponds to the grid getting about 45% of its electricity from wind and solar. Relative to investment period 5, higher wind and solar levels are more expensive as the model is forced to curtail more energy and deploy more energy storage systems. By investment period 10, costs are higher than they are today, but not as high as in Scenario 7 due to the ability to build transmission.

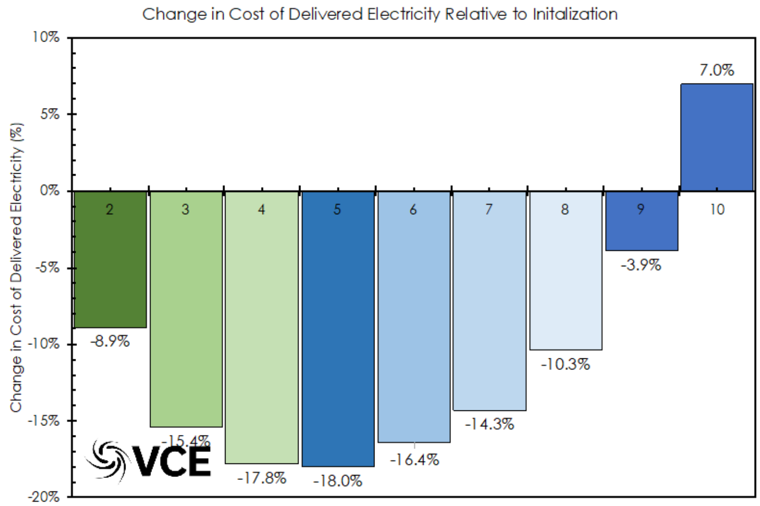


Figure 57: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 8.

Figure 58 shows the deployment of transmission in each state in EIC as well as to and from the MISO LRZs for Scenario 8. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. As transmission was allowed to expand between MISO and non-MISO regions in this scenario, we see much more transmission expansion relative to Scenario 7 and many states and LRZ regions more than doubled their transmission capacity. Note that the y-axis has changed scale and is about three times larger than in Scenario 7.

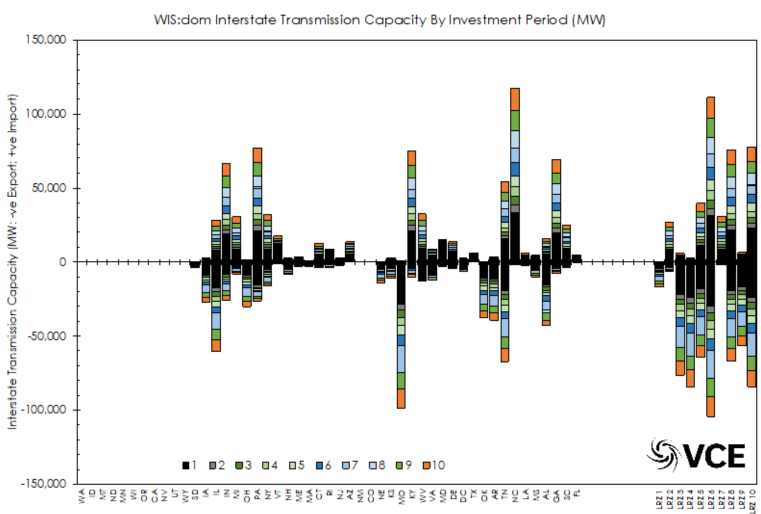


Figure 58: Interstate and inter-MISO region transmission capacity (MW) by investment period for Scenario 8. Negative values indicate capacity to export and positive values indicate capacity to import into that state/MISO region.

In Scenario 8, emissions fall across all categories with CO_2 emissions falling by about 93% by investment period 10. The decline is expected due to the deployment of high levels of renewables and all most fossil generation retiring. Full emissions details and accounting are available in the results spreadsheets.

Full time employment in the electricity sector in Scenario 8, by investment period 10 increases by about 356%, relative to today. While large numbers of coal and nuclear related jobs are reduced, there is explosive growth in the number of solar, wind, and transmission jobs needed to deploy the capacity needed in this scenario.

In Scenario 8, natural gas fuel burn increases to about 10.5 Quads in investment period 5 before falling to 2.7 Quads in investment period 10 as more solar and wind come online, coal fuel burn decreases from about 16.5 Quads to zero by investment period 8 and uranium fuel burn declines to zero by investment period 8. Full fuel burn details and accounting are available in the results spreadsheets.

4.9. Path to 100% Wind & Solar (EIC) without Transmission Expansion (Scenario 9)

This scenario charts the optimal pathway for the entire EIC to generate 100% of its power from wind and solar by the 10th investment period. In this scenario, the model is not allowed to expand transmission or energy trading between MISO and non-MISO regions of EIC. However, economical expansion of both are allowed between MISO LRZs.

Figure 59 shows the evolution of installed capacity by power plant type for Scenario 9. In general, all fossil and nuclear capacities fall while energy storage and renewable capacities rise. By investment period 10, over 3,345 GW of power plants, of all types exist in the EIC, up from about 790 GW in the first investment period. Between investment period 1 and 10, all fossil, nuclear, and hydro retires while storage increases by about 4,000%, wind increases by almost 1,250%, offshore wind increases by almost 270,000% (starting from 30 MW), solar increases by almost 36,000%, and the amount of energy storage energy capacity (MWh) increases by about 3,000%. In this scenario, the model builds over double the amount of utility-scale PV (1,451 GW) as it did in Scenario 7 (604 GW for 90% wind and solar).

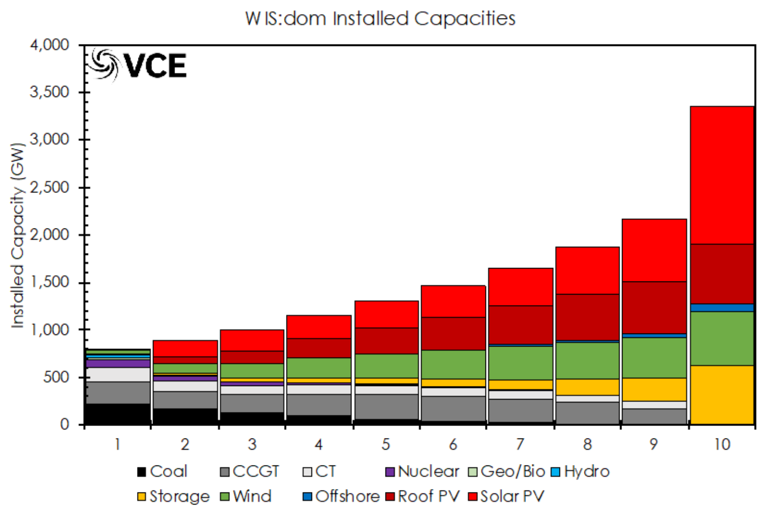


Figure 59: Power plant capacities by type in the EIC over each of the investment periods in Scenario 9. State and county level data are available in the included spreadsheets of the results.

Figure 60 shows the siting of power plants in the last investment period for Scenario 9. This Figure can be directly compared to Figure 2 as that is the same starting point for Scenarios 1-10. All county-level capacity data are available in the included results spreadsheets. In this scenario, we see large amounts of wind and solar in similar places to precious scenarios, as well as the deployment of offshore wind on the eastern and Texas Gulf coasts.

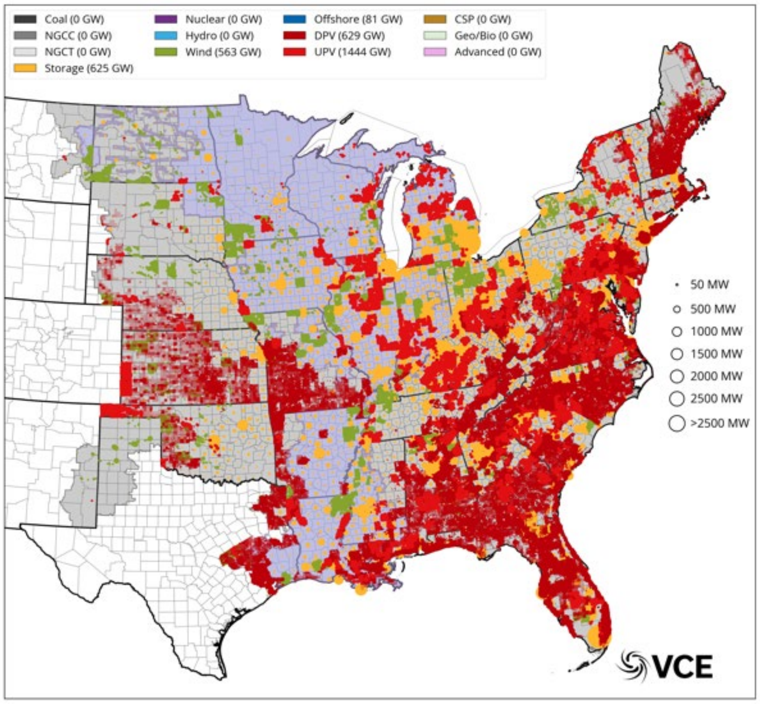
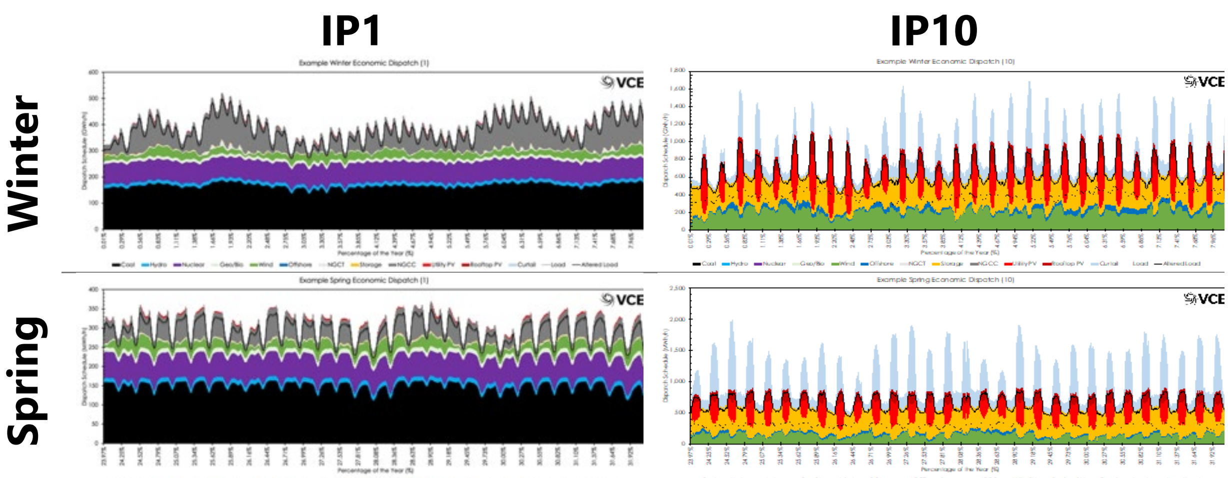


Figure 60: Location, type and size of powerplants in the EIC for Scenario 9, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 61 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire EIC system. Coal and nuclear generation disappear between the first and last investment periods while energy storage increasingly dispatches to compensate for ramps in demand and increased renewables output. NGCC output increased in the middle investment periods, but by investment period 10 has been eliminated to allow for 100% of generation to be met by wind and solar. We also see curtailment on most days by investment period 10. In all, over half of total generation is curtained across the system by the last investment period.



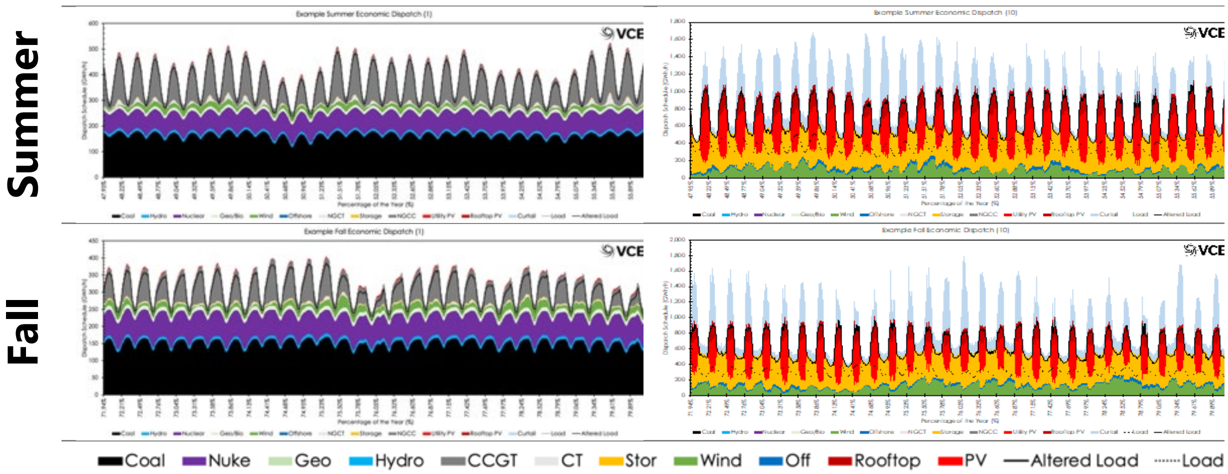


Figure 61: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 9.

By investment period 10 in Scenario 9, storage ramps 5% of its capacity per hour on average, up to 38% in some hours. Storage is also called upon to meet almost 96% of the load in some hours, but only about 16% on-peak.

Figure 62 shows the percent breakdown of generation from each technology for all investment periods in Scenario 9. Both fossil and nuclear generation decline rapidly to 0% throughout the investment periods to incorporate increasing amounts of solar and wind generation.

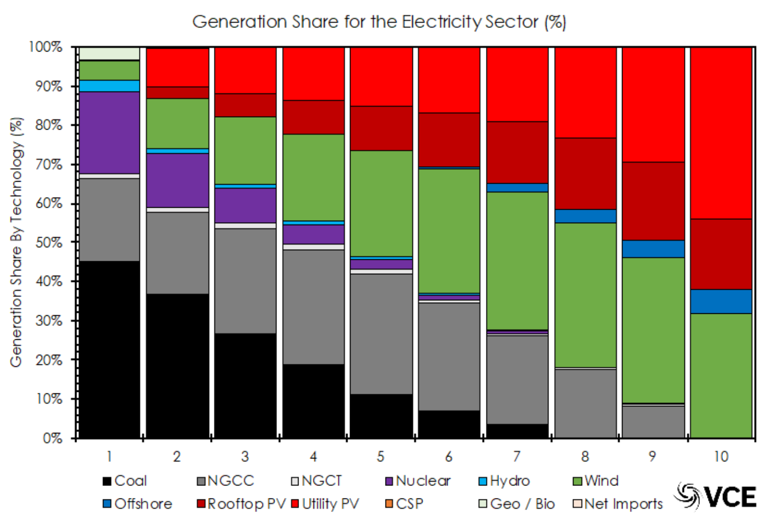


Figure 62: Percentage generation share for the electricity sector by technology and iteration number for Scenario 9.

Figure 63 shows the change in delivered electricity costs for each investment period, relative to the first investment period, or initialization. Costs decline quickly at first as the model retires the least economical units and then costs declines slow as the system deploys large amounts of renewables. While costs for all investment periods are lower than today's costs, the lowest costs are in investment period 4, which corresponds to the grid getting about 40% of its electricity from wind and solar. Relative to investment period 4, higher wind and solar levels are more expensive as the model is forced to curtail more energy and deploy more energy storage systems. By investment period 9, prices are higher than they are today due to the pushing of the system beyond economical deployments of wind and solar technologies. In investment period 10, prices are much higher than they are today illustrating just how expensive it is to get the last 10% of 100% renewables.

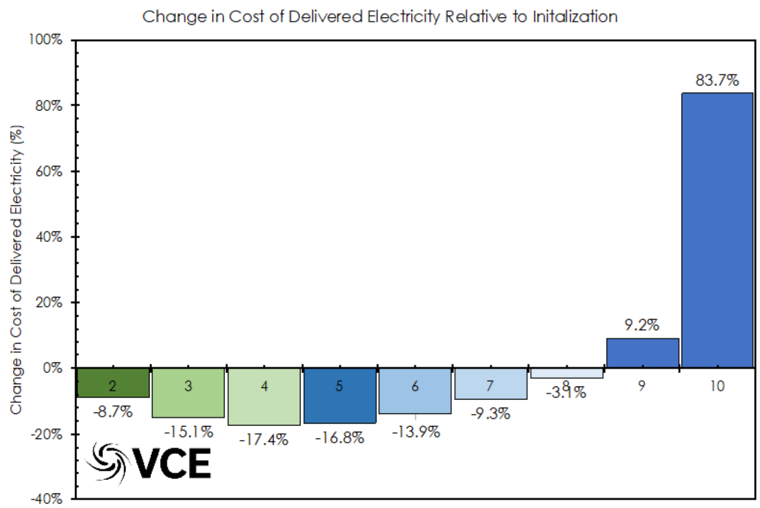


Figure 63: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 9.

Figure 64 shows the deployment of transmission in each state in EIC as well as to and from the MISO LRZs for Scenario 9. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. Note that in this scenario, transmission expansion between MISO and non-MISO regions was not allowed, but transmission expansion between MISO LRZs and expansion between non-MISO regions in EIC was allowed. However, more transmission capacity is built in this scenario and within MISO, the most transmission deployment was again between LRZ 9 and 10.

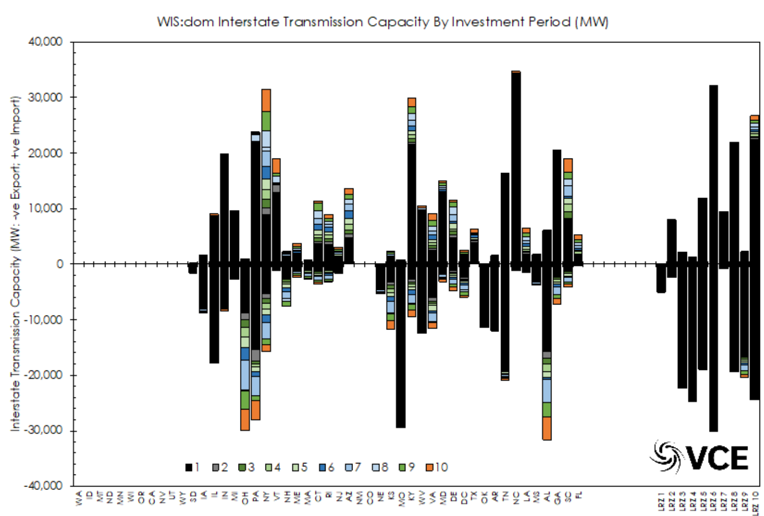


Figure 64: Interstate and inter-MISO region transmission capacity (MW) by investment period for Scenario 9. Negative values indicate capacity to export and positive values indicate capacity to import into that state/MISO region.

In Scenario 9, emissions fall 100% across the board by investment period 10. Full emissions details and accounting are available in the results spreadsheets.

Full time employment in the electricity sector in Scenario 5, by investment period 10 increases by about 520%, relative to today. There is explosive growth in the number of solar and wind jobs, especially in investment period 10, needed to deploy the renewables needed for this scenario.

Fuel burn data and figures are available in the results spreadsheets. In Scenario 9, natural gas fuel burn increases to about 9.7 Quads in investment period 5 before falling to zero in investment period 10 as more solar and wind come online, coal fuel burn decreases from about 16.5 Quads to zero by investment period 8 and uranium fuel burn declines to zero by investment period 8.

4.10. Path to 100% Wind & Solar (EIC) with Transmission Expansion (Scenario 10)

This scenario charts the optimal pathway for the entire EIC to generate 100% of its power from wind and solar by the 10th investment period. This scenario is similar to Scenario 9 except that transmission expansion is allowed between MISO and non-MISO regions.

Figure 65 shows the evolution of installed capacity by power plant type for Scenario 10. By investment period 10, over 3,275 GW of power plants, of all types exist in the EIC, up from about 790 GW in the first investment period. Between investment period 1 and 10, all fossil, hydro, and nuclear capacity retires while storage increases by about 3,680%, wind increases by about 1,500%, offshore wind increases by almost 270,000% (starting from 30 MW), solar increases by almost 32,000%, and energy storage capacity (MWh) increases by over 2,300%. In this scenario, the model builds over double the amount of utility-scale PV (1,333 GW) as it did in Scenario 8 (484 GW for 90% wind and solar with transmission expansion).

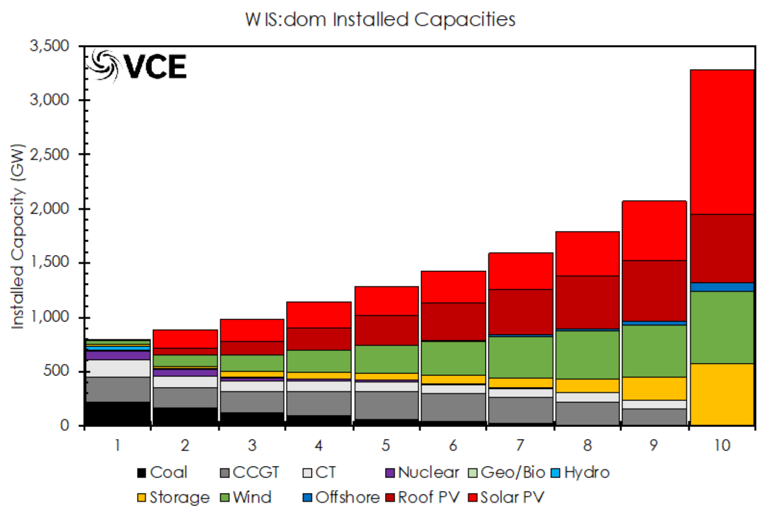


Figure 65: Power plant capacities by type in the EIC over each of the investment periods in Scenario 10. State and county level data are available in the included spreadsheets of the results.

Figure 66 shows the siting of power plants in the last investment period for Scenario 10. This Figure can be directly compared to Figure 2 as that is the same starting point for Scenarios 1-10. All county-level capacity data are available in the included results spreadsheets. In this scenario, we see large amounts of wind and solar in similar places to precious scenarios, as well as the deployment of about 80 GW offshore wind on the eastern and Texas Gulf coasts.

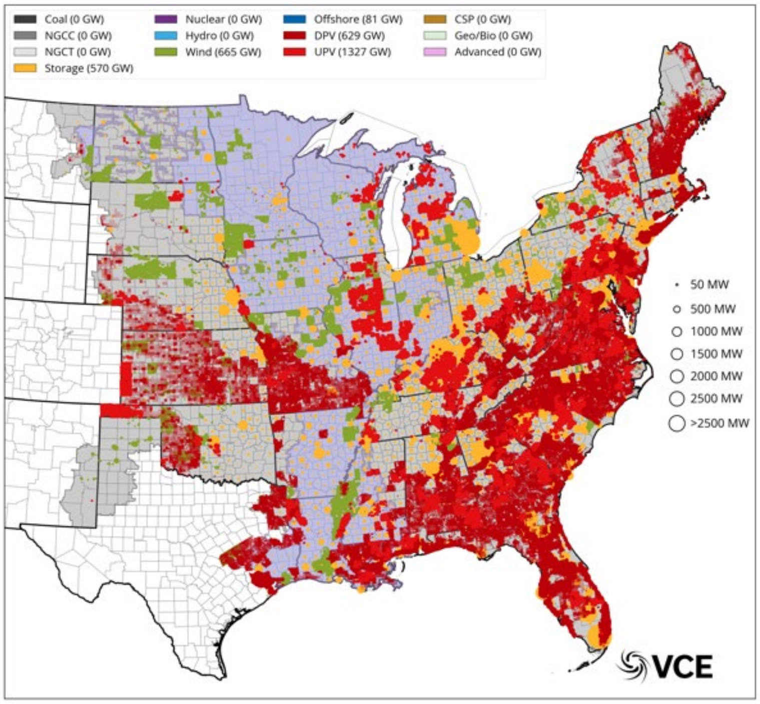
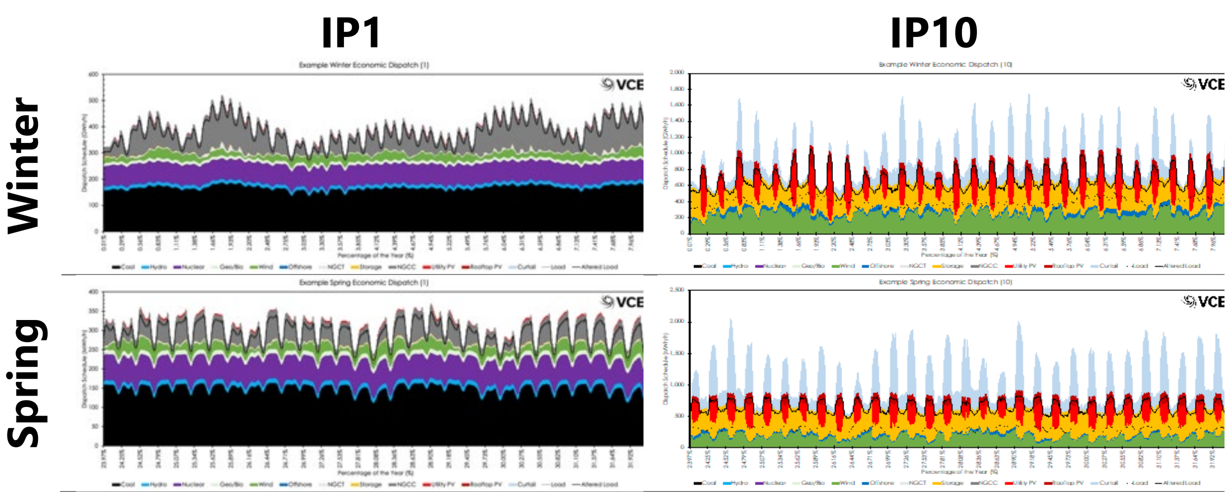


Figure 66: Location, type and size of powerplants in the EIC for Scenario 10, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 67 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire EIC system. Fossil generation disappears between the first and last investment periods while energy storage increasingly dispatches to compensate for ramps in demand and increased renewables output. NGCC output increased in the middle investment periods, but by investment period 10 has gone to zero to allow for 100% of generation to be met by wind and solar. We also see curtailment on most days by investment period 10. In all, about half of total generation is curtained across the system by the last investment period, similar to Scenario 9.



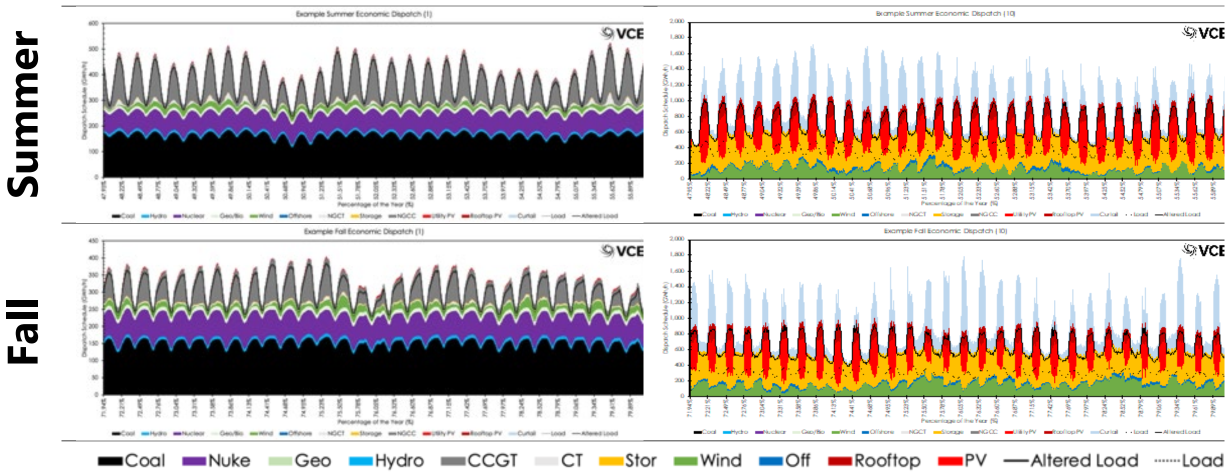


Figure 67: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 10.

By investment period 10 in Scenario 10, storage ramps 5% of its capacity per hour on average, up to 41% in some hours. Storage is also called upon to meet almost 92% of the load in some hours, but only about 15% on-peak. The transmission expansion allowed in Scenario 10 (vs. Scenario 9) again sees the installed storage capacity used more often, but less relied on for peak demand.

Figure 68 shows the percent breakdown of generation from each technology for all investment periods in Scenario 10. Both fossil and nuclear generation decline to zero through the investment periods to incorporate increasing amounts of solar and wind generation.

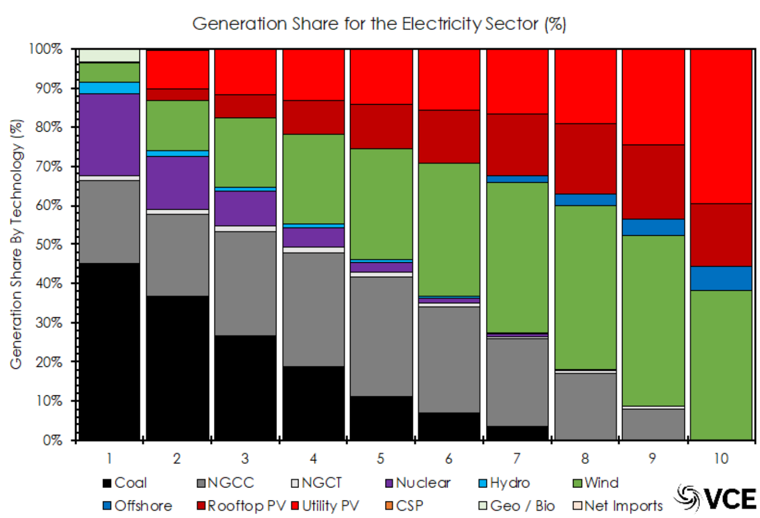


Figure 68: Percentage generation share for the electricity sector by technology and iteration number for Scenario 10.

Figure 69 shows the change in delivered electricity costs for each investment period, relative to the first investment period, or initialization. Costs decline quickly at first as the model retires the least economical units and then costs declines slow as the system deploys large amounts of renewables. While costs for all investment periods are lower than the initialization costs, the lowest costs are in investment period 4, which corresponds to the grid getting about 40% of its electricity from wind and solar. Relative to investment period 4, higher wind and solar levels are more expensive as the model is forced to curtail more energy and deploy more energy storage systems. By investment period 9, costs are higher than they are today, and by investment period 10, costs are over 70% higher than today.

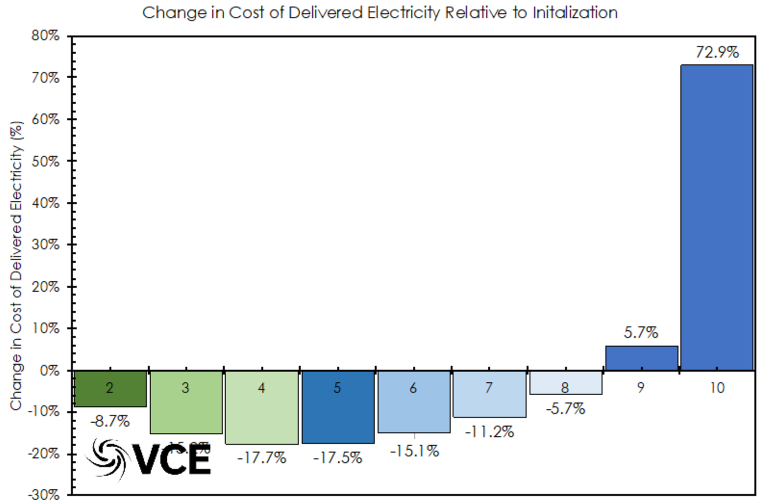


Figure 69: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 10.

Figure 54 shows the deployment of transmission in each state in EIC as well as to and from the MISO LRZs for Scenario 10. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. As transmission was allowed to expand between MISO and non-MISO regions in this scenario, we see much more transmission expansion relative to Scenario 9 and many states and LRZ regions more than doubled, in some cases tripled, their transmission capacity. Note that the y-axis has changed scale and is about three times larger than in Scenario 9.

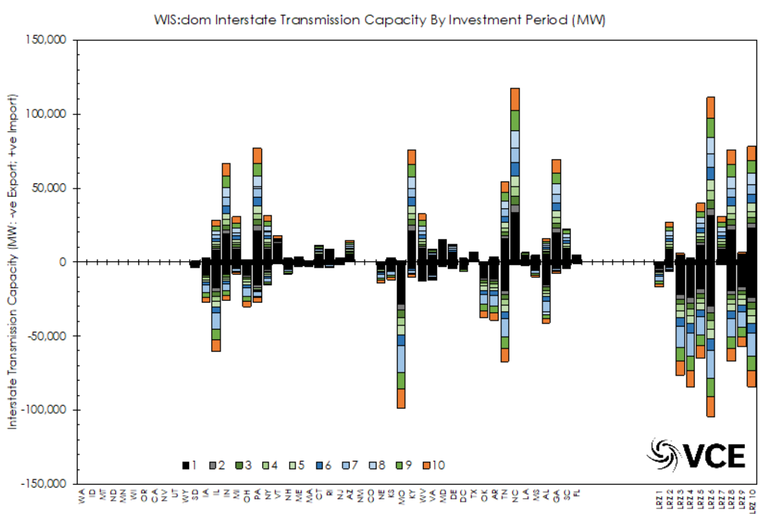


Figure 70: Interstate and inter-MISO region transmission capacity (MW) by investment period for Scenario 10. Negative values indicate capacity to export and positive values indicate capacity to import into that state/MISO region.

In Scenario 10, emissions fall 100% across the board by investment period 10. Full emissions details and accounting are available in the results spreadsheets.

Full time employment in the electricity sector in Scenario 10, by investment period 10 increases by about 560%, relative to today. There is explosive growth in the number of solar, wind, and transmission jobs, especially in investment period 10, needed to deploy the renewables needed for this scenario.

Fuel burn data and figures are available in the results spreadsheets. In Scenario 10, natural gas fuel burn increases to about 9.6 Quads in investment period 5 before falling to zero in investment period 10 as more solar and wind come online, coal fuel burn decreases from about 16.5 Quads to zero by investment period 8 and uranium fuel burn declines to zero by investment period 8.

5. Details of the MISO Modeling Scenarios

5.1. Optimal expansion for MISO (Scenario 11)

The first scenario considered here is an optimal expansion of MISO where transmission and energy trading expansion with non-MISO areas is not allowed to expand. In this scenario, the WIS:dom® optimization model was allowed to choose the location and amount of each type of generation resource available to it with the objective to least-cost optimize the matching of electricity supply and demand for every five-minute interval of each investment period.

Figure 71 shows the evolution of installed capacity by power plant type for Scenario 11. In general, coal, NGCT (natural gas combustion turbines), and nuclear capacities fall while NGCC (natural gas combines cycle), energy storage and renewable capacities rise. By investment period 10, about 233 GW of power plants, of all types exist in MISO, up from about 197 GW in the first investment period. Between investment period 1 and 10, coal decreases by about 85%, NGCC increases by about 45%, NGCT decreases by about 23%, storage increases by about 1,400%, all nuclear and hydro retire, wind increases by almost 155%, and solar (utility and rooftop) increases by over 14,000%. Economic dispatch of the fleet causes the capacity factors of the remaining thermal plants to generally rise over the investment periods as the fleet transitions.

Between investment periods 3 and 4, we see the maximum system load exceeding firm generation supply (coal, gas, nuclear, hydro and storage). This does not mean that the model was not able to match supply and demand, but that, on peak, the system is counting on some renewables to be online.

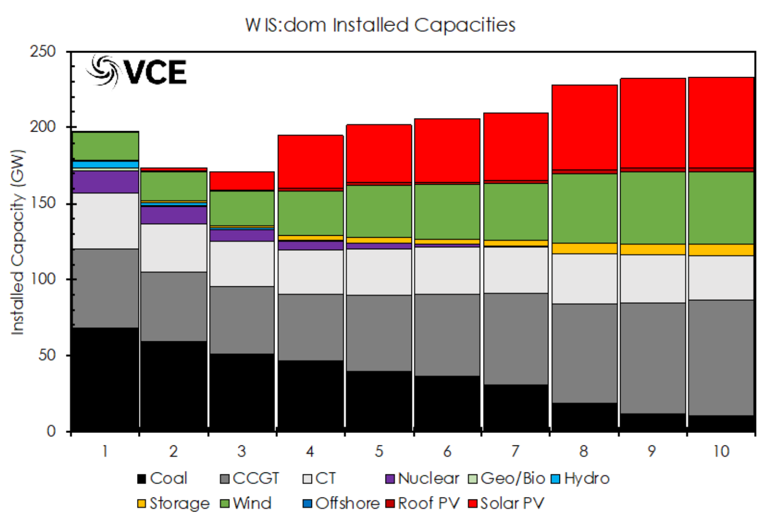


Figure 71: Power plant capacities by type in MISO over each of the investment periods in Scenario 11. State and county level data are available in the included spreadsheets of the results.

Figure 72 and Figure 73 show the difference in where WIS:dom® sites power plants between the first and last investment period. Note that power plants larger than 2,500 MW were all assigned the same size circle to make the maps easier to read. All county-level capacity data are available in the included results spreadsheets.

Most noticeable between the two figures is the replacement of the large coal and nuclear units with large NGCC and storage units along with the deployment of large amounts of solar PV across MISO's footprint.

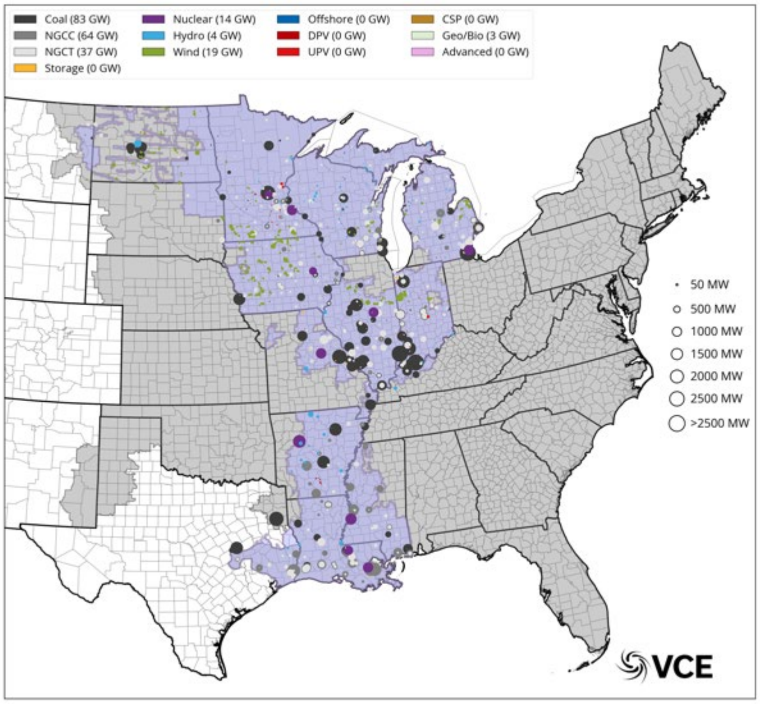


Figure 72: Location, type and size of powerplants in MISO for Scenario 11, investment period 1. The gray base color is the entire Eastern Interconnect and the purple base color is MISO. This figure serves as the "starting point" for Scenarios 11-19 and, for brevity, will only be shown here.

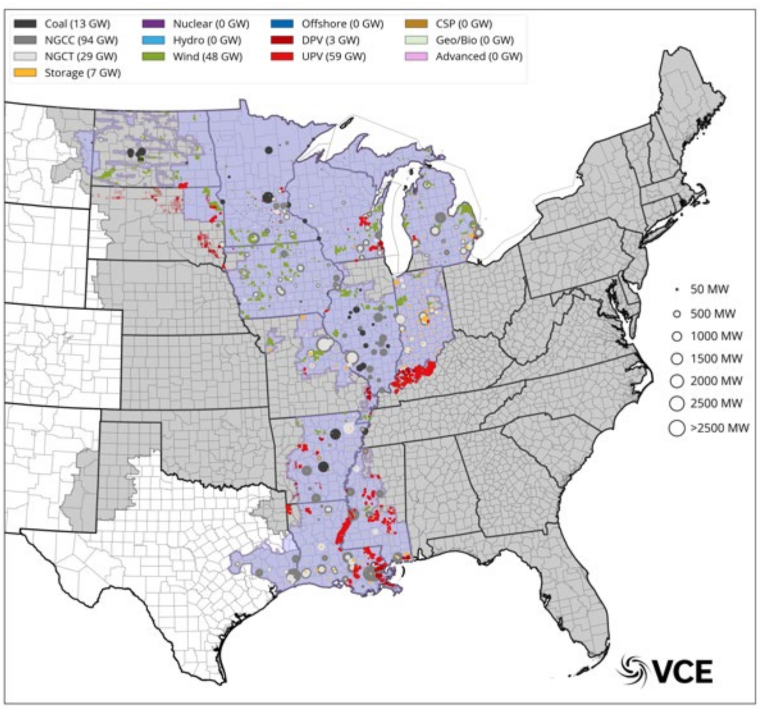


Figure 73: Location, type and size of powerplants in MISO for Scenario 11, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 74 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire MISO system. Coal generation is largely reduced between the first and last investment periods while NGCC plants increasingly dispatches to compensate for ramps in demand and increased renewables output.

Overall, the model is able to patch supply and demand for every 5-minute period of the year with this optimal MISO mix.

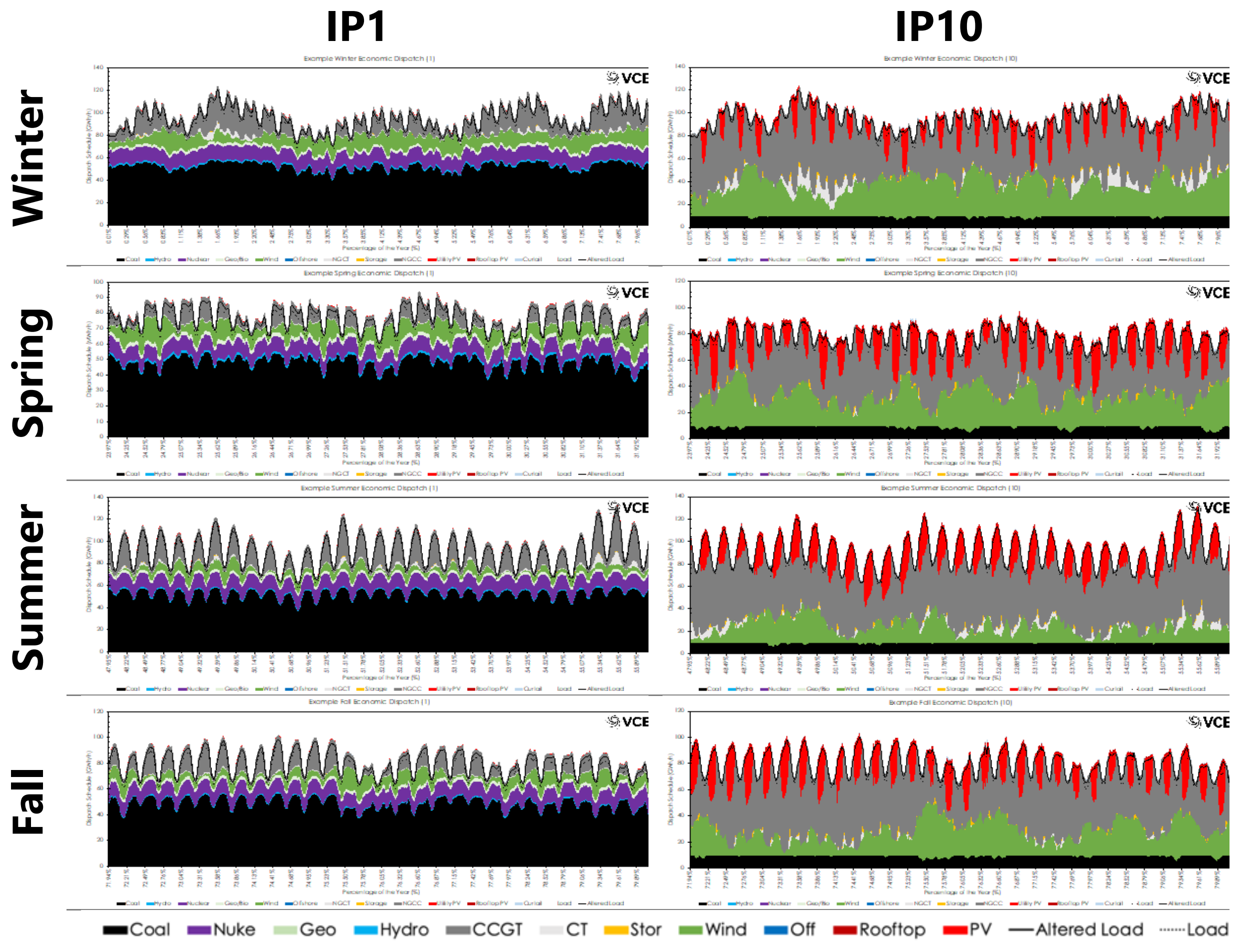


Figure 74: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 11.

In investment period 1 of Scenario 11, which acts as the same base case for Scenarios 11-19, average ramps for NGCC, NGCT, and storage are 2.8%, 0.4%, and 3.1%, respectfully, and maximum ramps are 13.5%, 9.7%, and almost 94% for each of the technologies. By investment period 10 in Scenario 11, average ramps for NGCC, NGCT, and storage have increased to 3.8%, 2.4%, and 7.7%, respectfully, and maximum ramps also increased to 17.7%, 40.8%, and almost 100% for each of the technologies. Coal on average ramps less by investment period 10, but has slightly higher maximum ramps. By investment period 10, storage is relied upon to provide almost 10% of the entire MISO altered load for some hours, but only about 1% on-peak.

Figure 75 shows the percent breakdown of generation from each technology for all investment periods in Scenario 11. The percentage of generation from coal and gas plants combined stays above 60% for all investment periods, but nuclear power disappears by investment period 8. Note that load grows about 3% from investment period 1 to 10.

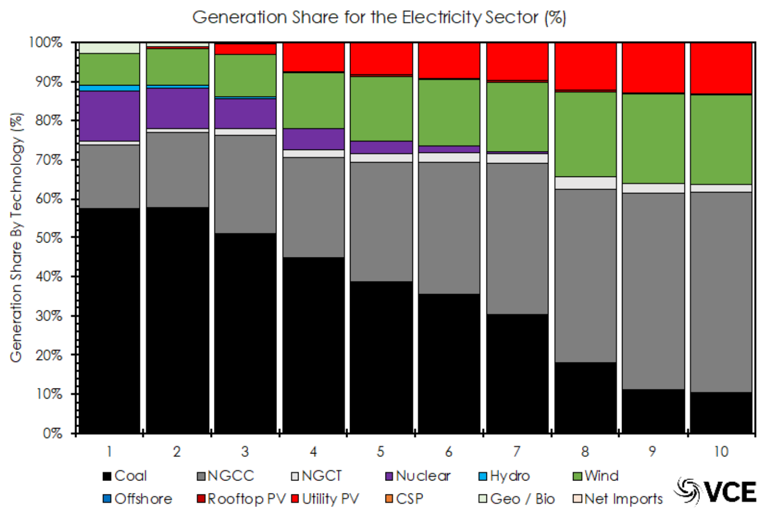


Figure 75: Percentage generation share for the electricity sector by technology and iteration number for Scenario 11.

Figure 76 shows the change in emissions, relative to the first iteration, for iterations 2-9. In this Scenario, emissions decline across the board due to coal to gas switching and increasing renewable generation. Some emissions fall faster than others, such as SO_2, because coal plants generally emit much larger quantities than gas plants. Carbon emissions fall by almost 50% largely due to retiring coal plants being replaced with cleaner natural gas and renewables.

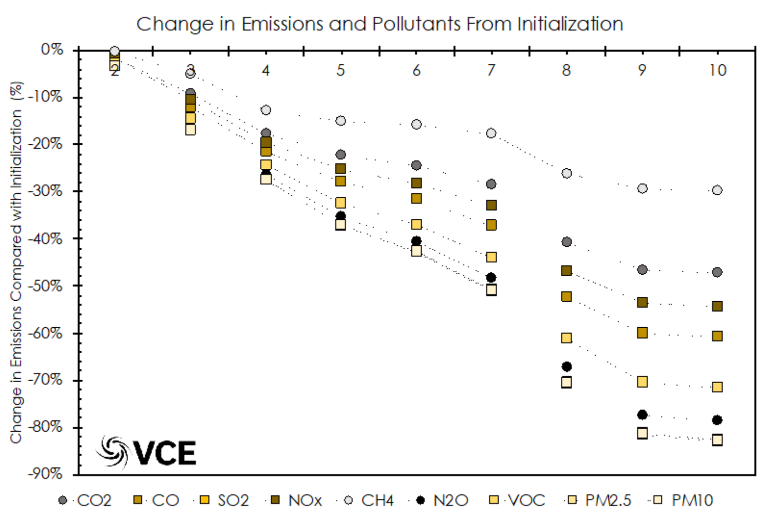


Figure 76: Emissions impacts in MISO given the changes in electricity generation for all investment periods of Scenario 11, relative to investment period 1.

Figure 77 shows the change in employment in the electricity sector for each iteration, relative to the first iteration. Between the first and tenth iteration, and after some initial losses, electricity sector employment grows by about 82%, adding over 150,000 jobs. However, the jobs created are in different sectors. Coal jobs decrease by about 85%, nuclear jobs disappear and natural gas jobs increase by about 20%. Renewable energy jobs increase significantly with wind jobs growing by about 160%, transmission jobs increasing by over 40%, and solar jobs increase the most, by almost 15,000%, relative to the first iteration.

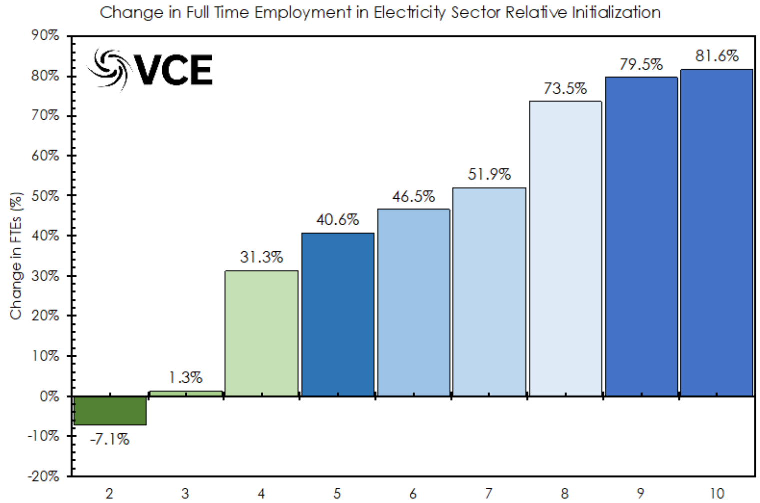


Figure 77: Employment (full-time equivalent) impacts given the changes in MISO's electricity sector for Scenario 11.

Figure 78 shows the change in delivered electricity costs for each investment period, relative to the first investment period, or initialization. As this analysis is an optimal capacity expansion, the model chooses the least-cost suite of technologies to deploy each iteration and thus we see costs decline over all investment periods. Costs decline quickly at first as the model retires the least economical units and then costs declines slow as the system approaches the optimal grid mix.

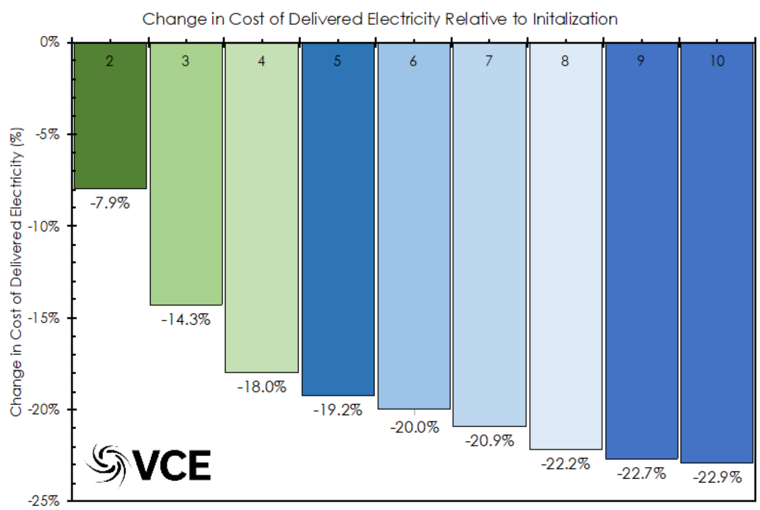


Figure 78: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 11.

Figure 79 shows the deployment of transmission in each MISO LRZ. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. Most LRZs add both import and export transmission capacity in at least one of the investment periods, particularly the model finds that it is optimal to over triple the export capacity of LRZ5.

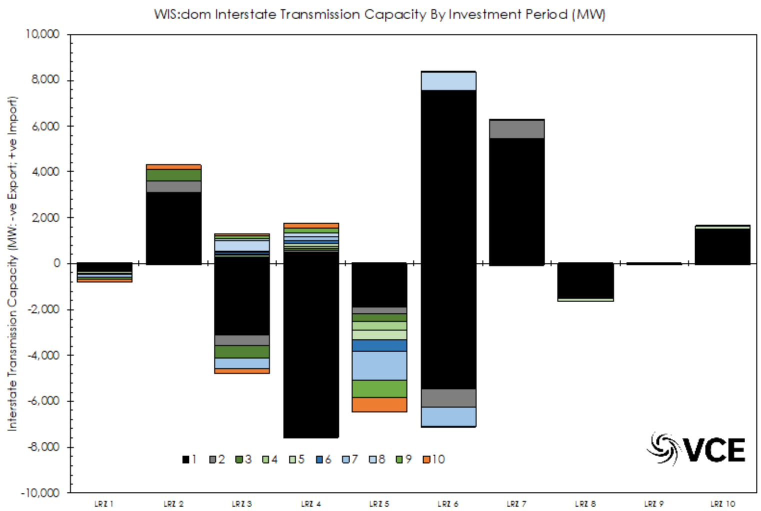


Figure 79: Inter-MISO region transmission capacity (MW) by investment period. Negative values indicate capacity to export from and positive values indicate capacity to import into that MISO region.

Figure 80 through Figure 82 show the coal, natural gas, and uranium fuel burns in Quads for each investment period, respectfully. Coal fuel burn declines across the board in every region, except LRZ1, as other technologies are deployed and dispatched. Natural gas fuel burn trends upward over all investment periods in almost every region. Uranium fuel burn declines rapidly until investment period 8 where it essentially goes to zero, there is some residual nuclear generation in the latter investment periods, but the vast majority of nuclear capacity retires over the MISO service area.

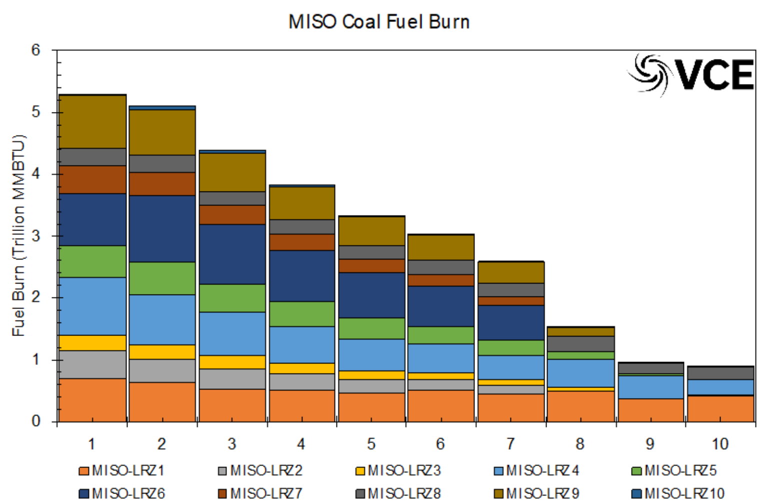


Figure 80: Coal fuel burn for each MISO LRZ for Scenario 11.

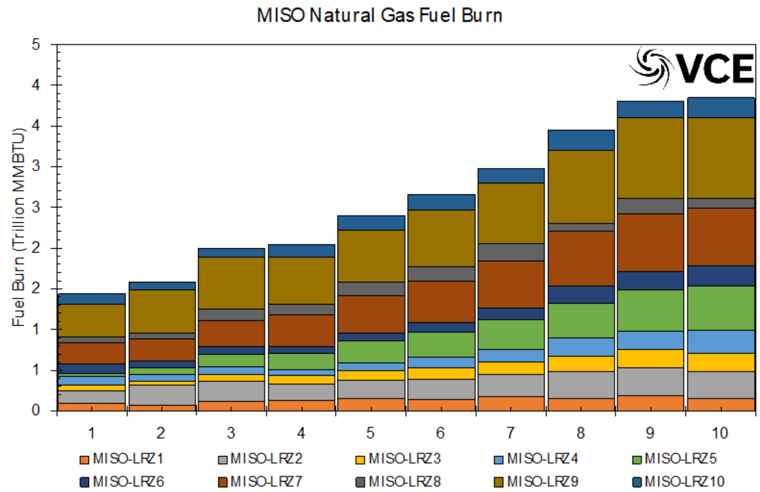


Figure 81: Natural gas fuel burn for each MISO LRZ for Scenario 11.

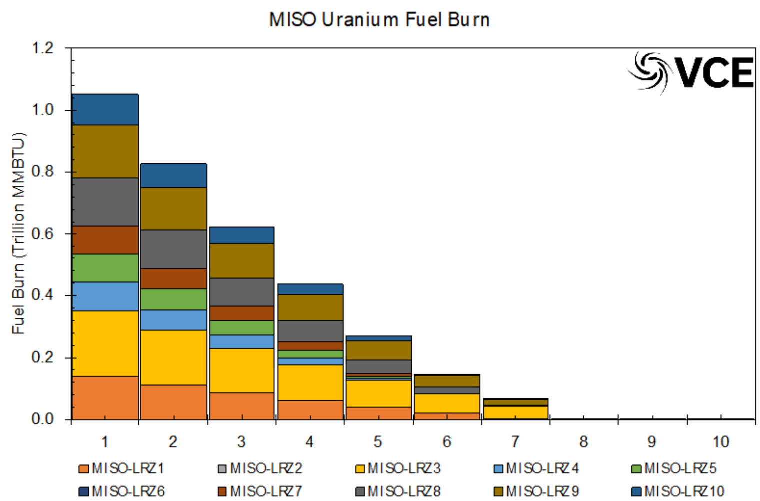


Figure 82: Uranium fuel burn for each MISO LRZ for Scenario 11.

Scenarios 12 through 19 are designed to test the MISO system by forcing the model to deploy certain amounts of technology by the 10th investment period in each scenario. For example, Scenario 12 includes the optimal pathway to 100% wind power in MISO and each investment period corresponds to a direct percentage of that goal, i.e. investment period 7 of a 100% wind goal would mean that in investment period 7, MISO must get 70% of its energy from wind.

5.2. Path to 100% Wind in MISO (Scenario 12)

This scenario charts the optimal pathway for MISO to generate all of its electricity needs from wind power by the 10th investment period. The model can also deploy storage to manage the variability of the wind resource to, at all times, match supply and demand.

Figure 83 shows the evolution of installed capacity by power plant type for Scenario 12. As per the scenario parameters, the model ends up with only wind and storage capacity by the 10th investment period. The MISO system finalizes with over 680 GW of wind and almost 150 GW of storage capacity deployed. The model tries to hold onto some natural gas capacity as long as it can (until the 9th investment period), and even builds some solar capacity in the intervening periods to try and balance supply and demand in a more cost-effective manner.

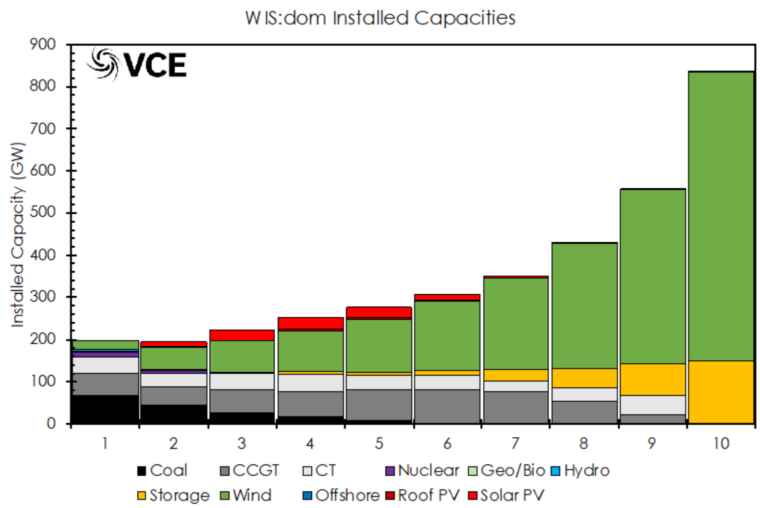


Figure 83: Power plant capacities by type in MISO over each of the investment periods in Scenario 12. State and county level data are available in the included spreadsheets of the results.

Figure 84 shows the siting of power plants in the last investment period for Scenario 9. This Figure can be directly compared to Figure 72 as that is the same starting point for Scenarios 11-19. In this scenario, we see large amounts of wind spread out among MISO's footprint as well as some offshore wind deployed off the Louisiana coast.

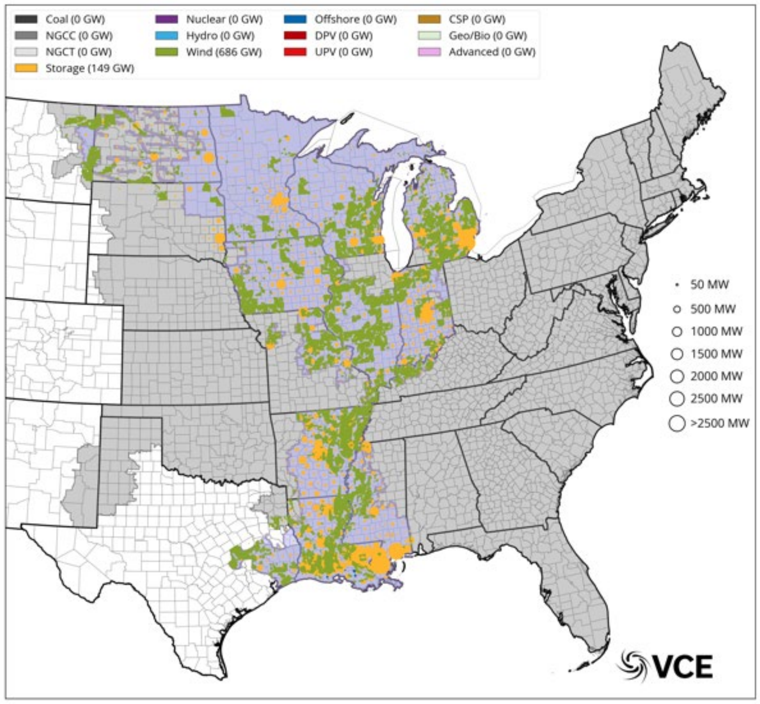
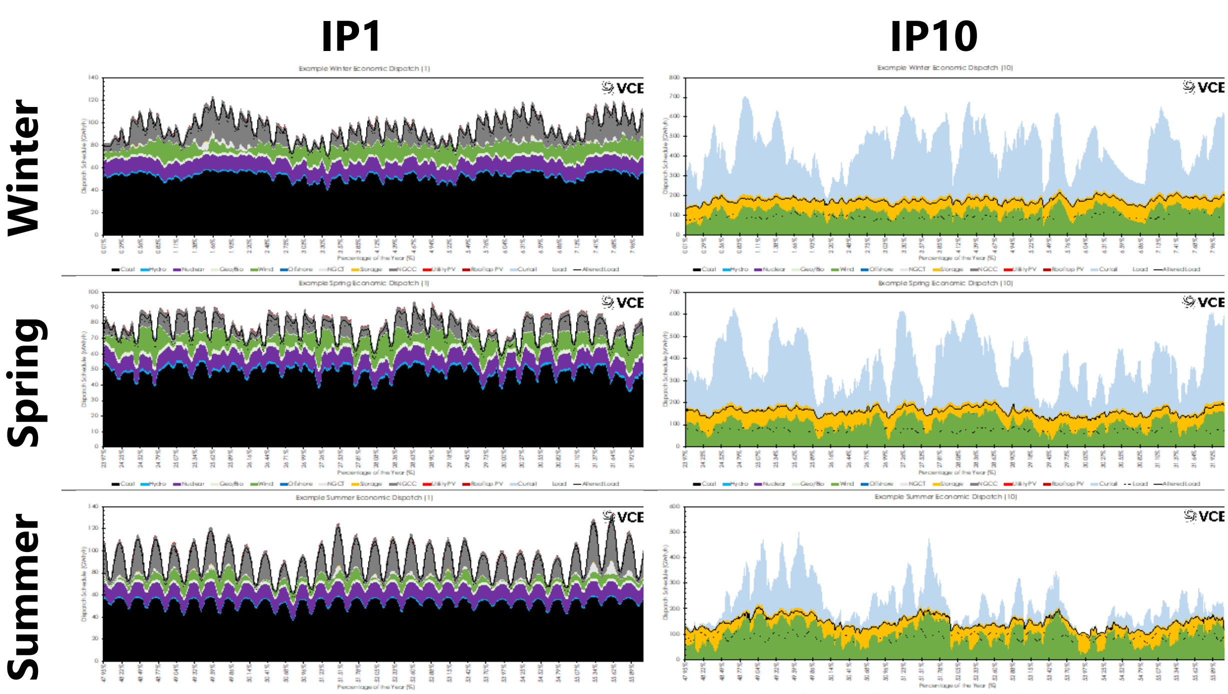


Figure 84: Location, type and size of powerplants in MISO for Scenario 12, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 86 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire MISO system. Everything but wind and storage are eliminated from the system by the 10th investment period. Overall the model is able to match supply and demand for every 5-minute period of the year using only wind, but it also curtails about 70% more energy than it actually delivers to load.



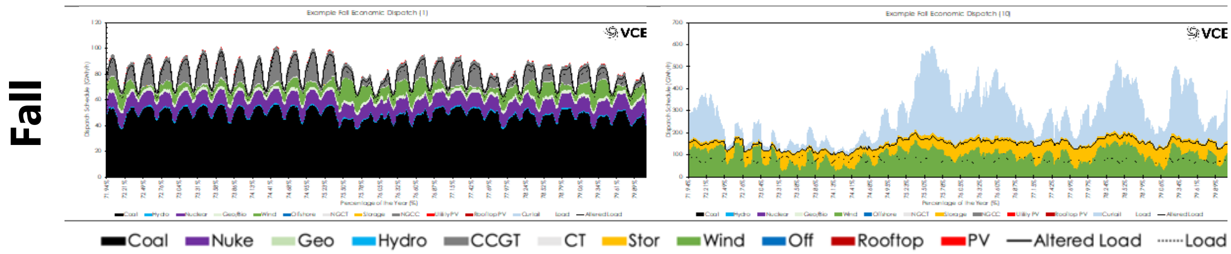


Figure 85: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 12.

By investment period 10 in Scenario 12, storage ramps about 2.2% of its capacity on average per hour, up to 34% and some hours require over 100% of the load to be met by storage systems (includes reserves).

Figure 86 shows the percent breakdown of generation from each technology for all investment periods in Scenario 12. The percentage of fossil generation steadily declines as one would expect given the scenario constraints, nuclear power also disappears by investment period 4. By investment period, 100% of energy generated in MISO comes from wind.

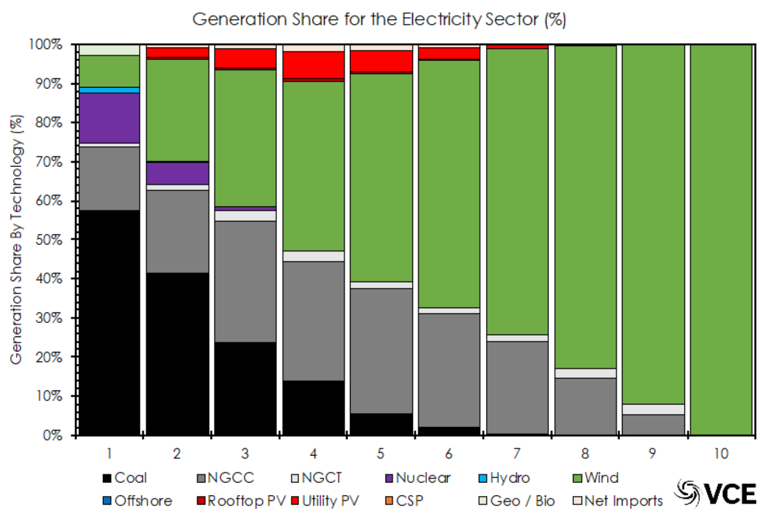


Figure 86: Percentage generation share for the electricity sector by technology and iteration number for Scenario 12.

Figure 87 shows the change in delivered electricity costs for each investment period, relative to the first investment period, or initialization. The model finds that the minimum system costs occur around investment period 4, or about 40% wind on the MISO system. After that, costs start to increase and by investment period 7 are above the initialization costs. The jump from investment period 9 to 10, or the last 10% of getting to 100% wind is very expensive and costs are over 700% higher than they are today.

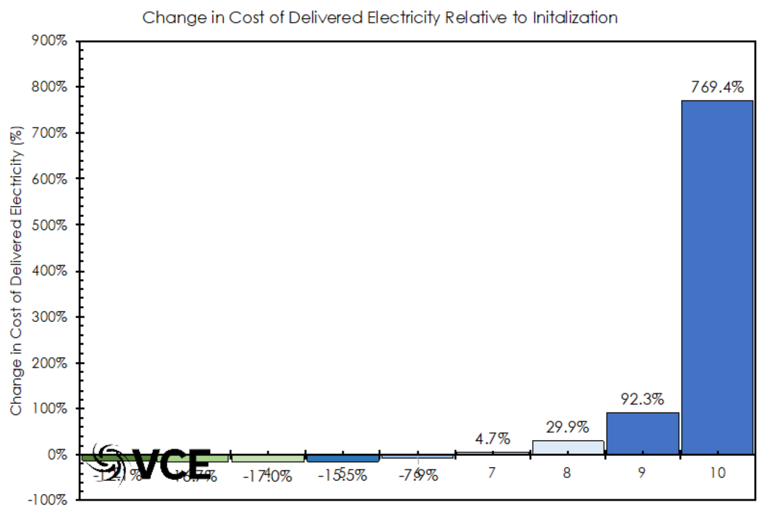


Figure 87: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 12.

Figure 88 shows the deployment of transmission in each MISO LRZ. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. Most LRZs more than double their connections with each other to more effectively move power through the MISO system.

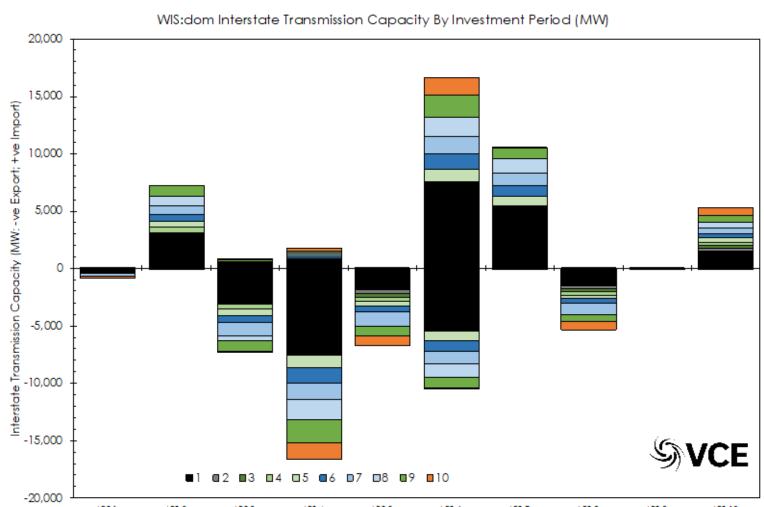


Figure 88: Inter-MISO region transmission capacity (MW) by investment period. Negative values indicate capacity to export from and positive values indicate capacity to import into that MISO region.

In Scenario 12, emissions fall 100% across the board by investment period 10. Full emissions details and accounting are available in the results spreadsheets.

Full time employment in the electricity sector in Scenario 12, by investment period 10 increases by almost 500%, relative to today. There is explosive growth in the number of wind and transmission jobs, especially in investment period 10, needed for this scenario.

Fuel burn data and figures are available in the results spreadsheets. In Scenario 12, natural gas fuel burn increases to about 2.6 Quads in investment period 4 before falling to zero in investment period 10 as more solar and wind come online, coal fuel burn decreases from about 5.3 Quads to zero by investment period 7 and uranium fuel burn declines to zero by investment period 4.

5.3. Path to 100% Solar in MISO (Scenario 13)

This scenario charts the optimal pathway for MISO to generate all of its power from solar power only by the 10th investment period. The model can also deploy storage to manage the variability of the wind resource to, at all times, match supply and demand.

Figure 89 shows the evolution of installed capacity by power plant type for Scenario 13. As per the scenario parameters, the model ends up with only solar (utility and rooftop) and storage capacity by the 10th investment period. The system ends up with over 900 GW of solar and almost 228 GW of storage capacity deployed. The model tries to hold onto some gas capacity as long as it can (until the 9th investment period).

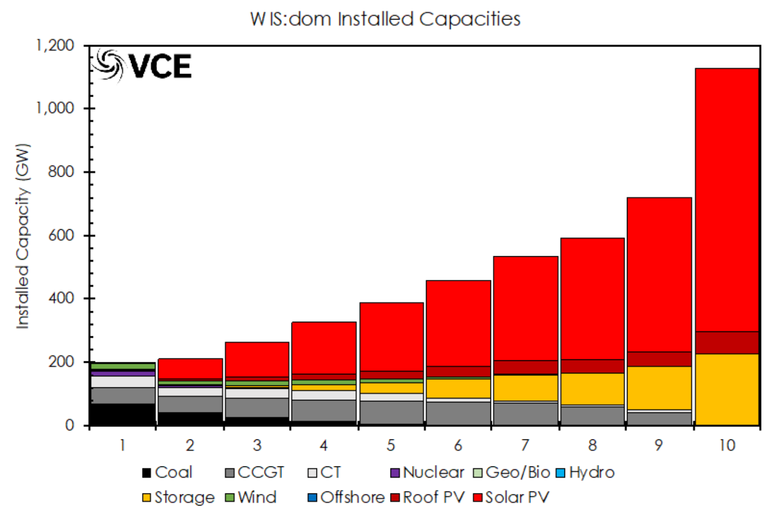


Figure 89: Power plant capacities by type in MISO over each of the investment periods in Scenario 13. State and county level data are available in the included spreadsheets of the results.

Figure 90 shows the siting of power plants in the last investment period for Scenario 13. This Figure can be directly compared to Figure 72 as that is the same starting point for Scenarios 11-19. All county-level capacity data are available in the included results spreadsheets.

Large amounts of solar PV are deployed in the southern portion and eastern and western edges of the MISO system. The model deploys solar heavily in these regions as it is trying to deploy solar in complimentary locations, but is limited by MISO's longitudinal narrowness. The model is trying to pick up the morning sun on the eastern edge, the best midday production in the south, and the afternoon sun on the western edge. This strategic "chasing the sun" deployment by WIS:dom® is why more northern and central MISO states such as Minnesota do not have as much solar capacity installed.

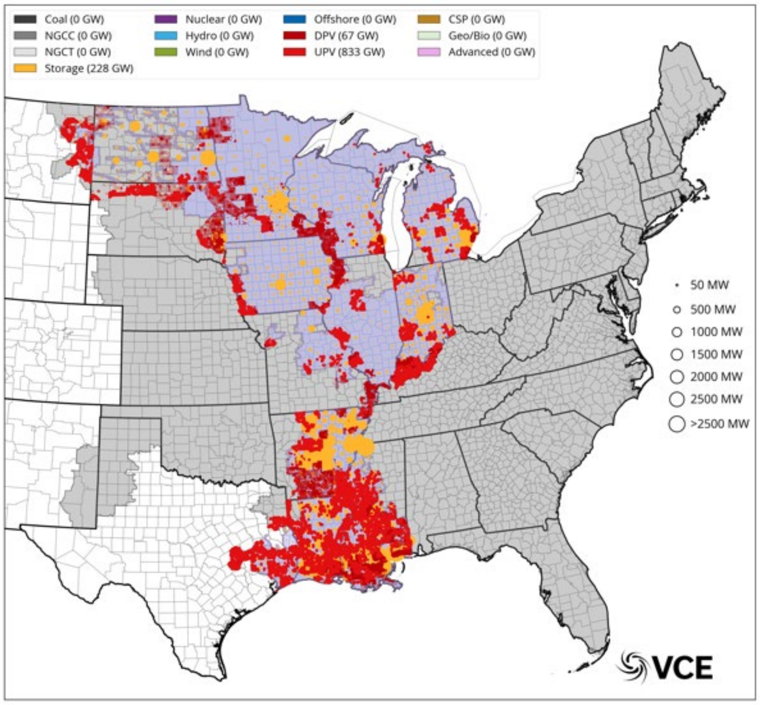
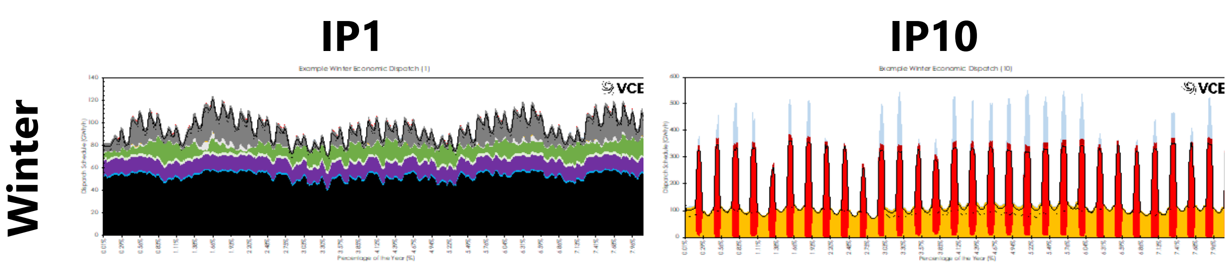


Figure 90: Location, type and size of powerplants in MISO for Scenario 13, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 91 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire MISO system. Everything but solar and storage are eliminated from the system by the 10th investment period. Overall the model is able to match supply and demand for every 5-minute period of the year using only wind, but it also curtails about half of the total amount of energy generated.

One might notice that, at very high levels of renewables, such as investment period 10 in this scenario, the model is discharging storage to curtailment. This is a modeling artifact based on there being no cost to discharging storage (it was wrapped up in the fixed charges). Thus, the model found it cheaper to cycle power through energy storage first (because of losses) and thus the resulting curtailment would be less than if the solar had just curtailed directly. These artifacts disappear in the earlier investment periods when dispatchable generation, such as gas, is available. Getting rid of these artifacts would drive costs for this unlikely scenario even higher.



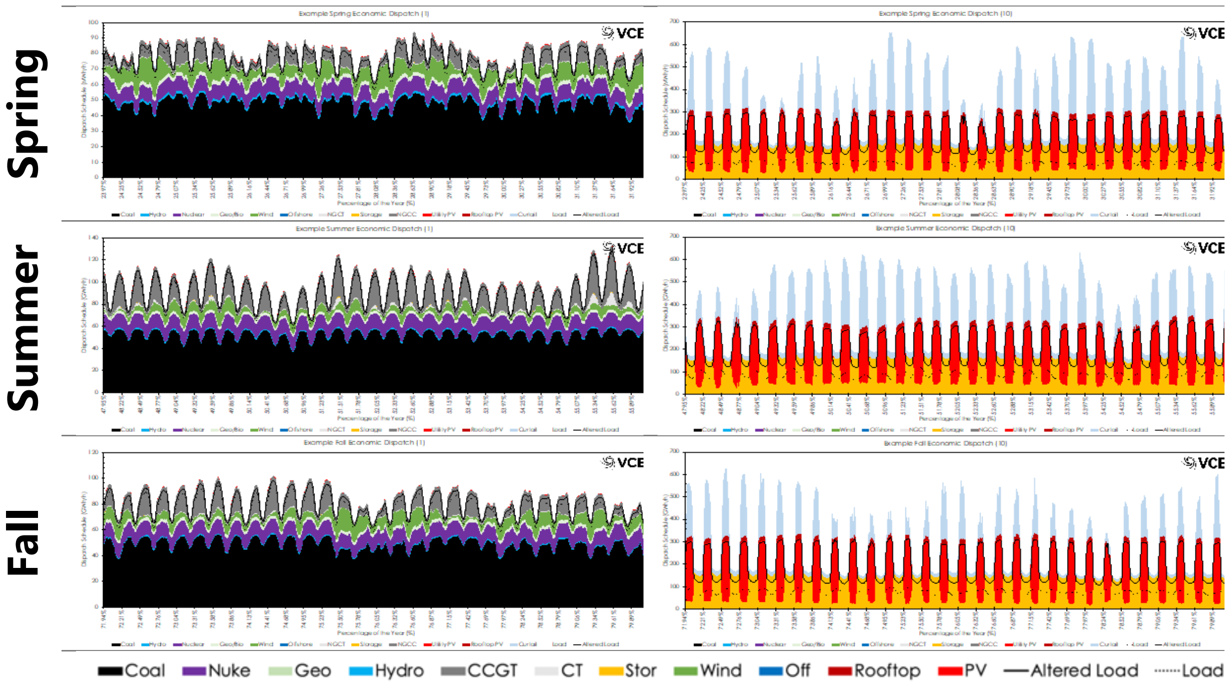


Figure 91: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 13.

By investment period 10 in Scenario 13, storage ramps about 4.8% of its capacity on average per hour, up to 51% and some hours require over 100% of the load to be met by storage systems (includes reserves). Storage has to work harder for 100% solar than for 100% wind as wind ramps tend to be less severe and happen less frequently.

Figure 92 shows the percent breakdown of generation from each technology for all investment periods in Scenario 13. The percentage of fossil generation steadily declines as one would expect given the scenario constraints, nuclear power also disappears by investment period 4. By investment period, 100% of energy generated in MISO comes from solar PV.

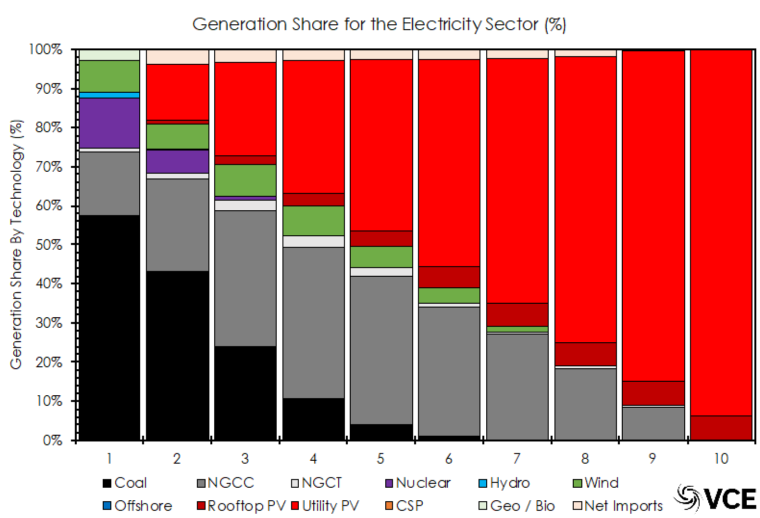


Figure 92: Percentage generation share for the electricity sector by technology and iteration number for Scenario 13.

Figure 93 shows the change in delivered electricity costs for each investment period, relative to the first investment period, or initialization. The model finds that the minimum system costs occur around investment period 3, or about 30% of energy from solar on the MISO system. After that, costs start to increase and by investment period 6 are above the initialization costs. The jump from investment period 9 to 10, or the last 10% of getting to 100% solar is the most expensive and costs are almost 130% higher than they are today.

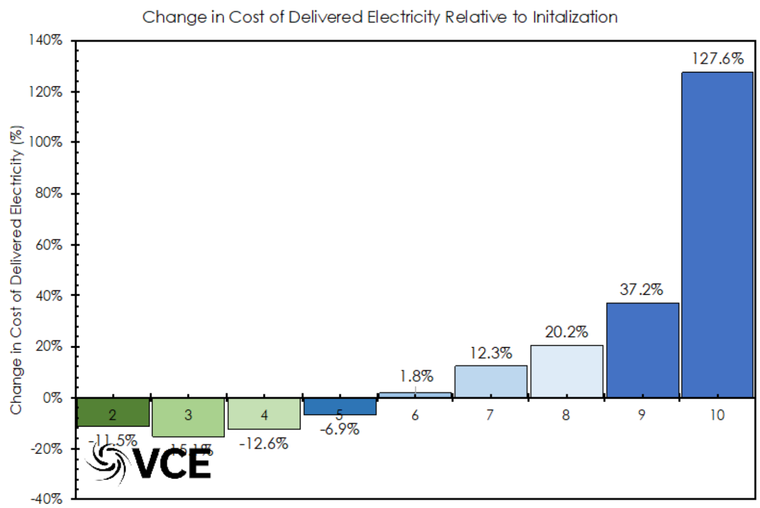


Figure 93: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 13.

Figure 94 shows the deployment of transmission in each MISO LRZ. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. This scenario requires the most build out of transmission than any other MISO-specific scenario considered in this analysis. Most LRZs deploy very large amounts of transmission capacity expansion, particularly in the last three investment periods.

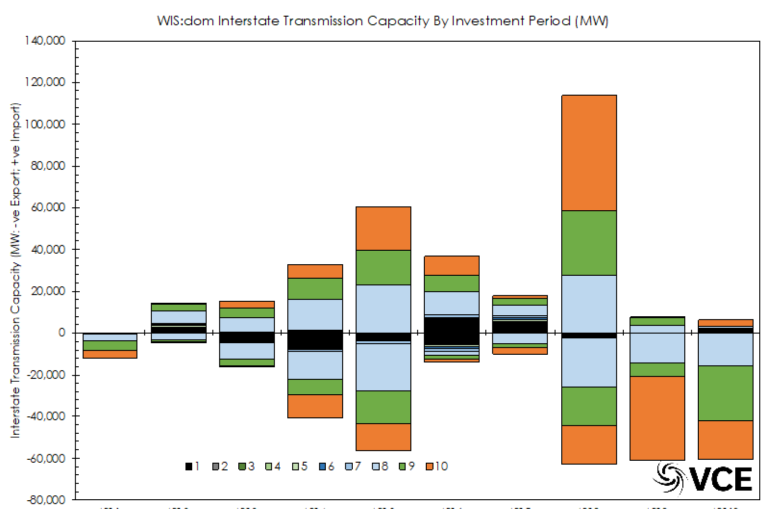


Figure 94: Inter-MISO region transmission capacity (MW) by investment period. Negative values indicate capacity to export from and positive values indicate capacity to import into that MISO region. Note that the y-axis is much larger than in previous scenarios.

In Scenario 13, emissions fall 100% across the board by investment period 10. Full emissions details and accounting are available in the results spreadsheets.

Full time employment in the electricity sector in Scenario 13, by investment period 10, increases by over 1,000%, relative to today. There is explosive growth in the number of solar and transmission jobs, especially after investment period 7, needed to deploy the capacity needed for this scenario.

Fuel burn data and figures are available in the results spreadsheets. In Scenario 9, natural gas fuel burn increases to about 3.3 Quads in investment period 4 before falling to zero in investment period 10 as more solar comes online, coal fuel burn decreases from about 5.3 Quads to zero by investment period 7 and uranium fuel burn declines to zero by investment period 4.

5.4. Path to 2% Energy Storage in MISO (Scenario 14)

In this scenario, the WIS:dom® model charts the optimal pathway for MISO given that the model must also build enough energy storage capacity to hold 2% of annual generation by the 10th investment period. Otherwise, the model is able to least-cost optimize the rest of the system.

Figure 95 shows the evolution of installed capacity by power plant type for Scenario 14. As per the scenario parameters, the model ends up with over 36 GW storage capacity by the 10th investment period. Overall the system ends up with about 269 GW of power plants of all types (up from about 197 GW in the first investment period). Relative to the overall optimal pathway, this scenario deploys more renewables and retires more fossil generators as the system is able to take advantage of the required energy storage capacity.

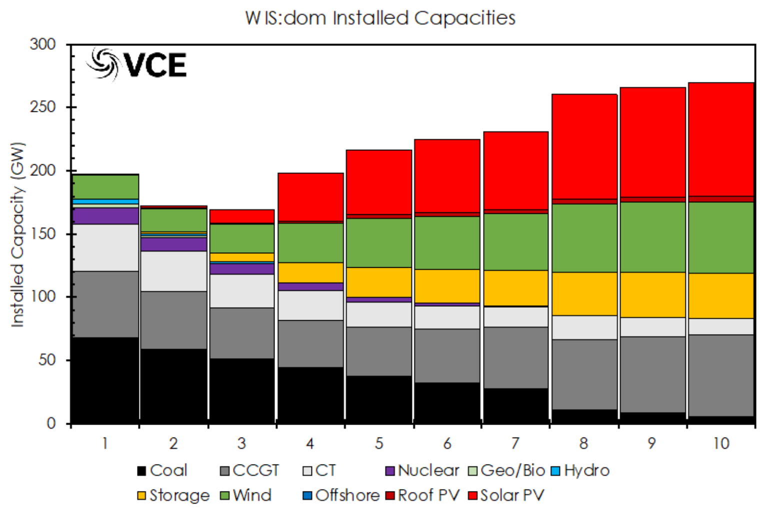


Figure 95: Power plant capacities by type in MISO over each of the investment periods in Scenario 14. State and county level data are available in the included spreadsheets of the results.

Figure 96 shows the siting of power plants in the last investment period for Scenario 14. This Figure can be directly compared to Figure 72 as that is the same starting point for Scenarios 11-19. All county-level capacity data are available in the included results spreadsheets.

The model builds a large amount of wind and solar PV and energy storage assets are strategically placed within the MISO footprint. The model places the assets in locations that are most advantageous, solar on the edges and in the south and wind in the locations with the better resources and transmission availability.

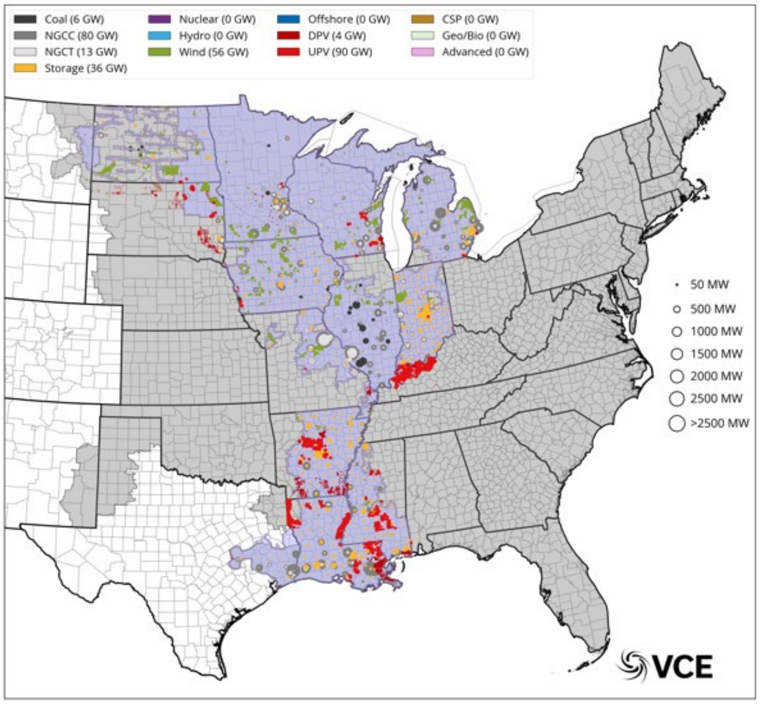
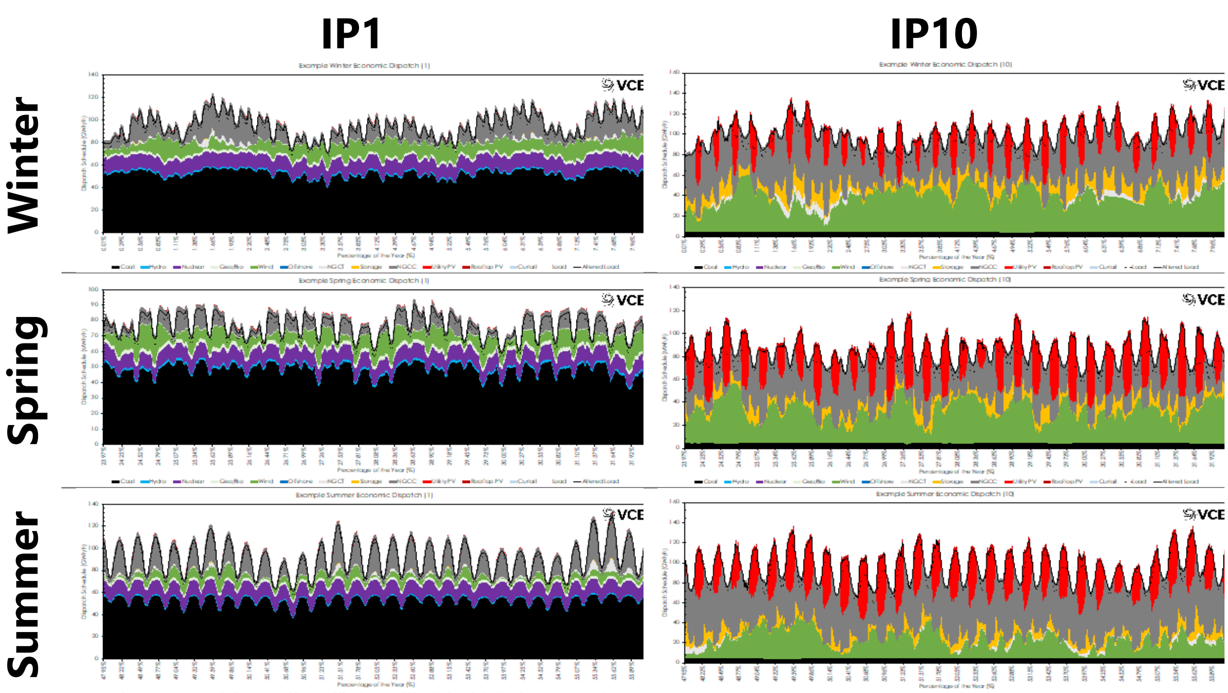


Figure 96: Location, type and size of powerplants in MISO for Scenario 14, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 97 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire MISO system. Coal generation is largely reduced between the first and last investment periods while NGCC and storage plants increasingly dispatch to compensate for ramps in demand and increased renewables output. Overall the model is able to patch supply and demand for every 5-minute period of the year with this optimal MISO mix.



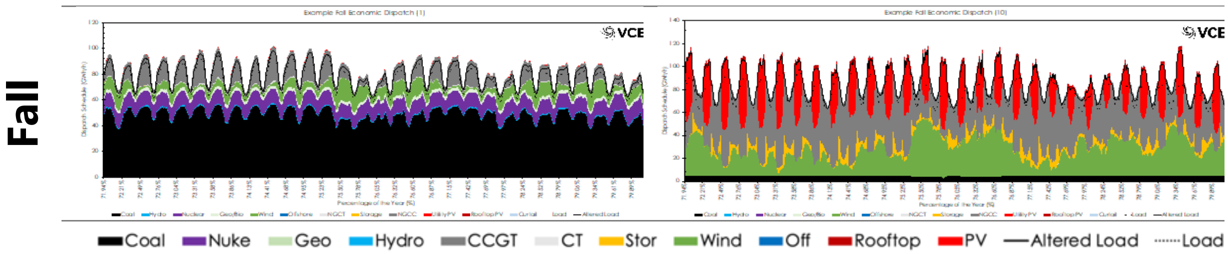


Figure 97: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 14.

By investment period 10 in Scenario 14, average ramps for NGCC, NGCT, and storage are 3%, 1.4%, and 6.3%, respectfully, and maximum ramps are 15.3%, 47.6%, and about 73% for each of the technologies. Coal on average ramps less by investment period 10, but has slightly higher maximum ramps. Coal on average ramps less by investment period 10, but has higher maximum ramps, almost to 10% of capacity. By investment period 10, storage is relied upon to provide almost 40% of the entire MISO altered load for some hours including about 7% on-peak. In general, the ramps and storage use are less than the optimal Scenario 11 given the much larger level of storage available to the system in this scenario.

Figure 98 shows the percent breakdown of generation from each technology for all investment periods in Scenario 14. The percentage of fossil generation, after initial increase, declines as the model deploys more renewables and takes advantage of the available energy storage capacity and nuclear power also disappears by investment period 8. By investment period 10, about half of generation in MISO is fossil and the other half from renewable sources.

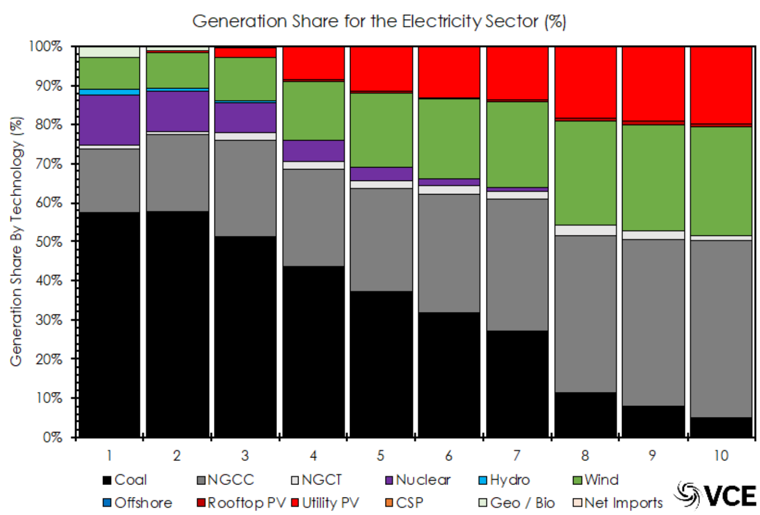


Figure 98: Percentage generation share for the electricity sector by technology and iteration number for Scenario 14.

Figure 99 shows the system cost for each investment period, relative to the 1st. Even though this scenario is able to incorporate large amounts of renewables, the mandatory deployment of energy storage assets increases costs in every investment period, reaching almost a 400% increase by the last investment period.

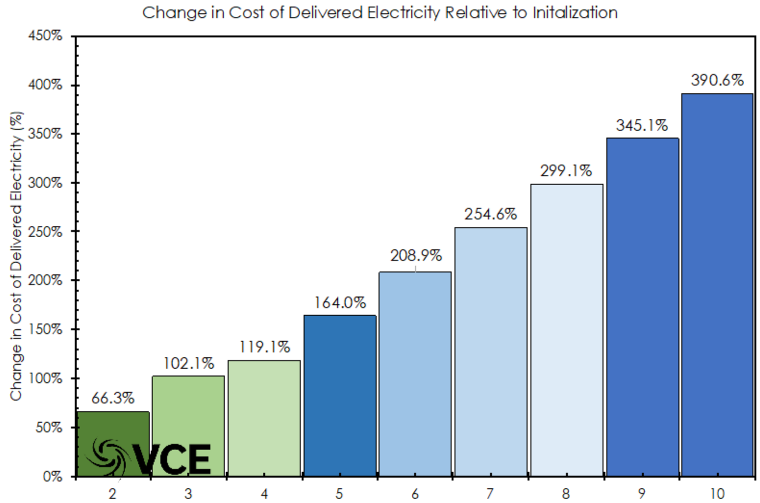


Figure 99: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 14.

Figure 100 shows the deployment of transmission in each MISO LRZ. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. Given the ability of energy storage to offset the need for system upgrades, the transmission buildout in this scenario is relatively mild in comparison with others. However, LRZ5 does build more export capacity to move energy to other sections.

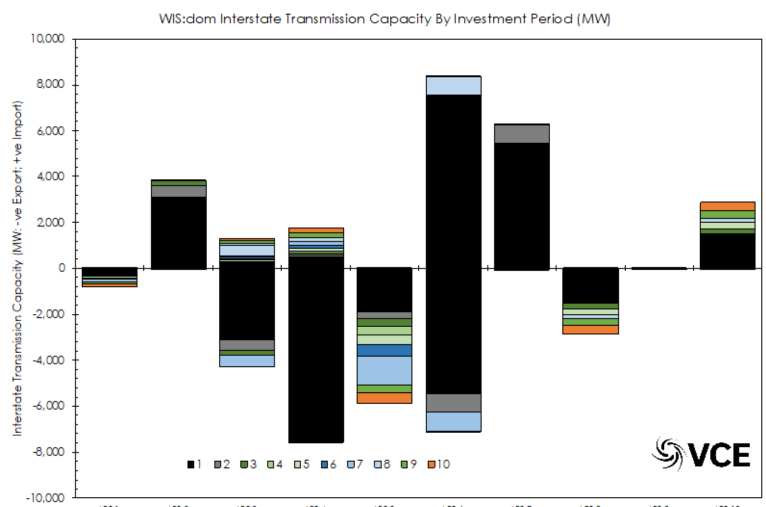


Figure 100: Inter-MISO region transmission capacity (MW) by investment period. Negative values indicate capacity to export from and positive values indicate capacity to import into that MISO region. Note that the y-axis is much larger than in previous scenarios.

In Scenario 14, emissions fall as more coal retires and renewables enter the system. Carbon emissions drop by about 60% by investment period 10. Full emissions details and accounting are available in the results spreadsheets.

Full time employment in the electricity sector in Scenario 14, by investment period 10 increases by about 110%, relative to today. This growth is mainly driven by the increased deployment of wind and solar. Full jobs data can be found in the results spreadsheets.

Fuel burn data and figures are available in the results spreadsheets. In Scenario 14, natural gas fuel burn increases from 1.4 to about 3.3 Quads in investment period 10, coal fuel burn decreases from about 16.5 to 0.4 Quads by investment period 10 and uranium fuel burn declines to zero by investment period 8.

5.5. Path to 10% Distributed PV in MISO (Scenario 15)

In this scenario, the WIS:dom® model charts the optimal pathway for MISO given that the model must deploy enough distributed PV to meet 10% of annual generation by the 10th investment period. Otherwise, the model is able to least-cost optimize the rest of the system.

Figure 101 shows the evolution of installed capacity by power plant type for Scenario 15. As per the scenario parameters, the model ends up with over 36 GW storage capacity by the 10th investment period. Overall the system ends up with about 259 GW of power plants of all types, including over 53 GW of distributed solar PV. Overall, this scenario installs more solar PV capacity than the optimal scenario as distributed PV generally has a lower capacity factor than utility-scale systems.

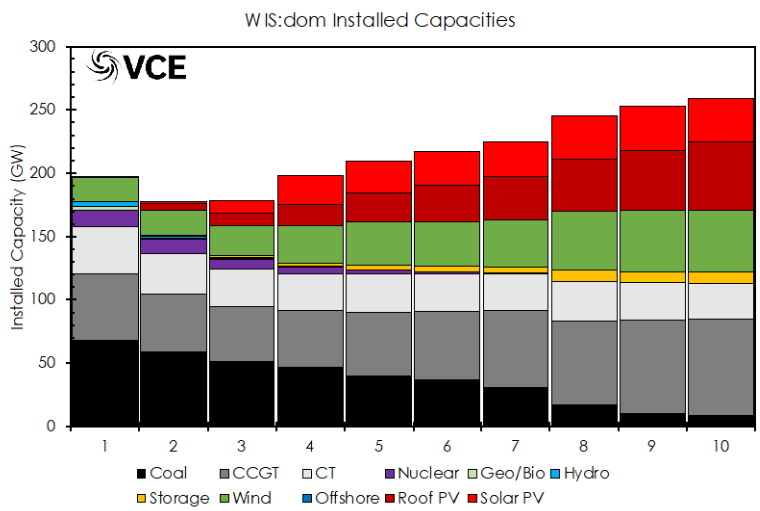


Figure 101: Power plant capacities by type in MISO over each of the investment periods in Scenario 15. State and county level data are available in the included spreadsheets of the results.

Figure 102 shows the siting of power plants in the last investment period for Scenario 15. This Figure can be directly compared to Figure 72 as that is the same starting point for Scenarios 11-19. All county-level capacity data are available in the included results spreadsheets.

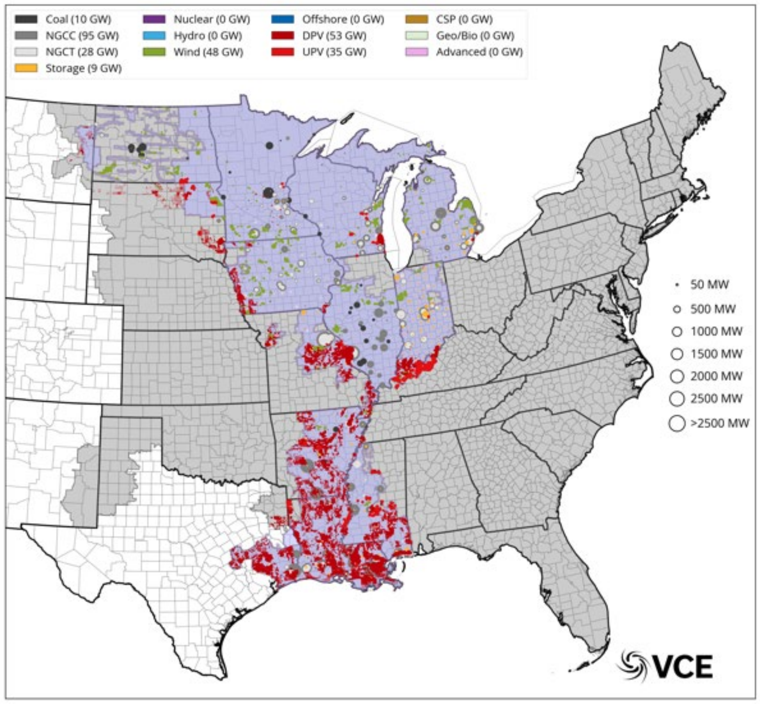
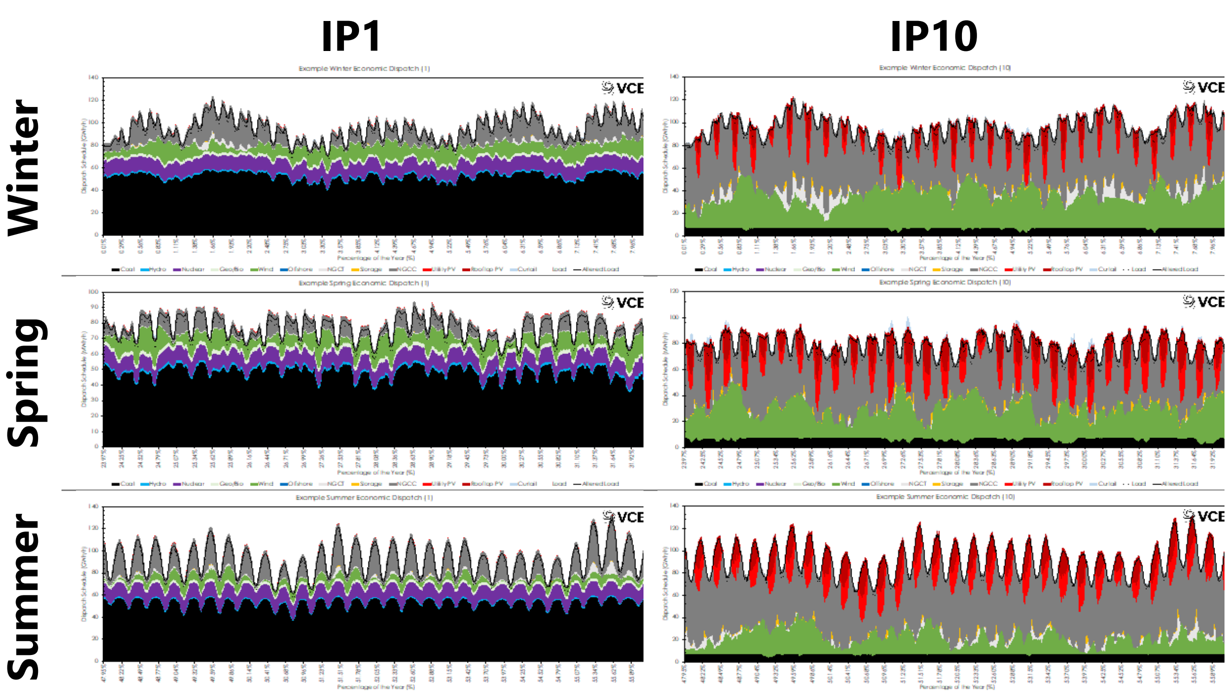


Figure 102: Location, type and size of powerplants in MISO for Scenario 15, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 103 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire MISO system. Coal generation is largely reduced between the first and last investment periods while NGCC plants increasingly dispatches to compensate for ramps in demand and increased renewables output, including the rooftop solar PV generation.



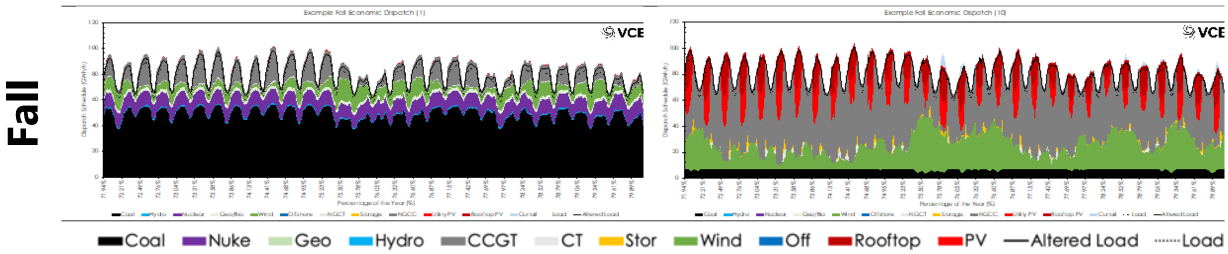


Figure 103: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 15.

By investment period 10 in Scenario 15, average ramps for NGCC, NGCT, and storage are 4.2%, 2.6%, and 8%, respectfully, and maximum ramps are 18.8%, 43%, and about 99% for each of the technologies. Coal on average ramps less by investment period 10, but has higher maximum ramps, up to about 11% of capacity. By investment period 10, storage is relied upon to provide almost 13% of the entire MISO altered load for some hours, but less than 1% on-peak. Ramps in Scenario 15 are slightly larger than the optimal Scenario 11 given the larger amount of solar PV deployed as required.

Figure 104 shows the percent breakdown of generation from each technology for all investment periods in Scenario 15. The percentage of fossil generation generally declines with each investment period as more energy comes from renewables. By investment period 10, 10% of generation comes from distributed PV.

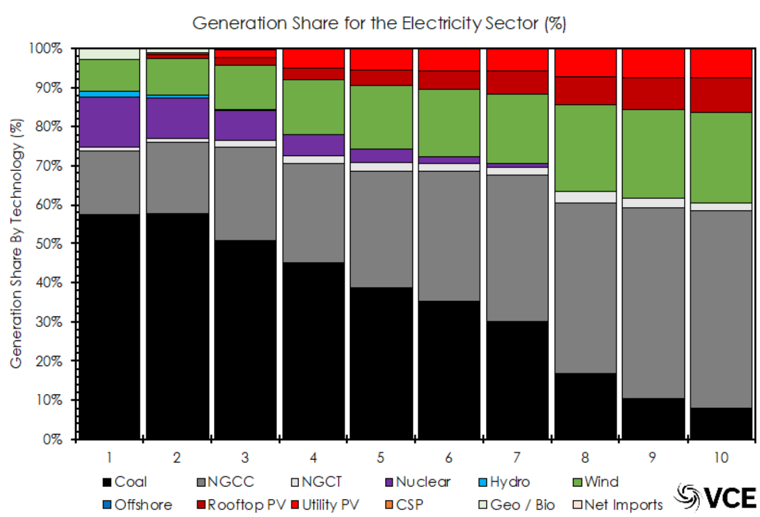


Figure 104: Percentage generation share for the electricity sector by technology and iteration number for Scenario 15.

Figure 105 shows the change in delivered electricity costs for each investment period, relative to the first investment period for Scenario 15. Costs decline quickly at the beginning of the scenario as older, less efficient generators retire and are replaced by gas and renewables. Cost generally decline to investment period 8 and then remain about the same for the remainder of the model run. Costs do not fall as much as they do in the optimal scenario, but are generally about 20% lower than in the first period.

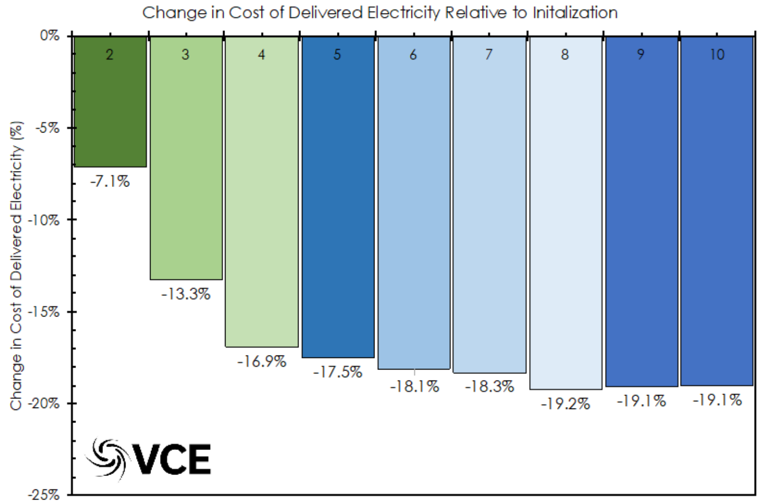


Figure 105: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 15.

Figure 106 shows the deployment of transmission in each MISO LRZ. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. Given that, by definition, distributed PV is installed close to load, the transmission buildout in this scenario is relatively mild in comparison with others. However, LRZ5 does build more export capacity to move energy to other locations.

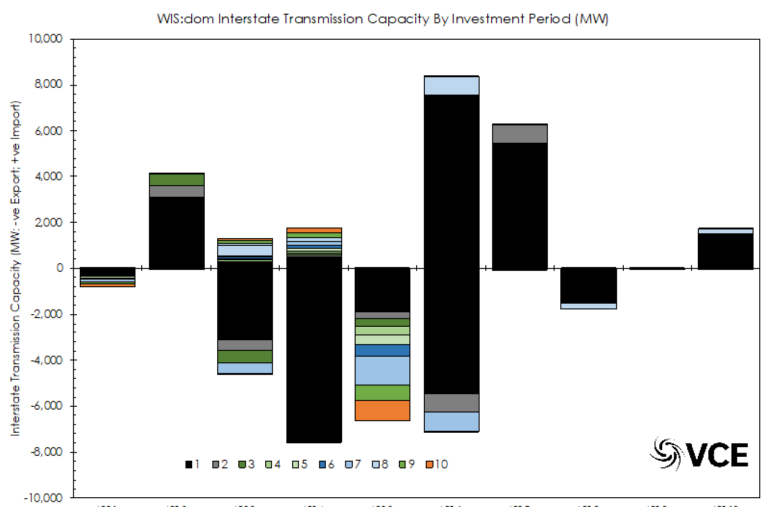


Figure 106: Inter-MISO region transmission capacity (MW) by investment period. Negative values indicate capacity to export from and positive values indicate capacity to import into that MISO region. Note that the y-axis is much larger than in previous scenarios.

In Scenario 15, emissions fall as more coal retires and renewables enter the system. Carbon emissions drop about 51% by investment period 10. Full emissions details and accounting are available in the results spreadsheets.

Full time employment in the electricity sector in Scenario 15, by investment period 10 increases by about 110%, relative to today, driven mostly by growth in the solar and wind sectors. Full job details are available in the results spreadsheets.

Fuel burn data and figures are available in the results spreadsheets. In Scenario 15, natural gas fuel burn increases steadily to about 3.8 Quads in investment period 10, coal fuel burn decreases from about 16.5 to 0.6 Quads by investment period 10 and uranium fuel burn declines to zero by investment period 8.

5.6. Optimal Expansion for MISO with 10% DSM (Scenario 16)

In this scenario, the WIS:dom® model charts the optimal pathway for MISO given that the model is able to access more flexible demand, up to 10% of the demand side management load, than in the other scenarios (2.5%). Given the new demand flexibility, the model then develops an optimal MISO pathway around it.

Figure 107 shows the evolution of installed capacity by power plant type for Scenario 16. In this scenario, the MISO system ends up with about 232 GW of power plants by investment period 10. These capacity results are very similar to the optimal case (Scenario 11). It can be seen that the peak load is reduced with the deployment of DSM across the MISO footprint.

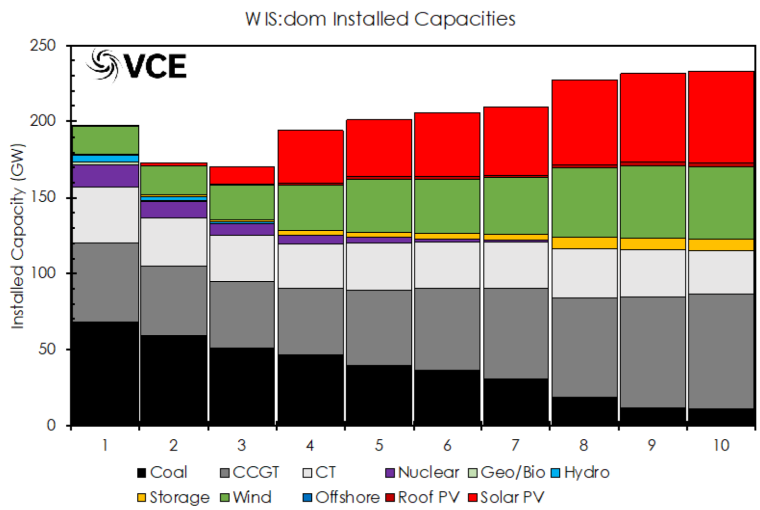


Figure 107: Power plant capacities by type in MISO over each of the investment periods in Scenario 16. State and county level data are available in the included spreadsheets of the results.

Figure 108 shows the siting of power plants in the last investment period for Scenario 16. This Figure can be directly compared to Figure 72 as that is the same starting point for Scenarios 11-19. All county-level capacity data are available in the included results spreadsheets. Again, in terms of capacity, this scenario is very similar to the optimal pathway, Scenario 11.

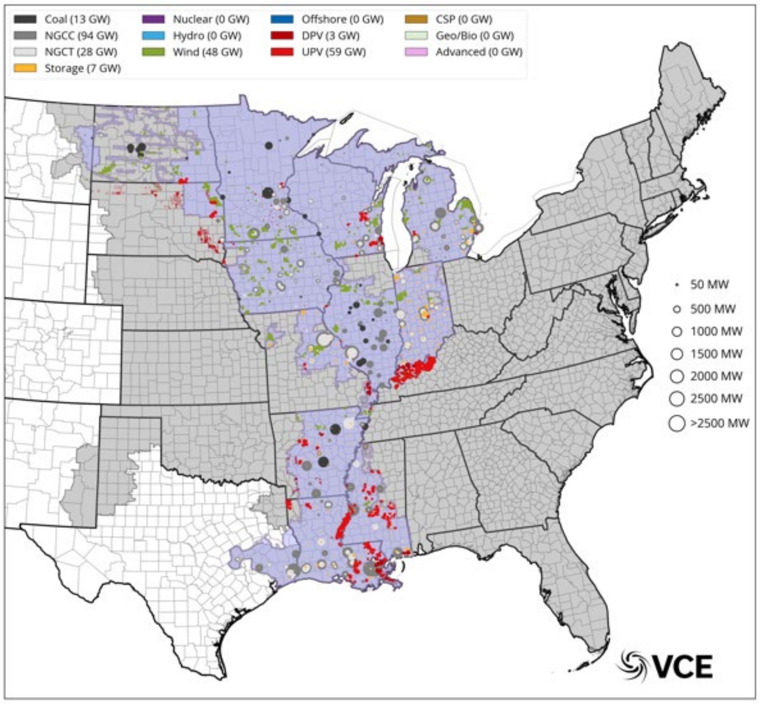
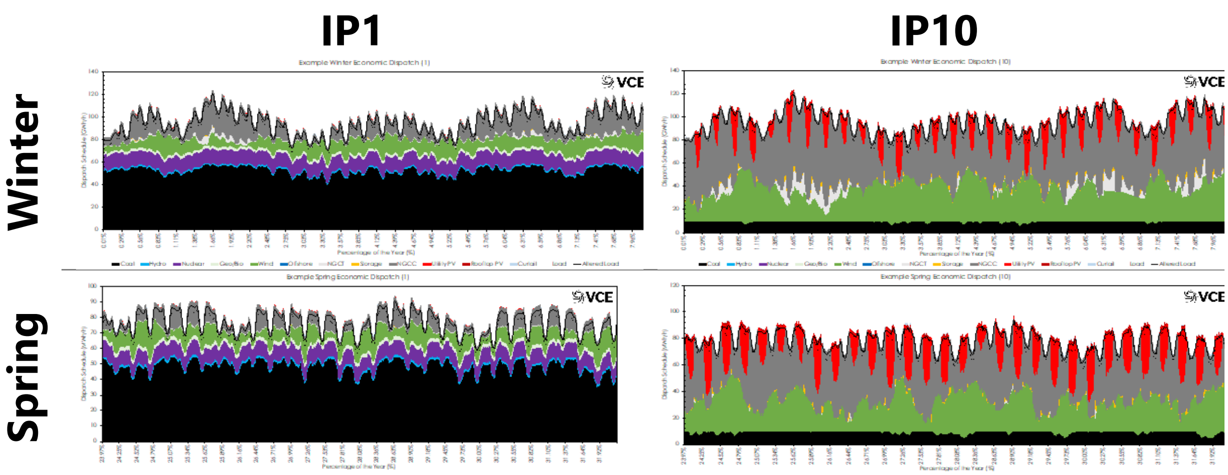


Figure 108: Location, type and size of powerplants in MISO for Scenario 16, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 109 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire MISO system. Coal generation is largely reduced between the first and last investment periods while natural gas plants increasingly dispatch to compensate for ramps in demand and increased renewables output. Overall the model is able to patch supply and demand for every 5-minute period of the year with this optimal MISO mix. Although difficult to see in these figures, this scenario was allowed to access more demand response resources than other scenarios and so most differences show up in the dispatch, in this case, the model choose to flex about 150 MW more load than in the optimal scenario.



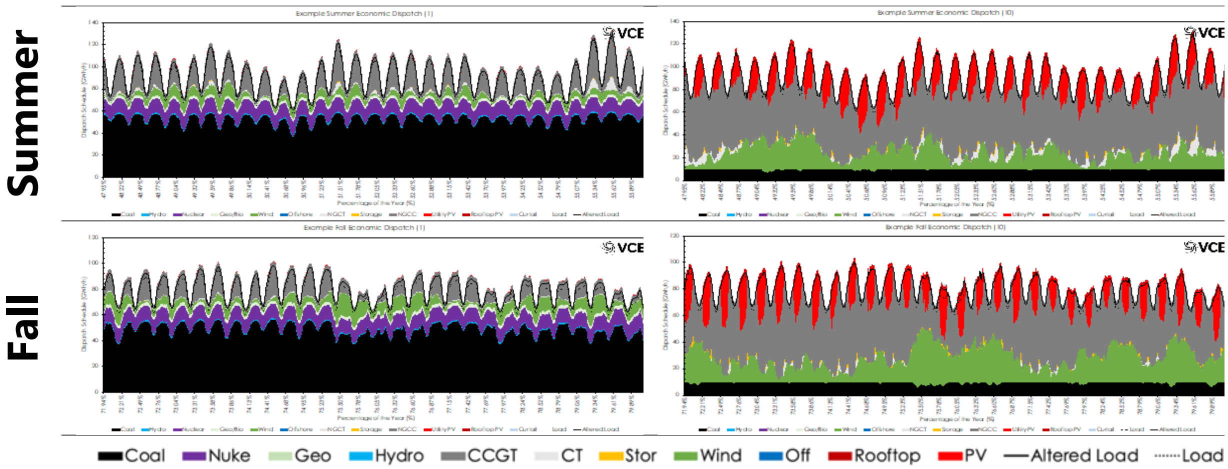


Figure 109: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 16.

By investment period 10 in Scenario 16, average ramps for NGCC, NGCT, and storage are 3.8%, 2.4%, and 7.7%, respectfully, and maximum ramps are 17.8%, 41%, and almost 100% for each of the technologies. Coal on average ramps less by investment period 10, but has higher maximum ramps, up to about 8.4% of capacity. By investment period 10, storage is relied upon to provide about 10% of the entire MISO altered load for some hours, but only about 1% on-peak – results almost identical to the optimal Scenario 11, indicating that more demand side management (10% of DSM loads available vs. 2.5% of EV and DSM in the other cases) was not more useful to the model.

Figure 110 shows the percent breakdown of generation from each technology for all investment periods in Scenario 16. Similar, to Scenario 11, the percentage of generation from coal and gas plants combined stays above 60% for all investment periods, but nuclear power disappears by investment period 8.

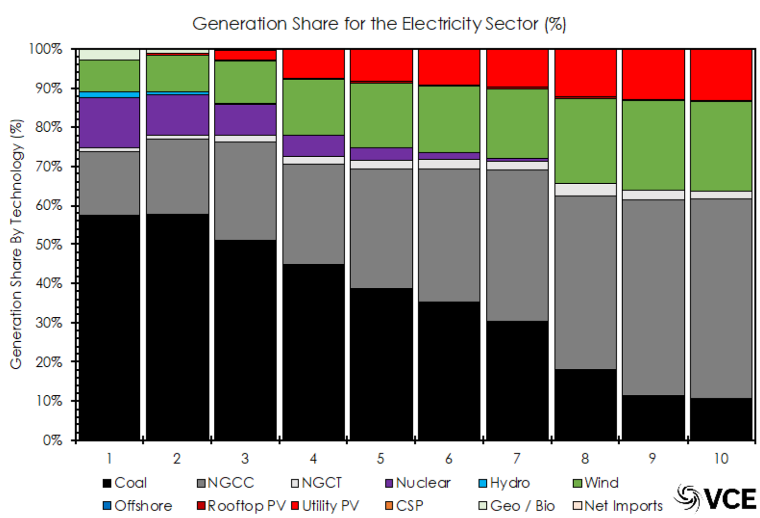


Figure 110: Percentage generation share for the electricity sector by technology and iteration number for Scenario 16.

Figure 111 shows the change in delivered cost of electricity relative to the first investment period. Again, similar to Scenario 11, costs decline continuously as the system is able to optimize the network, dropping to almost 23% below costs today.

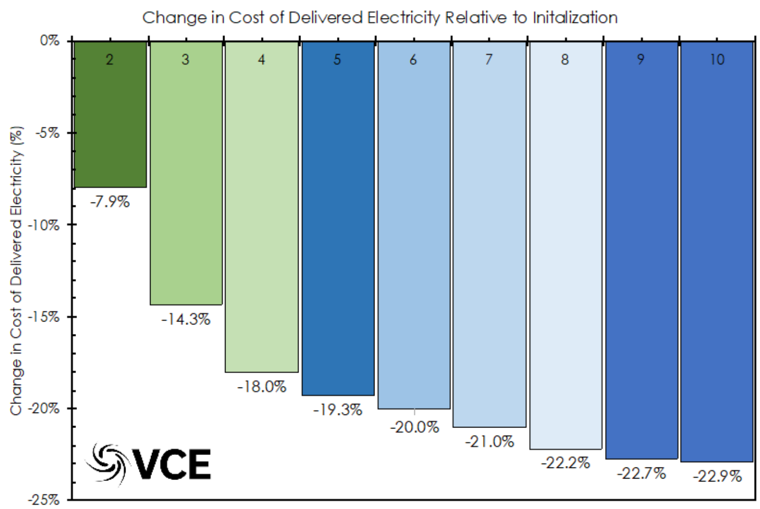


Figure 111: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 16.

Figure 112 shows the deployment of transmission in each MISO LRZ. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. This transmission buildout is very similar to Scenario 11 and again we see LRZ5 build more export capacity to move energy to other locations.

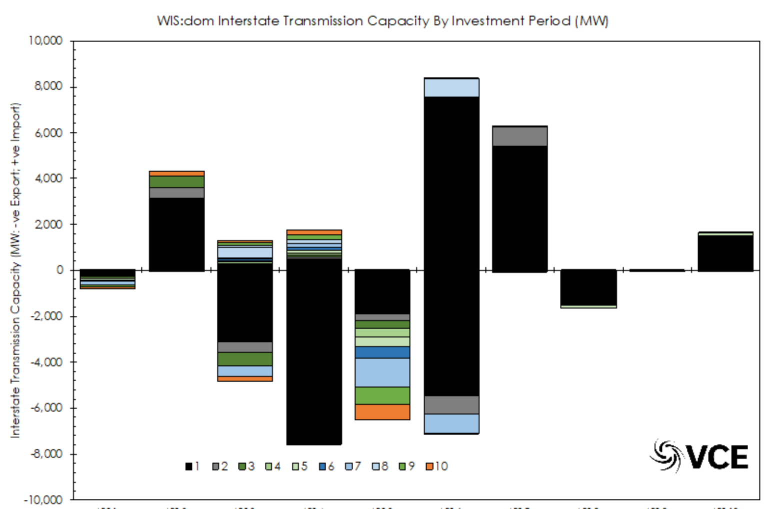


Figure 112: Inter-MISO region transmission capacity (MW) by investment period. Negative values indicate capacity to export from and positive values indicate capacity to import into that MISO region. Note that the y-axis is much larger than in previous scenarios.

In Scenario 16, emissions fall across the board as more coal retires and renewables are deployed. Carbon emissions decline by almost 50%. Full emissions details and accounting are available in the results spreadsheets.

Full time employment in the electricity sector in Scenario 16, by investment period 10 increases by about 80%, relative to today. The majority of jobs increases are in the wind and solar sectors. Full jobs details and accounting are available in the results spreadsheets.

Fuel burn data and figures are available in the results spreadsheets. In Scenario 16, natural gas fuel burn increases from about 1.4 to about 3.8 Quads by investment period 10, coal fuel burn decreases from about 5.3 to 0.9 Quads by investment period 10 and uranium fuel burn declines to zero by investment period 8.

5.7. Optimal Expansion for MISO with 10% EVs (Scenario 17)

In this scenario, the WIS:dom® model charts the optimal pathway for MISO given that the model is able to access more flexible EV load and flex up to 10% of EV demand. Given the new demand flexibility, the model then develops an optimal MISO pathway around it. Because not that much flexibility is needed, the model results are similar to the optimal case (Scenario 11).

Figure 113 shows the evolution of installed capacity by power plant type for Scenario 17. In this scenario, the MISO system ends up with about 233 GW of power plants by investment period 10. These capacity results are very similar to the optimal case (Scenario 11).

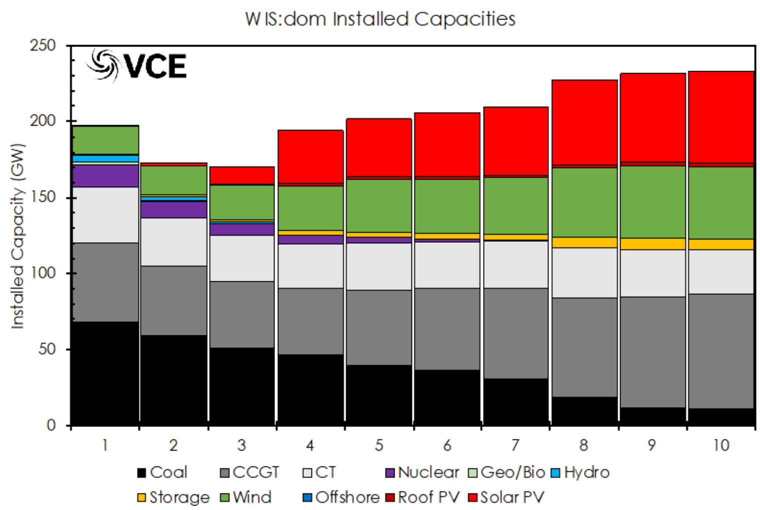


Figure 113: Power plant capacities by type in MISO over each of the investment periods in Scenario 17. State and county level data are available in the included spreadsheets of the results.

Figure 114 shows the siting of power plants in the last investment period for Scenario 17. This Figure can be directly compared to Figure 72 as that is the same starting point for Scenarios 11-19. All county-level capacity data are available in the included results spreadsheets. Again, in terms of capacity and placement, this scenario is very similar to the optimal pathway, Scenario 11.

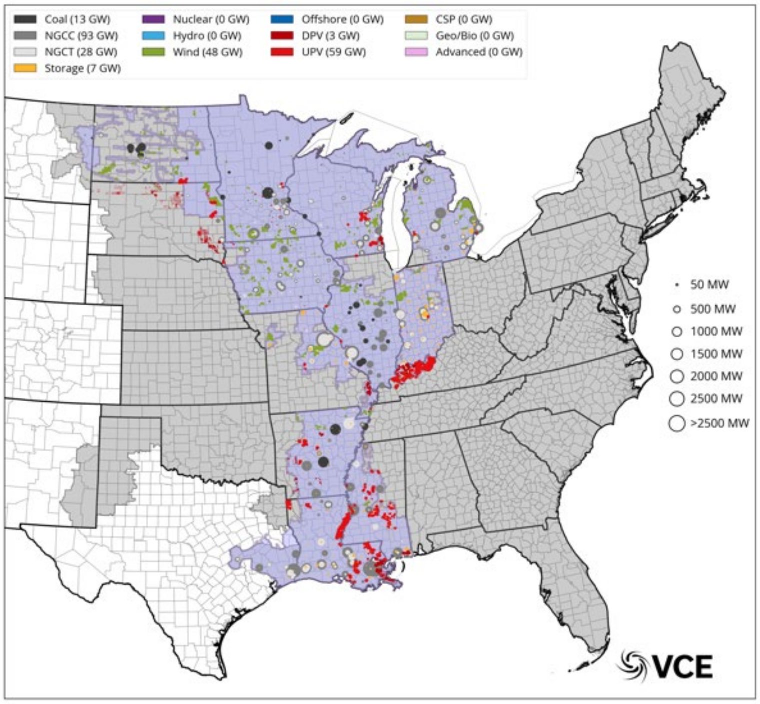
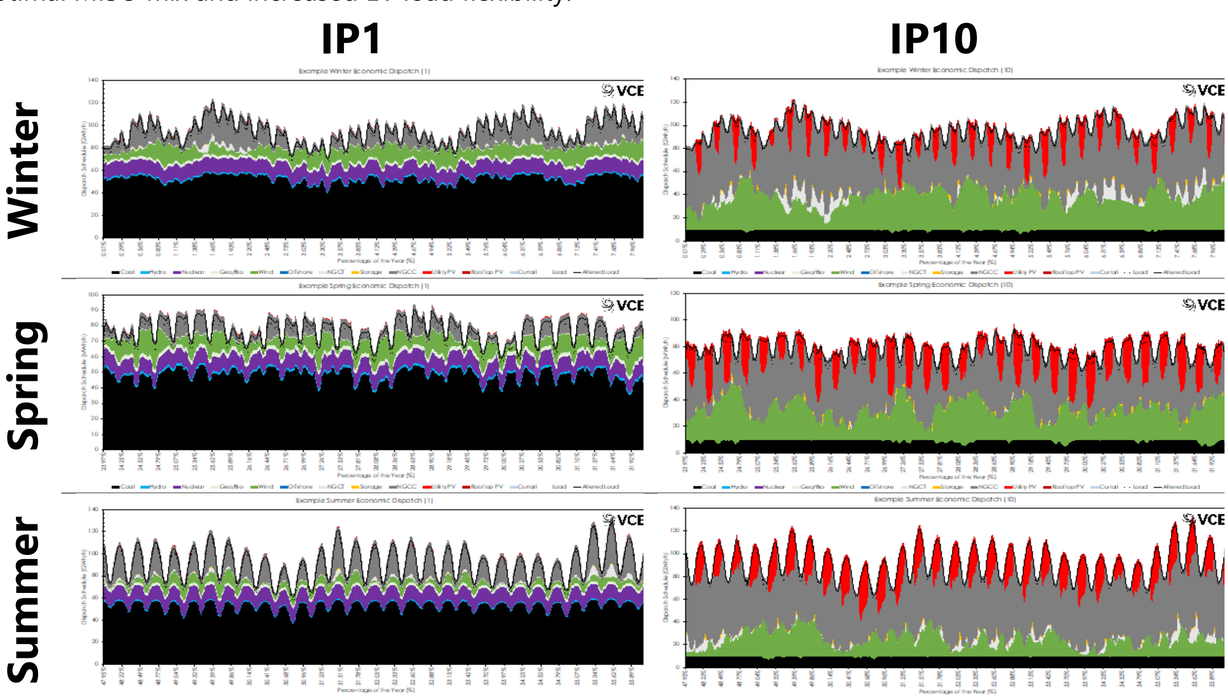


Figure 114: Location, type and size of powerplants in MISO for Scenario 17, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 115 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire MISO system. Coal generation is largely reduced between the first and last investment periods while NGCC plants increasingly dispatches to compensate for ramps in demand and increased renewables output. Overall the model is able to patch supply and demand for every 5-minute period of the year with this optimal MISO mix and increased EV load flexibility.



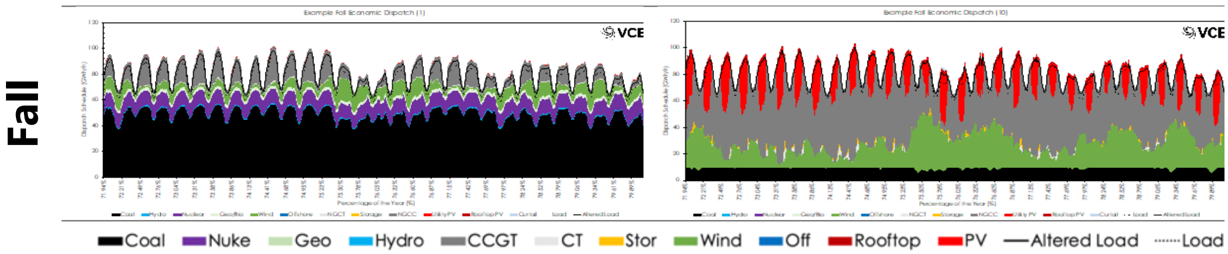


Figure 115: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 17.

By investment period 10 in Scenario 17, average ramps for NGCC, NGCT, and storage are 3.8%, 2.4%, and 7.6%, respectfully, and maximum ramps are 17.8%, 41%, and almost 100% for each of the technologies. Coal on average ramps less by investment period 10, but has higher maximum ramps, up to about 8.5% of capacity. By investment period 10, storage is relied upon to provide about 10% of the entire MISO altered load for some hours, but only about 1% on-peak – results almost identical to the optimal Scenario 11, indicating that more EV charging flexibility (10% of EV load vs. 2.5% of EV and DSM loads in the other cases) was not useful for the model.

Figure 116 shows the percent breakdown of generation from each technology for all investment periods in Scenario 17. The percentage of fossil generation stays steadily and, by investment period 10 is at about 65% of total generation. Nuclear power exits by investment period 8, and the balance of generation is made up by renewables.

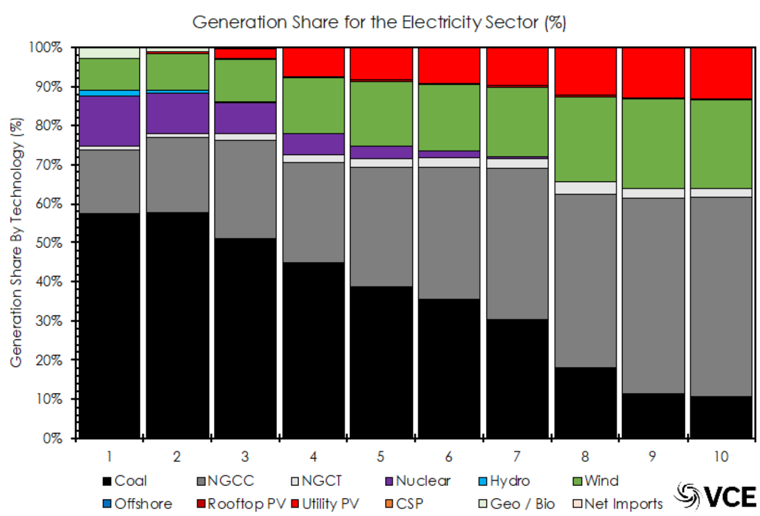


Figure 116: Percentage generation share for the electricity sector by technology and iteration number for Scenario 17.

Figure 117 shows the change in delivered cost of electricity relative to the first investment period. Again, similar to Scenario 11, costs decline continuously as the system is able to optimize the network, dropping to almost 23% below costs today.

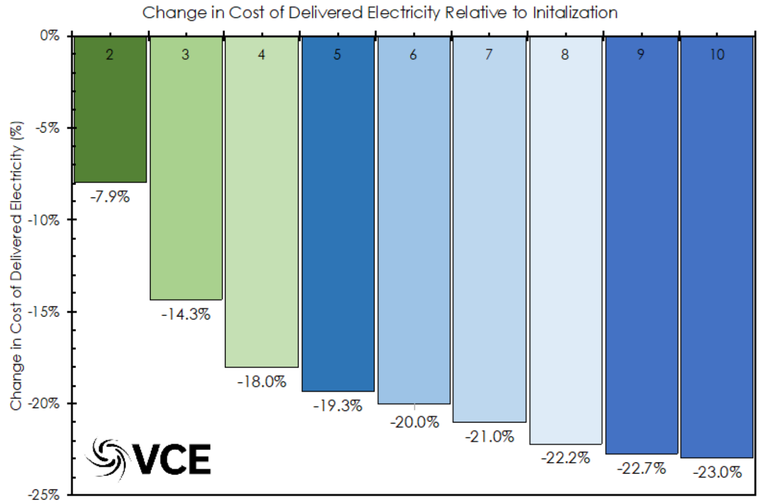


Figure 117: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 17.

Figure 118 shows the deployment of transmission in each MISO LRZ. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. This transmission buildout is very similar to Scenario 11 and again we see LRZ5 build more export capacity to move energy to other locations.

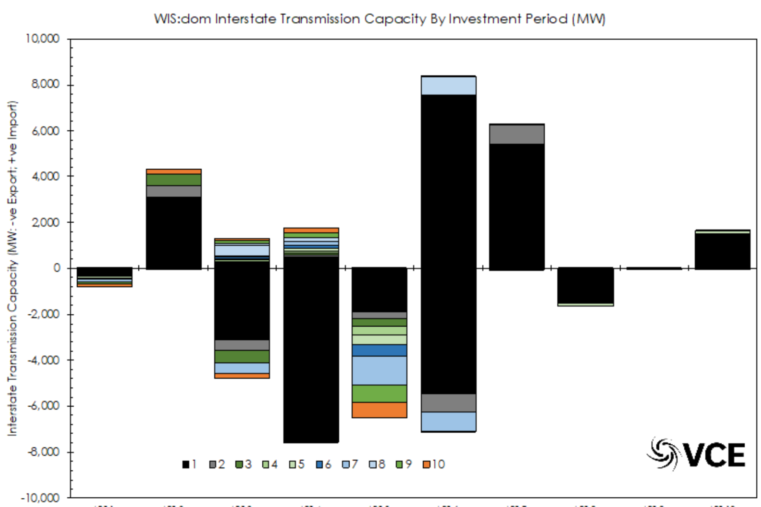


Figure 118: Inter-MISO region transmission capacity (MW) by investment period. Negative values indicate capacity to export from and positive values indicate capacity to import into that MISO region. Note that the y-axis is much larger than in previous scenarios.

In Scenario 17, emissions generally fall across the board driven by coal to gas switching and the deployment of renewables. By investment period 10, carbon emissions fall by about 47% relative to today. Full emissions details and accounting are available in the results spreadsheets.

Full time employment in the electricity sector in Scenario 17, by investment period 10 increases by about 80%, relative to today. Job growth is mainly found in the solar and wind sectors, but the natural gas and transmission sectors also add jobs.

Fuel burn data and figures are available in the results spreadsheets. In Scenario 17, natural gas fuel burn increases steadily to about 3.8 Quads in investment period 10, coal fuel burn steadily decreases from about 5.3 to 0.9 Quads 10 and uranium fuel burn declines to zero by investment period 8.

5.8. Path to 50% Wind & 50% Solar in MISO (Scenario 18)

In this scenario, the WIS:dom® model charts the optimal pathway for MISO to obtain 50% of its energy from wind and the remaining 50% from solar PV, both utility and rooftop.

Figure 119 shows the evolution of installed capacity by power plant type for Scenario 18. In this scenario, the MISO system ends up with about 777 GW of power plants by investment period 10, about 208 GW of wind, almost 397 GW of utility-scale PV, about 50 GW of rooftop solar PV, along with 123 GW and 2,340 GWh of energy storage capacity.

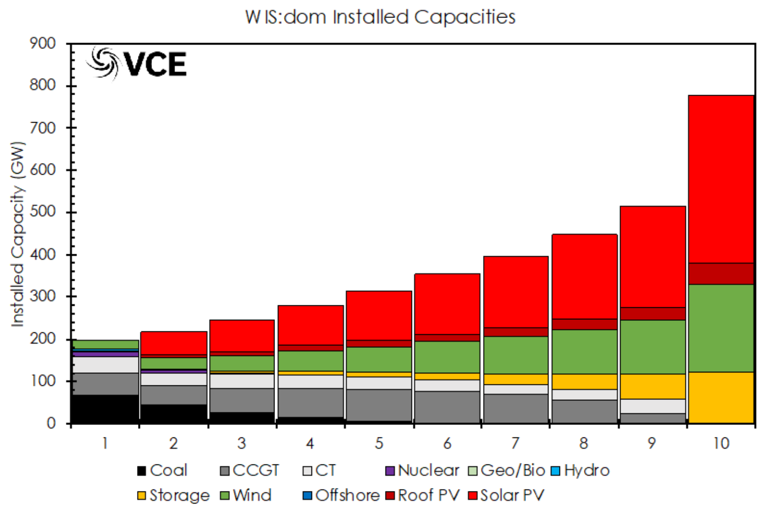


Figure 119: Power plant capacities by type in MISO over each of the investment periods in Scenario 18. State and county level data are available in the included spreadsheets of the results.

Figure 120 shows the siting of power plants in the last investment period for Scenario 16. This Figure can be directly compared to Figure 72 as that is the same starting point for Scenarios 11-19. All county-level capacity data are available in the included results spreadsheets.

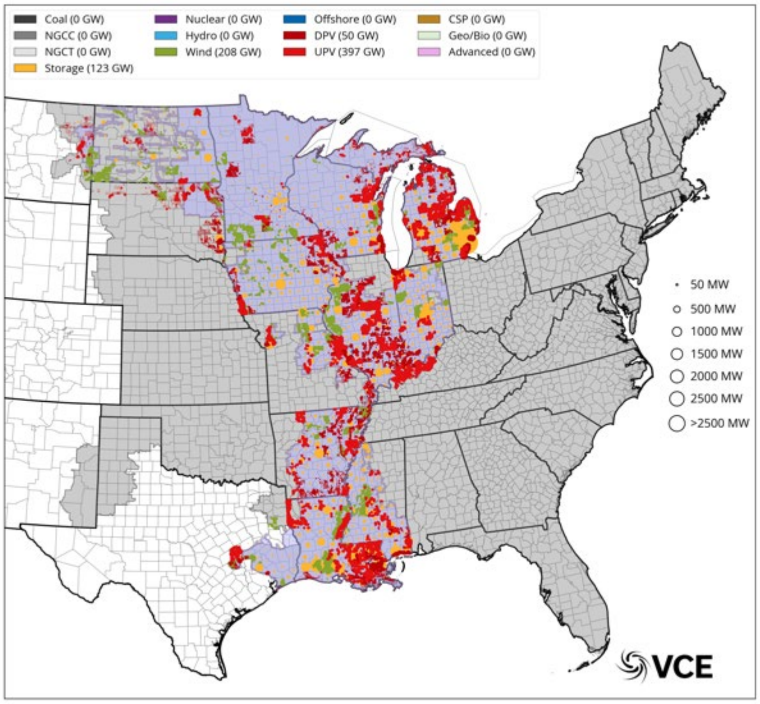
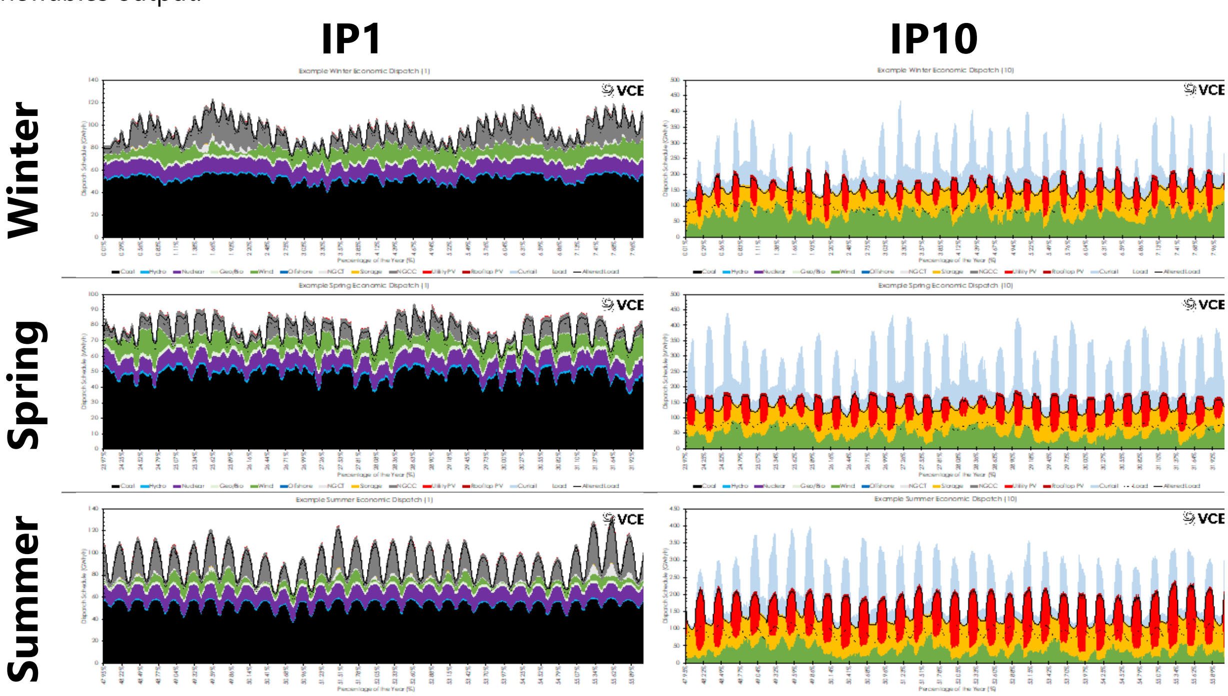


Figure 120: Location, type and size of powerplants in MISO for Scenario 18, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 121 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire MISO system. Everything but solar, wind, and storage disappear between the first and last investment periods as storage plants increasingly dispatch to compensate for ramps in demand and increased renewables output.



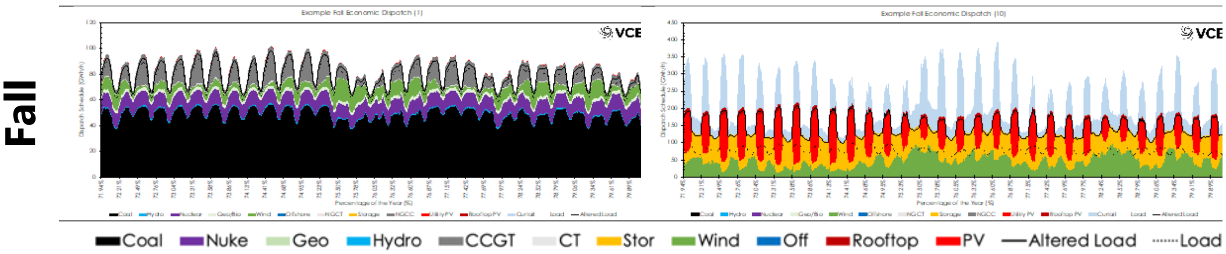


Figure 121: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 18.

By investment period 10 in Scenario 18, storage ramps about 4.3% of its capacity on average per hour, up to about 48% and some hours require almost 94% of the load to be met by storage systems, but only about 14% of storage capacity is required on-peak.

Figure 122 shows the percent breakdown of generation from each technology for all investment periods in Scenario 18. The percentage of fossil generation steadily declines as one would expect given the scenario constraints, nuclear power also disappears by investment period 4. By investment period 10, half of energy generated in MISO comes from wind and solar each.

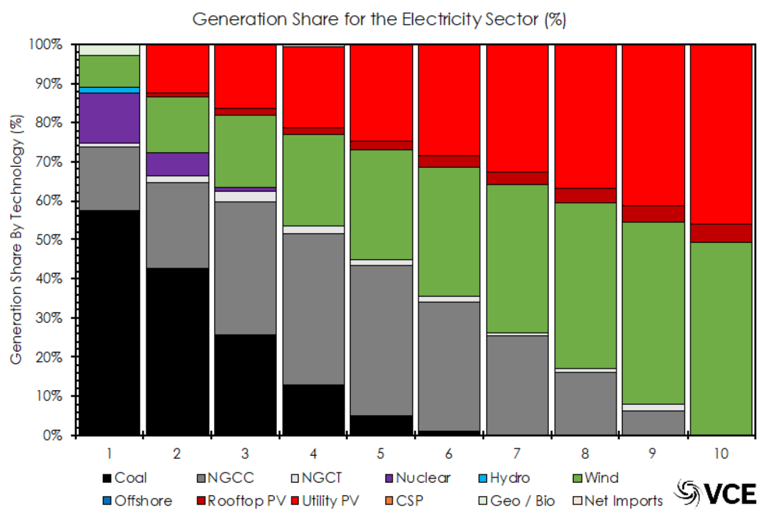


Figure 122: Percentage generation share for the electricity sector by technology and iteration number for Scenario 18.

Figure 123 shows the change in delivered cost of electricity relative to the first investment period. Again, similar to Scenario 11, costs decline continuously until investment period 5 (corresponding to about 25% wind and 25% solar on the system) and then begin to rise. By investment period 9 (45% wind and 45% solar), costs are about 10% above today's costs and pushing for the last 10% of energy to come from wind and solar drives up costs to over 110% of today's costs.

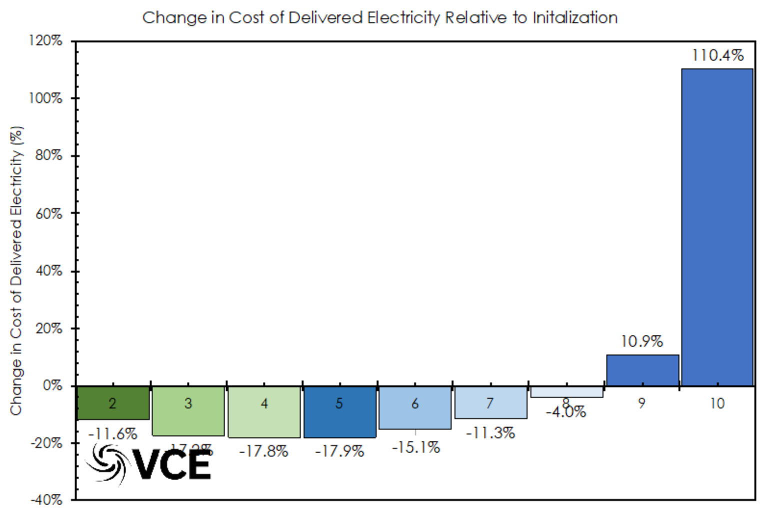


Figure 123: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 18.

Figure 124 shows the deployment of transmission in each MISO LRZ. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. More transmission is required, particularly in the latter investment periods, but, given their complimentary nature, less buildout is required than in scenarios with just wind (Scenario 12) or just solar (Scenario 13).

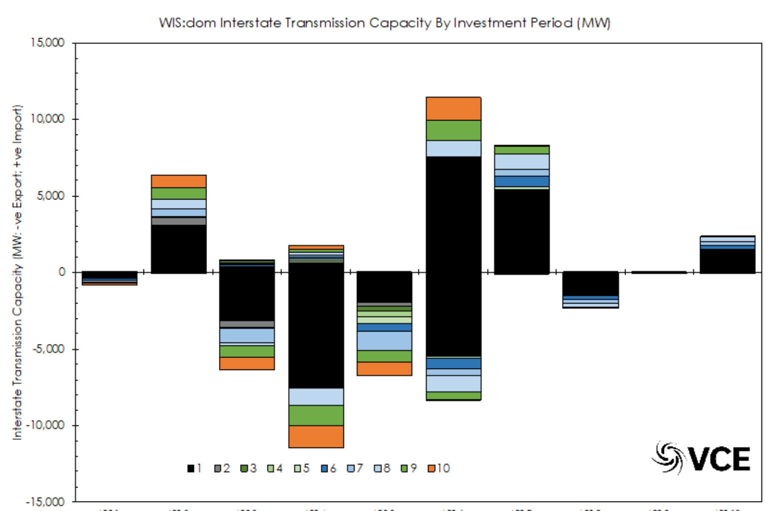


Figure 124: Inter-MISO region transmission capacity (MW) by investment period. Negative values indicate capacity to export from and positive values indicate capacity to import into that MISO region. Note that the y-axis is much larger than in previous scenarios.

In Scenario 18, emissions fall 100% across the board by investment period 10. Full emissions details and accounting are available in the results spreadsheets.

Full time employment in the electricity sector in Scenario 10, by investment period 10 increases by about 600%, relative to today. There is explosive growth in the number of wind and solar jobs, especially in investment period 10, needed to deploy the renewables needed for this scenario.

Fuel burn data and figures are available in the results spreadsheets. In Scenario 18, natural gas fuel burn increases to about 3.2 Quads in investment period 4 before falling to zero in investment period 10 as more solar and wind come online, coal fuel burn decreases from about 5.3 Quads to zero by investment period 7 and uranium fuel burn declines to zero by investment period 4.

5.9. Path to 100% Wind & Solar in MISO (Scenario 19)

In this last scenario, the WIS:dom® model charts the optimal pathway for MISO to obtain 100% of its energy from wind and solar, but unlike Scenario 18, the model is able to choose how much of each to deploy.

Figure 125 shows the evolution of installed capacity by power plant type for Scenario 19. In this scenario, the MISO system ends up with about 876 GW of power plants by investment period 10, about 178 GW of wind, almost 489 GW of utility-scale PV, about 61 GW of rooftop solar PV, along with 148 GW and 2,000 GWh of energy storage capacity, enough to cover peak demand for about 15 straight hours if fully charged.

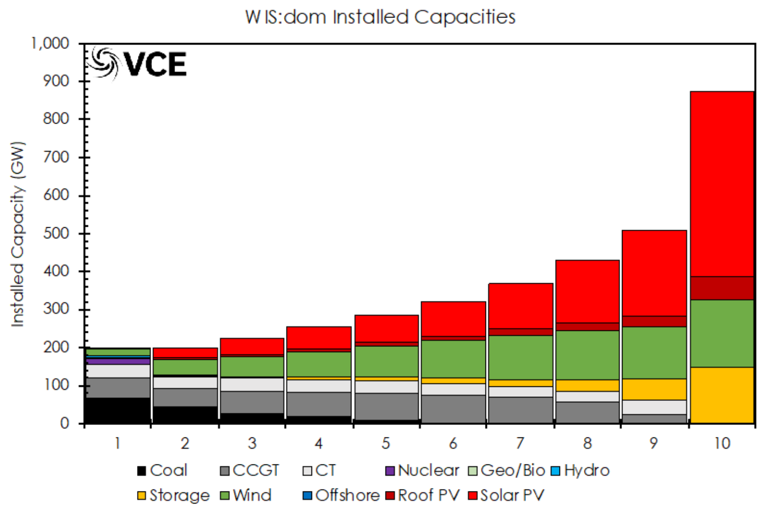


Figure 125: Power plant capacities by type in MISO over each of the investment periods in Scenario 19. State and county level data are available in the included spreadsheets of the results.

Figure 126 shows the siting of power plants in the last investment period for Scenario 19. This Figure can be directly compared to Figure 72 as that is the same starting point for Scenarios 11-19. All county-level capacity data are available in the included results spreadsheets.

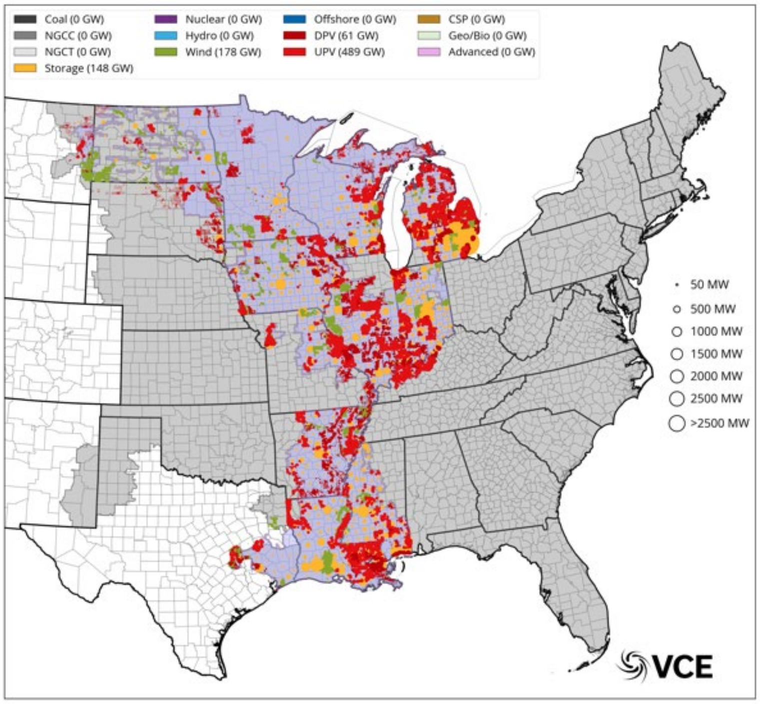
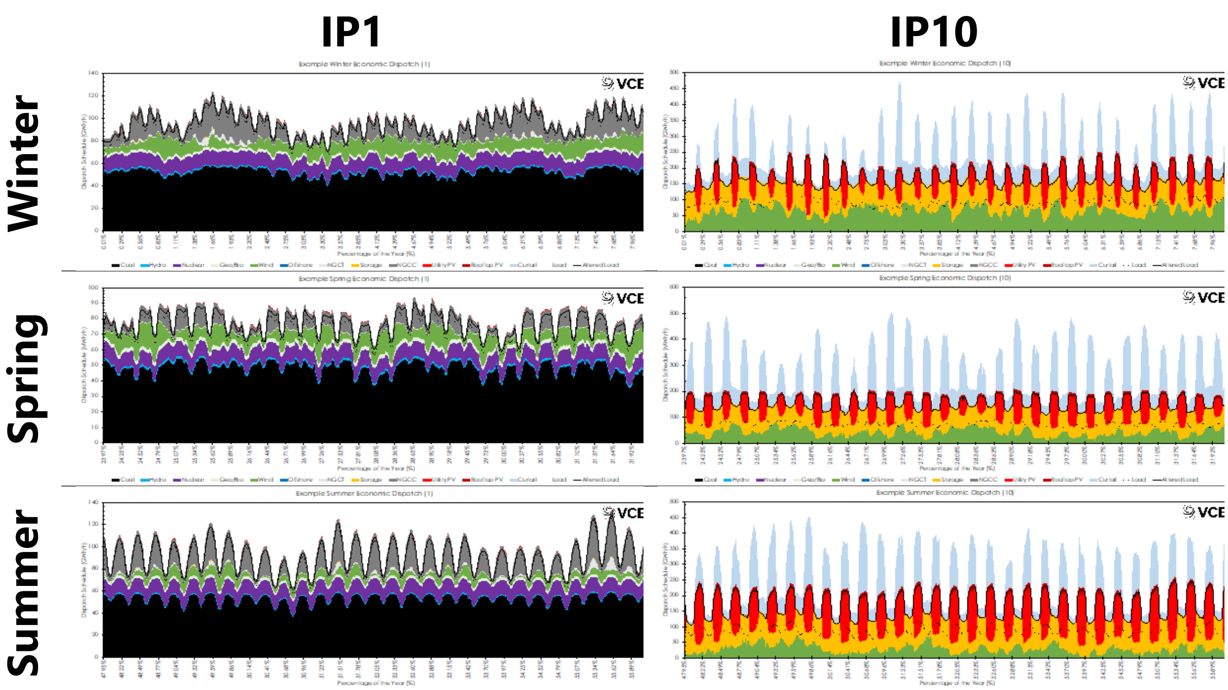


Figure 126: Location, type and size of powerplants in MISO for Scenario 19, investment period 10. The gray base color is the entire Eastern Interconnect and the purple base color is MISO.

Figure 127 shows example seasonal hourly dispatch patterns for the first and last iterations over the entire MISO system. Everything but wind and solar exit the system while storage plants increasingly dispatches to compensate for ramps in supply and demand.



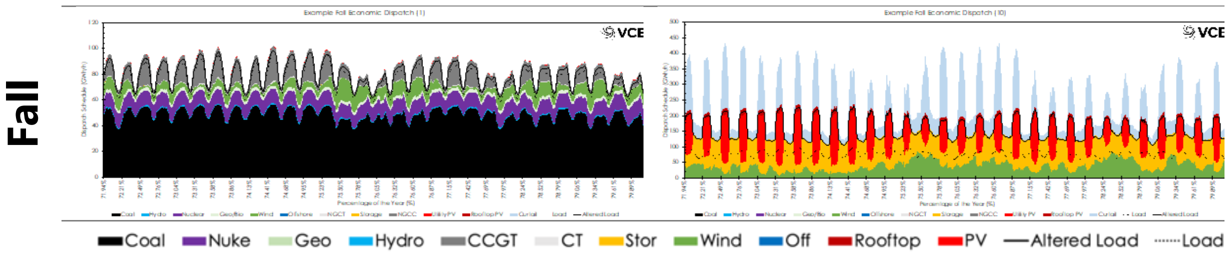


Figure 127: Seasonal example hourly dispatch of power plants in both the first and last investment period for Scenario 19.

By investment period 10 in Scenario 19, storage ramps about 4.2% of its capacity on average per hour, up to about 42% and some hours require almost 99% of the load to be met by storage systems, but only about 16% of storage capacity is required on-peak. Storage needs to ramp less in Scenario 19 than 18 because the optimal 100% wind and solar mix for MISO is not 50/50.

Figure 128 shows the percent breakdown of generation from each technology for all investment periods in Scenario 19. The percentage of fossil generation steadily declines as more wind and solar are deployed, nuclear power also disappears by investment period 4. By investment period 10, about 58% of energy comes from solar and the remaining 42% from wind, totaling 100%.

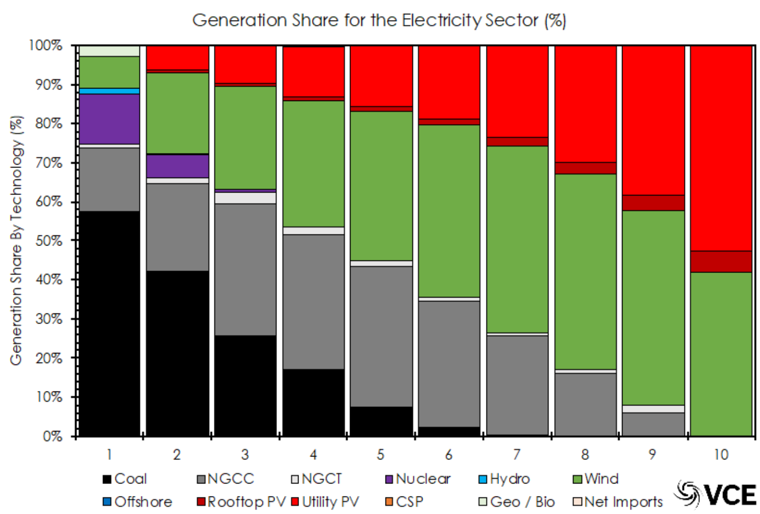


Figure 128: Percentage generation share for the electricity sector by technology and iteration number for Scenario 19.

Figure 129 shows the change in delivered cost of electricity relative to the first investment period. Again, similar to Scenario 18, costs decline until investment period 5 (corresponding to about 50% wind and solar on the system) and then begin to rise. By investment period 9 (90% wind and solar), costs are about 11% above today's costs and pushing for the last 10% of energy to come from wind and solar drives up costs to over 108% of today's costs. These costs are similar to Scenario 18, but the model was able to more efficiently deploy wind and solar so as to reduce overall costs.

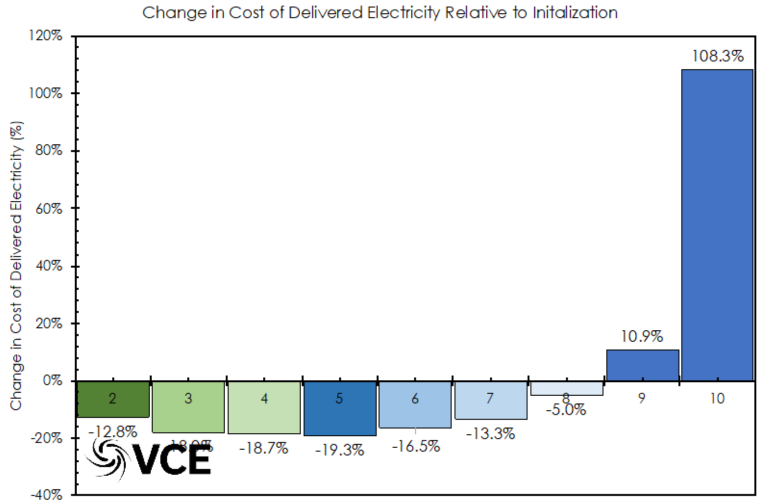


Figure 129: The change in costs of delivered electricity for each investment period, relative to the first investment period for Scenario 19.

Figure 130 shows the deployment of transmission in each MISO LRZ. Negative values indicate export capacity from that state and positive values indicate import capacity. The black sections of the bars (investment period 1) essentially denote the existing transmission capacity and the other colors denote additions for each investment period. This scenario builds more transmission capacity than Scenario 18 (50% wind + 50% solar), but less that Scenarios 12 (100% wind) and 13 (100% solar). It also builds transmission earlier in the process as it deploys more solar in earlier investment periods.

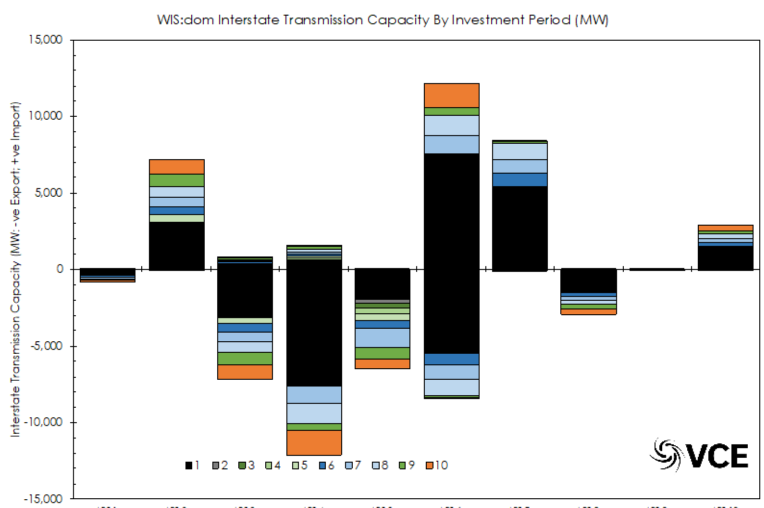


Figure 130: Inter-MISO region transmission capacity (MW) by investment period. Negative values indicate capacity to export from and positive values indicate capacity to import into that MISO region. Note that the y-axis is much larger than in previous scenarios.

In Scenario 19, emissions fall 100% across the board by investment period 10. Full emissions details and accounting are available in the results spreadsheets.

Full time employment in the electricity sector in Scenario 19, by investment period 10 increases by almost 700%, relative to today. There is large growth in the number of wind and, in particularly, solar jobs, especially in investment period 10, needed to satisfy this scenario.

Fuel burn data and figures are available in the results spreadsheets. In Scenario 18, natural gas fuel burn increases to about 2.9 Quads in investment period 4 before falling to zero in investment period 10 as more solar and wind come online, coal fuel burn decreases from about 5.3 Quads to zero by investment period 8 and uranium fuel burn declines to zero by investment period 4.