WIS:dom® Optimization Model Description (WECC)

Prepared By:

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Prepared For:

Public Release

WIS:dom® Optimization Model

The WIS:dom® (Weather-Informed Systems: design, operation, markets) optimization model is the flagship, state-of-the-art, product created by VCE®. A precursor to WIS:dom® was the seminal C-OEM (the Co-Optimized Energy Model) which was the first commercial model to be able to co-optimize variable generation, conventional generation, transmission, storage and power flow at a granularity of 13-km and 60-minute for the entire continental United States for a full year.

WIS:dom® contains numerous improvements from C-OEM in its description of power flow, investment time periods, retirements, cost of generation, granularity of data, pollutant tracking, dispatch, reserve requirements, and technology descriptions. Further, WIS:dom® has been designed to work at all geographic scales as well as include a wide range of technologies that are more appropriate for a wide range of studies. The WIS:dom® region for the Western Interconnection contains hundreds of thousands of potential variable generation resource sites as depicted in Figure W1. The images show the wind and solar resource at 3-km resolution for the entire WECC footprint.

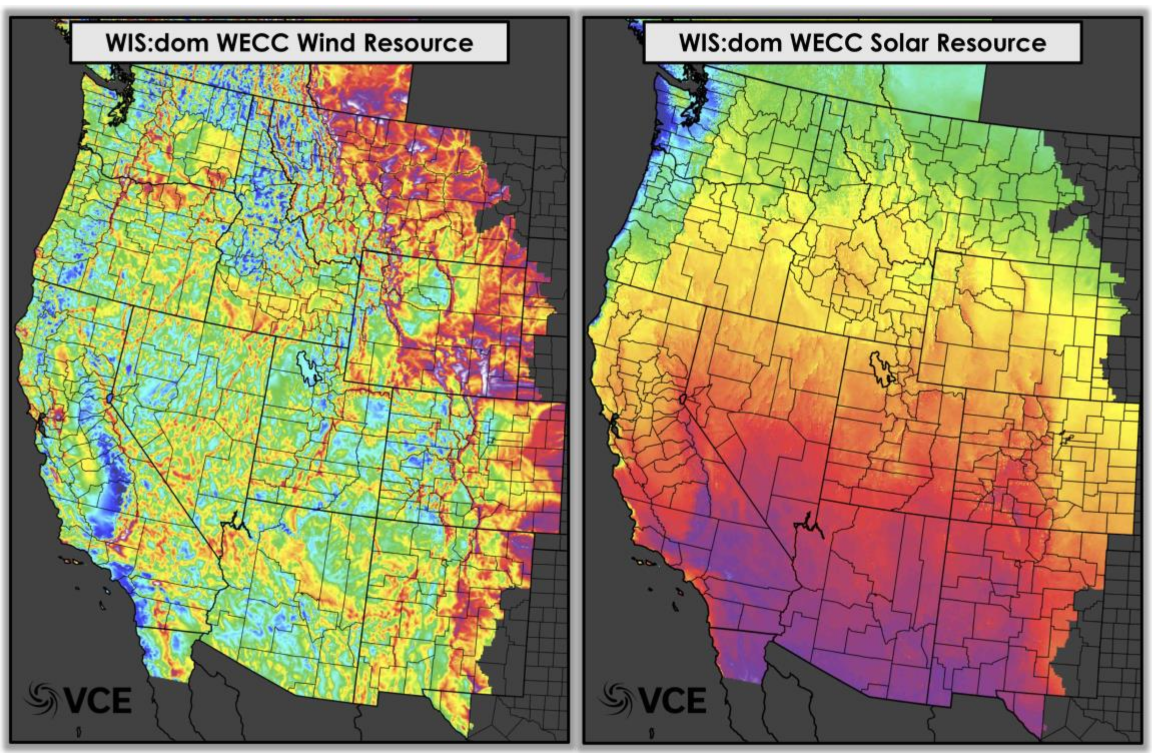


Figure W1: The geographic extent of the Western Interconnection showing the wind resource at 80m AGL (left) and solar PV resource (right). The Western Interconnection is the focus of this branch of WIS:dom®.

The weather data used includes 3-km and 13-km hourly data as well as 5-minute data at 3-km. These data run over 5 to 10 years. The data is use both to accurately estimate the variable generation resource, but to also constrain the load forecasts, alter the power flow potential, and determine extreme events the system must respond to. The weather data is based upon NOAA NWP data assimilation that includes 10 - 25,000 observations each hour. The observations include aircraft, ground based measurements, satellites, radar, and more. With the high density of observations, the data-assimilation is utilized to create an approximation to the state of the atmosphere at a given time. VCE® takes the data assimilation and strengthens the correlation between observations and model. VCE® also take into account the forecast errors that appear in weather models and create unique time series for each of the resource sites in the US. The time series for each resource site is then processed to create potential variable generation and is then further used in estimating electric loads for each resource site. Finally, the data is calibrated along transmission lines to determine the rating of the existing transmission infrastructure. The weather data is assembled in a database structure only readable by WIS:dom®. The purpose of the database is that it is interchangeable with other weather datasets if necessary, for comparison or dispatch characteristics under various scenarios. A further benefit of the database structure is that the WIS:dom® optimization model can read in the data in less than 5 minutes for ~1 million resource sites and 105,120 5-minute timesteps.

WIS:dom® is the only commercially (or academically) available model that can incorporate such a vast amount of weather data and combine high granularity data with capacity expansion and production cost simulations that can answer multiple questions simultaneously. For example, the WIS:dom® model can answer the questions of resource adequacy, generation retirement and expansion, dispatch of each generator, pollution tracking, policy drivers, and power flow in the system all in a single scenario.

To make WIS:dom® practically useful, the model has the ability to read in different data sets for different regions being studied. The consistent framework, while complicated at the outset, allows for simpler transition to new areas of investigation and easier dataset exchange. For each study, WIS:dom® will incorporate existing generation, transmission, and retirement dates for all the assets in the CONUS portion of the Western Interconnection. The Western Interconnection has large geographic extent and contains approximately 225,000 MW of generation capacity (shown in Figure W2). WIS:dom® has the ability to solve over such scales at 5-minute resolution for several years chronologically.

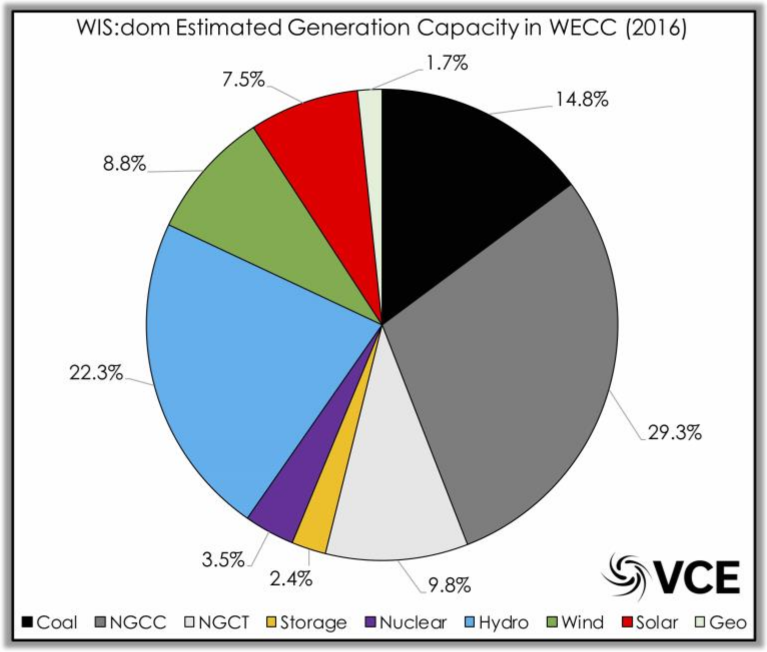


Figure W2: WIS:dom® estimated capacity share for the CONUS portion of the Western Interconnection. The total capacity modeled is 224,891 MW.

One of the most unique features of WIS:dom® (in addition to the high temporal granularity of the dispatch over a long time period and spatial scale) is its ability to site the generators, storage, transmission, and demand side resources. It does this at a 3-km resolution. Therefore, after a simulation is executed, a user can get the specific siting, capacity, transmission necessary for each asset within the footprint. WIS:dom® is not a replacement for a full stability study or AC power flow analysis, rather it is a synthesis model that encompasses the combined capabilities of traditional production cost and capacity expansion models. In doing so, WIS:dom® facilitates information exchange between the different scales while co-optimizing the build out of assets. In short, WIS:dom® allows more solution options and more information for the model to base its decisions upon, thus finding new pathways that are not available to other modeling platforms that exist in the market today. Figure W3 shows an example scenario for the Western Interconnection in 2016 versus 2030 under baseline conditions (some transmission expansion allowed, mid-range NREL ATB cost projections, existing policies and regulations).

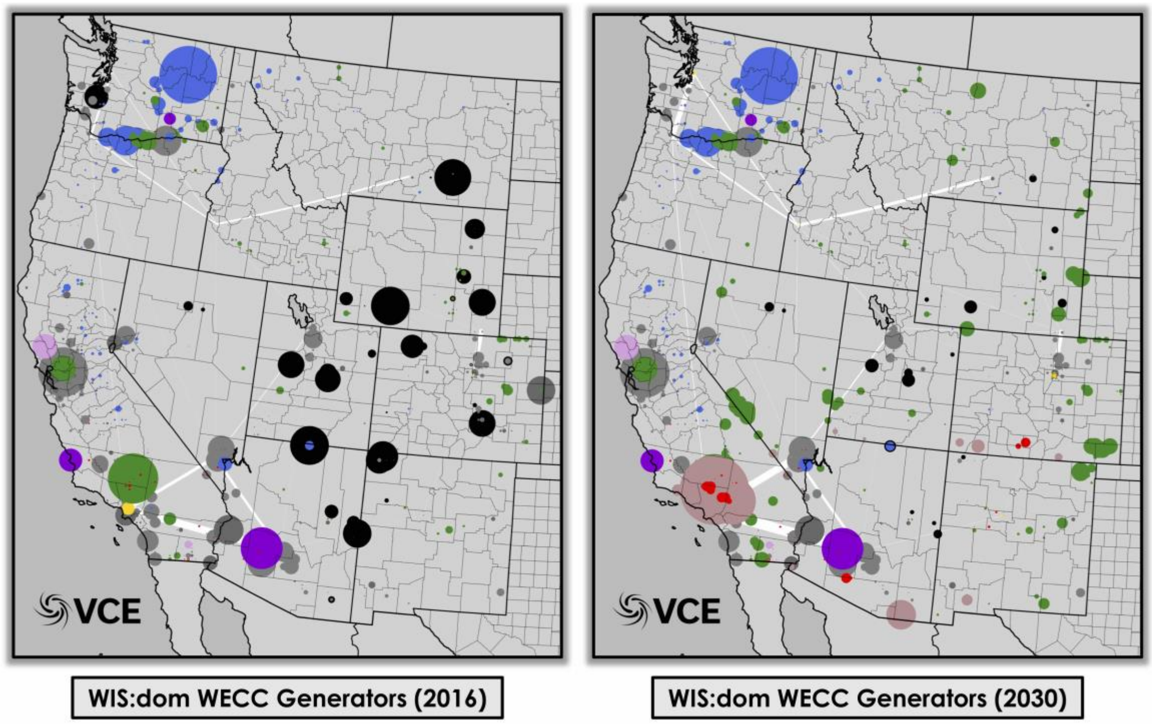


Figure W3: The CONUS portion of the Western Interconnection in 2016 (left) and 2030 (right). The white lines represent the interstate transmission capacity. Black is coal-fired power plants, gray (dark and light) are natural gas-fired power plants, purple is nuclear power plants, pink is geothermal power plants, light blue is hydroelectric power plants, green in wind farms, bright red is solar (utility scale), and pink/red is rooftop solar PV.

Since WIS:dom® resolves temporally (hourly, and 5-minutely) and spatially (13-km and 3-km) the outputs can be aggregated at almost any scale of interest: from counties within specific states, to state values, and the whole WECC aggregated. Figure W4 displays the state-level capacities for the solution in Figure W3.

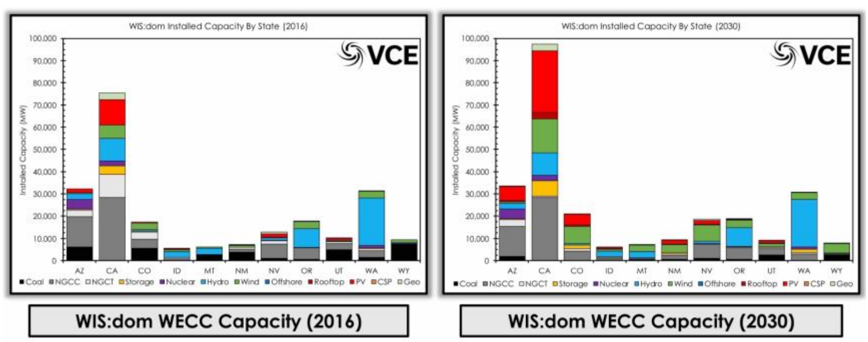


Figure W4: The state-level capacities for the Western Interconnection for 2016 (left) and 2030 (right).

The generation outputs can similarly be aggregated by region and as a whole system. Figure W5 illustrates an example of the Western Interconnection generation shares and the share for a single state, in this case Colorado.

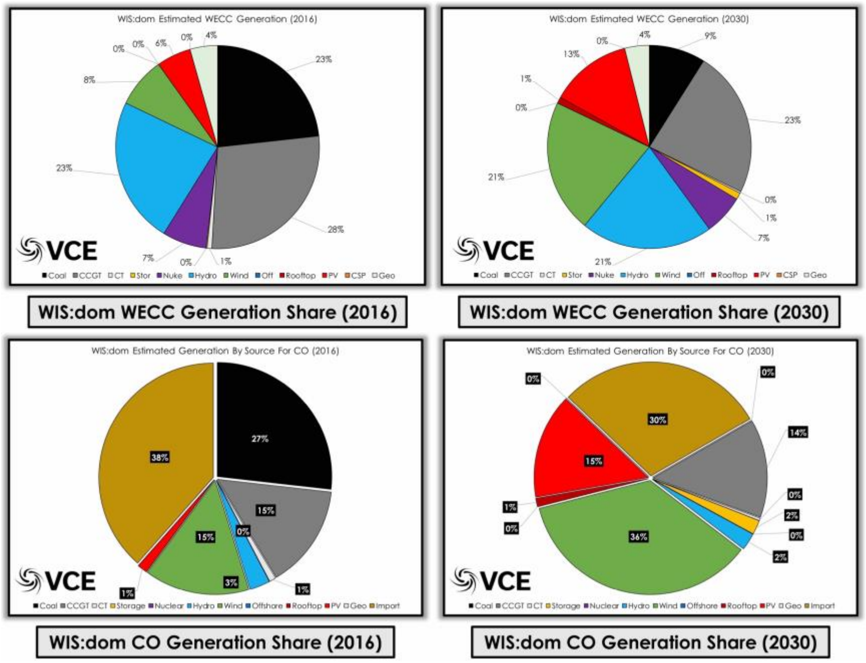


Figure W5: The Western Interconnection (top) and Colorado (bottom) generation share for 2016 (left) and 2030 (right). Note that for Colorado there is import as part of the generation share. WIS:dom® tracks the power flow in and out of regions to determine the risks for generation supply and for tracking pollution attribution.

Not only does WIS:dom® have the ability to aggregate the numbers for generation and capacity by spatial regions, it can discretize the outputs temporally. That is, WIS:dom® tracks each variable that has a temporal component throughout the model simulations. WIS:dom® stores this data and it can be output at the required aggregation level. Above, in Figure W5, it was shown at a total aggregation. In Figure W6, the aggregation is hourly for all of WECC and, in Figure W7, for the state of Colorado. Again, WIS:dom® can output these values for spatial granularity of individual power plants.

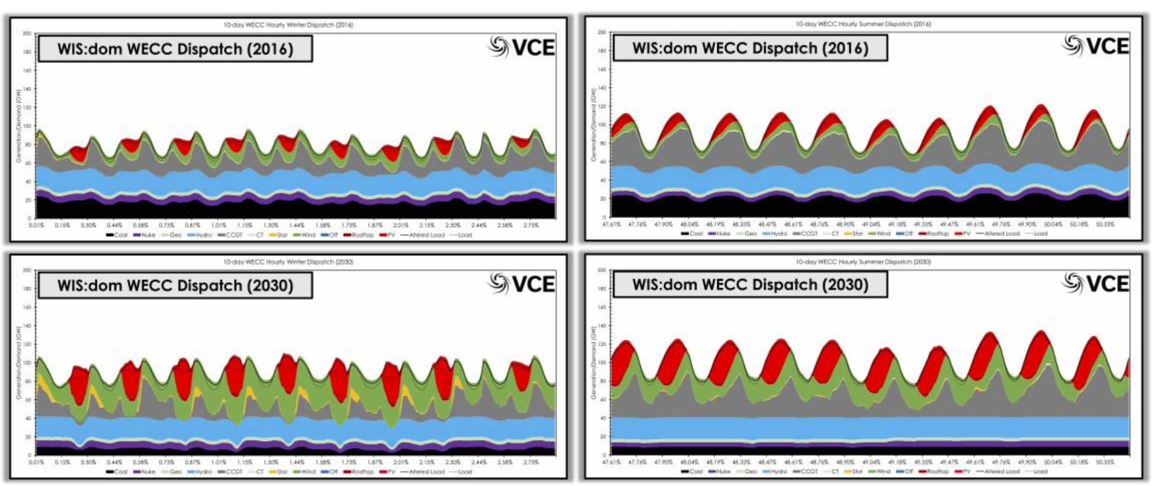


Figure W6: The Western Interconnection generation dispatch for a 10-day example over Winter (left) and Summer (right) for 2016 (top) and 2030 (bottom).

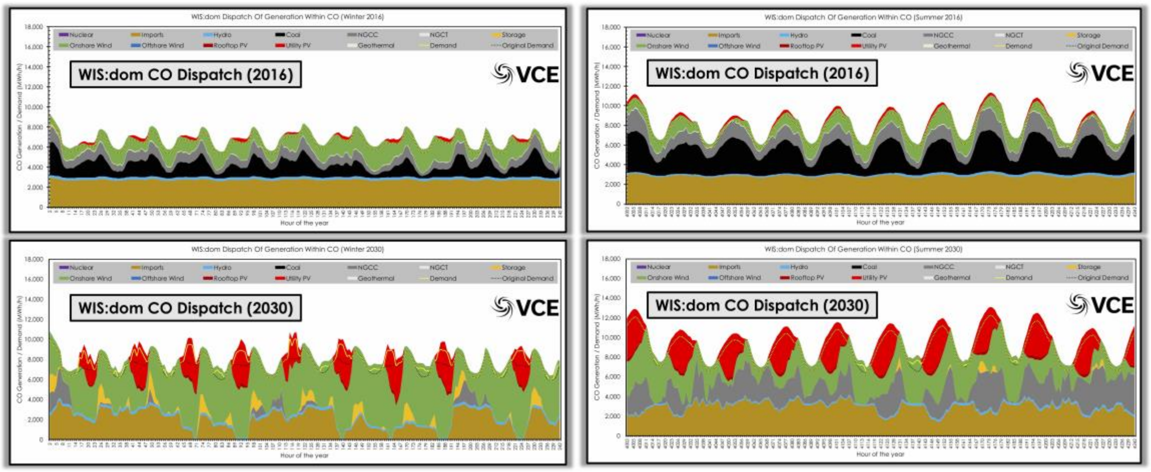


Figure W7: The Colorado generation dispatch for a 10-day example over Winter (left) and Summer (right) for 2016 (top) and 2030 (bottom). Notice, as with Figure 5, WIS:dom® is tracking the imports to the state generation for meeting the demand.

From Figures W5 and W6, it can be seen that storage is altering the demand profiles within both the state of Colorado and the wider WECC footprint. Figure W5 indicates that generation comes from storage. That is not true generation, but electricity stored from other time periods to be dispatched; the change in load shapes seen in the plots show demonstrates how storage alters demand and increases it at certain time periods, while being dispatched at other times. WIS:dom® has advanced techniques to model the storage component at high-temporal resolution to fully integrate the newer technology into the grid system that provides all the services required. With the WIS:dom® optimization model determining what the dispatch and charging strategy should be for the storage units as the grid evolves. This results in WIS:dom® being able to utilize and understand storage in a more realistic manner than most other models that deal with capacity expansion.

WIS:dom® does not only track the generation, it tracks where the electricity goes for end use. It determines how it is being used within the model and the outputs can be aggregates as all the other variables. An interesting feature is WIS:dom®'s ability to determine where the electric losses are occurring and evaluate whether wires, non-wire alternatives, generation, DSM, DR, or EE are best to reduce the losses or whether to allow the model to just deal with the losses that are there. Of course, there will always be losses in the system, but WIS:dom® is constantly seeking the least-cost pathways; sometimes resulting in more efficient dispatch or small changes in generator siting, which can improve the overall system performance. Figure W8 displays results from the example scenario for the Western Interconnection as to where the generation end uses are.

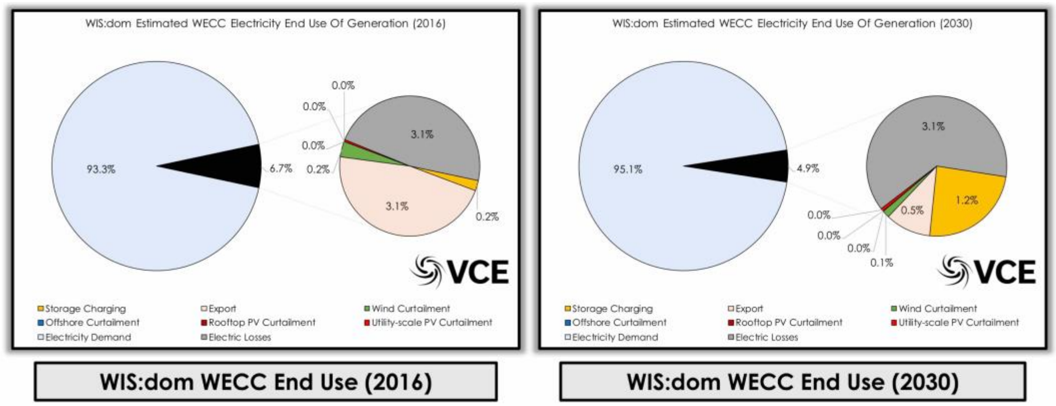


Figure W8: The generation end use of electricity for the Western Interconnection footprint in 2016 (left) and 2030 (right).

WIS:dom® was built to be able to provide analytical rigor to analyzing policies, impacts and societal changes that result from the electricity grid evolving. It was specifically designed around incorporating vast amounts of weather data as well as generator, transmission, and customer operational data. To that end WIS:dom® includes, as standard, the tracking and outputting of policy, economic, and pollution metrics. For example, WIS:dom® tracks several species of pollution, namely: Carbon Dioxide (CO_2), Carbon Monoxide (CO), Sulfur Dioxide (SO_2), Nitrogen Oxides (NO_x), Methane (CH_4), Nitrous Oxide (N_2O), Volatile Organic Compounds (VOC), and particulate matter ($PM_{2.5}$ and PM_{10}). The data from these pollutants are output by power plants and aggregated by county (typically). The plant-level data is stored. The pollution and emission from the power plants is related to their heat rates (which are provided for existing plants), their emission controls, the fuel being burned and the weather in the vicinity of the power plant. Figure W9 displays the estimated emission changes for the pollution species enumerated above for the Western Interconnection footprint from 2016 to 2050, using the example scenario.

In addition to changes in pollution emissions, WIS:dom® calculates the cumulative emissions, typically, by state to illustrate the buildup of emissions that are leaving the states into the atmosphere. The primary emission this is performed on is the carbon dioxide emissions, as illustrated by Figure W10.

WIS:dom® also computes and tracks the real-time costs of providing electricity as well as the average cost for each state over each investment period. In doing so, the model can estimate the impacts on rates and cost of electricity for consumers based upon the evolving composition of the electricity grid. Figure W11 displays the average retail cost of electricity for each WECC state from the example scenario.

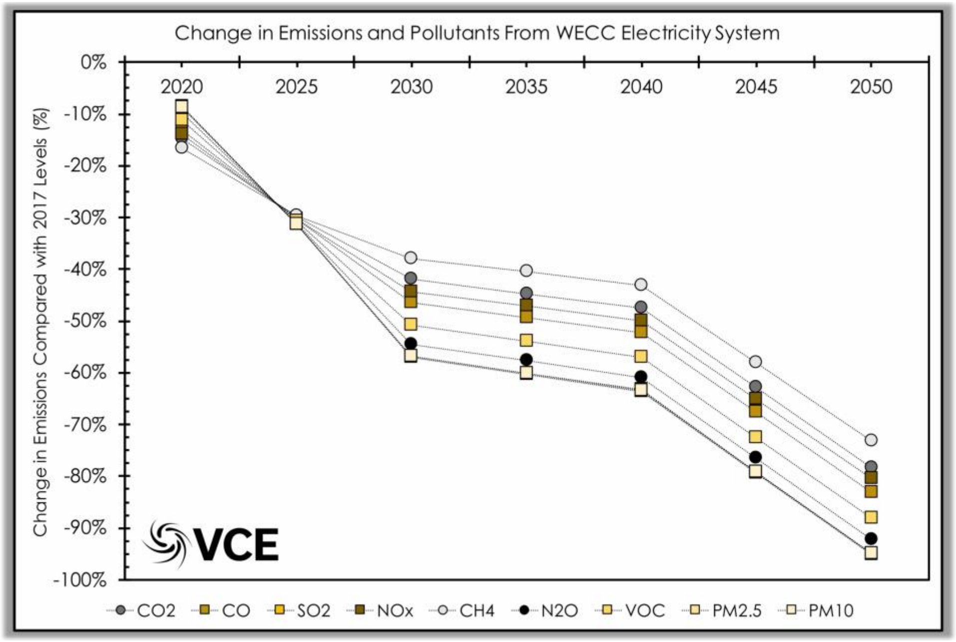


Figure W9: The change in emission of pollution for the WECC footprint from 2016 levels to 2050. Note that Methane does not drop as rapidly as other pollutants because of leakage from fuel extraction to provide the fuel for power plants.

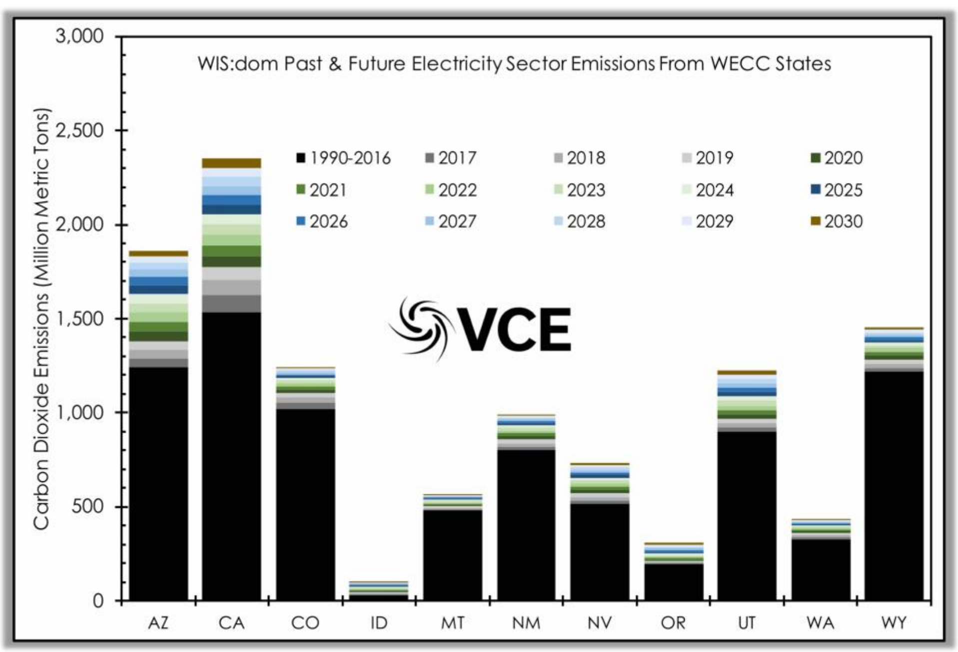


Figure W10: The cumulative carbon dioxide emissions from electricity production for 1990 to 2030 over the states in the Western Interconnection. It provides an immediate image of the added emissions expected over the coming 12 years to 2030.

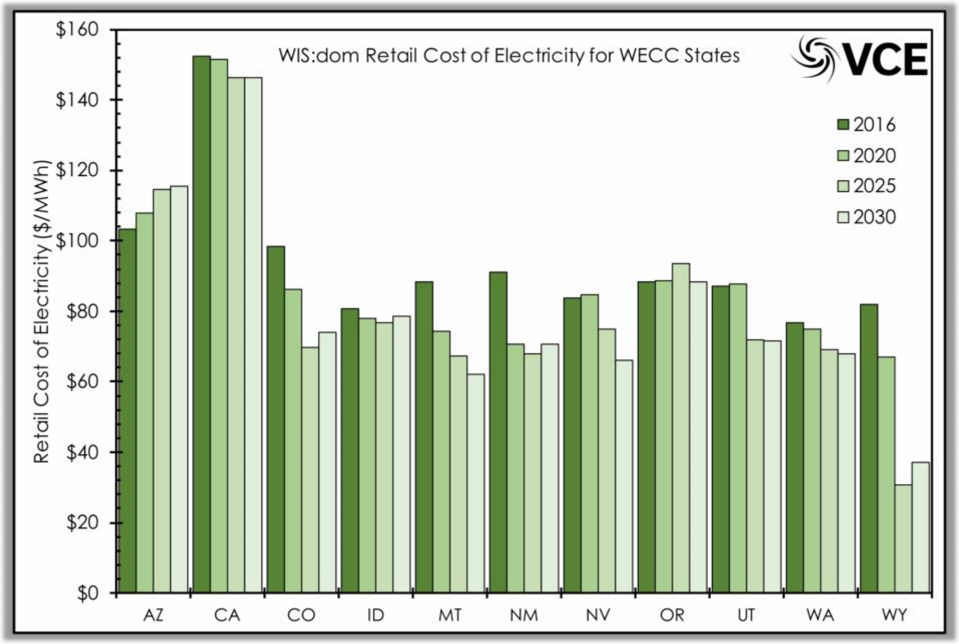


Figure W11: The average retail cost of electricity for each investment period to 2030. The costs include transmission upgrades, retirement costs, new generation build outs, fuel cost changes, and meeting all the existing policies and regulations that exist in the states.

Another important economic indicator that WIS:dom® computes and tracks within the modeling framework is the full-time jobs that are created and destroyed in each state for each technology. Currently, WIS:dom® does not possess estimates for the job numbers that would be provided by storage installations. VCE® is working on building estimates for this. For all other technology types VCE® uses publicly available data, particularly the NREL JEDI model for developing the inputs for WIS:dom® to compute the job impacts in each state. The same data is used to derive the salaries/wages and tax implications for changing generation mix. An example of this is shown in Figure W12 for the WECC scenario for each state and how jobs will change.

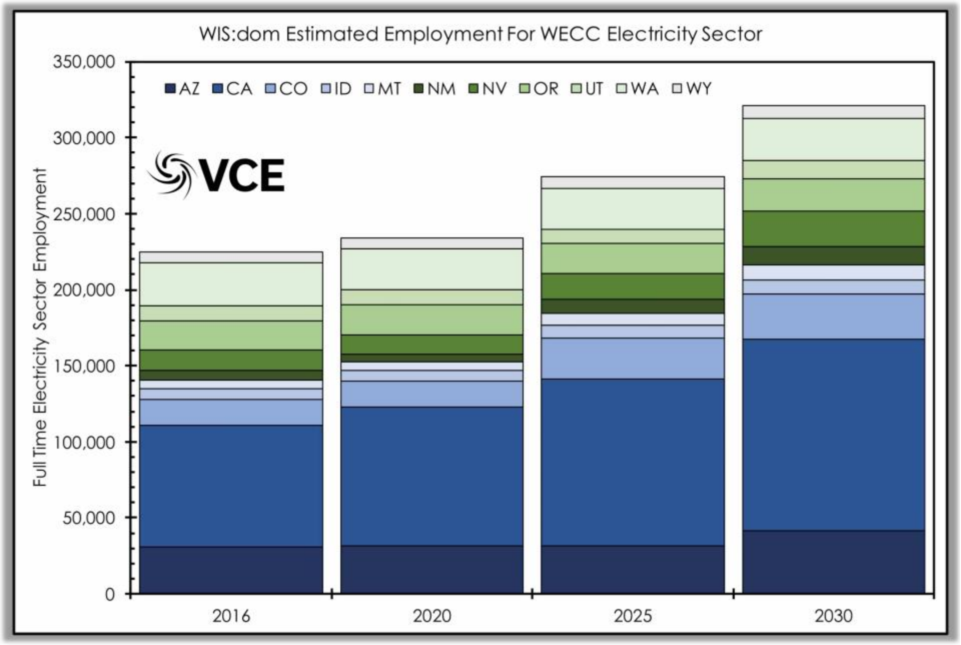


Figure W12: The full-time jobs within the electricity sector by state and investment period. The data is aggregated by county or state and by technology. The fossil fuels do incorporate the extraction of the fuel, but (as per the NREL JEDI model) not all the jobs created by changing the electricity grid in a particular state will be created in that state.

Since WIS:dom® is co-optimizing generation, storage, transmission and DERs it can output the variables for each of these. For transmission this can be harder to translate. WIS:dom® does not select specific corridors for development in an exact manner with respect to construction. Rather, it has the existing transmission system and computes a reduced form that matches the transmission system in capacity, but all lengths are determined as geodesics. This means that expansion and new lines will be computed as geodesics, also. This results in both intra- and inter- state transmission numbers. For simplicity, WIS:dom®'s default output is the interstate transmission capacity by investment period. Higher granularity can be added as outputs and/or specific lines can be modified to determine the differences. This does not substantially impact WIS:dom®'s ability to model the power flow within the model as additional losses are applied to simulate the "real" distances on the lines, as well as the actual line paths are input for the derating due to weather conditions. Figure W13 shows the interstate transmission capacity output for the example Western Interconnection scenario.

There are many other variables and metrics that WIS:dom® can be programmed to output from the model scenarios. That is one reason why all results are stored in binary secured databases, so that users can go back and compute a new metric based on previously executed scenarios.

The WIS:dom® optimization model is a complex platform that investigates the evolution of the electricity grid from what exists today (end of 2016) out to 2050 and beyond. The simulations can be shortened to an earlier date if required for faster turnaround. In the next few pages, the important features of WIS:dom® in terms of data and logic will be discussed. The purpose of the description is not to provide a complete overview of WIS:dom®, but rather facilitate a flavor of the possibilities of WIS:dom® and how it might differ from models that readers may be more familiar with.

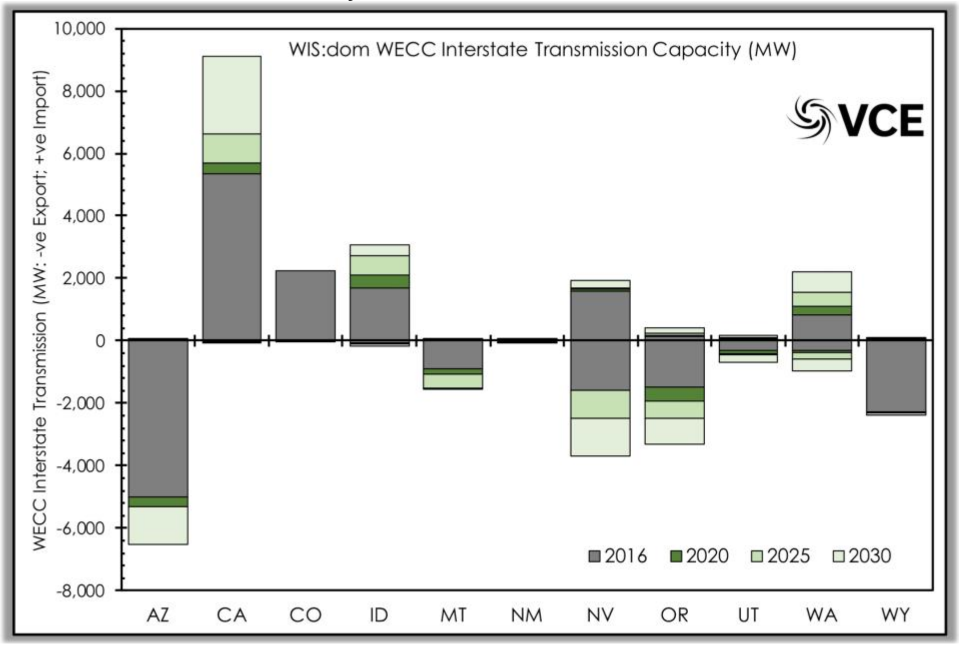


Figure W13: The interstate transmission capacity for investment periods. Each color represents the new capacity built in that particular investment period. The total height of the columns at the end of each investment period is the total capacity. Above the abscissa is import capacity and below is export capacity. For this scenario, Colorado does not expand its interstate transmission at all.

If there is information missing from the descriptions that is critical for a particular project, please contact VCE® and they will provide whether WIS:dom® can do what is being asked and how WIS:dom® performs that particular task.

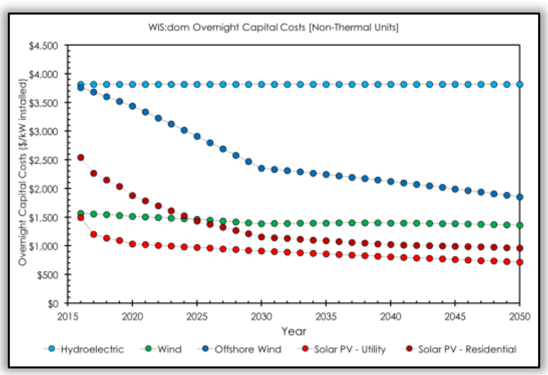
One of the most important components of WIS:dom® is the input data. As much as practically possible WIS:dom® incorporates publicly available data and contains specific values for generators, transmission, storage, production cost, and resource siting. The use of publicly available data facilitates clients using all of the results without restriction. Further, in general, WIS:dom® is designed to allow "plug-and-play" capability, whereby it can take advantage of customized datasets required for detailed modeling of specific questions, markets or balancing areas. For example, higher-resolution weather data over a utility or ISO; or proprietary heat rates for generators within a utility; or localized demand profiles. The main sources of default data for WIS:dom® is provided in Figure W14.

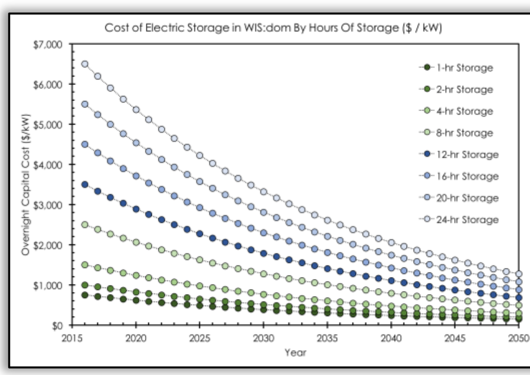
Some data analysis is performed on the input datasets. First, the existing generators within the Western Interconnection are aggregated by type within 3-km resolution grid cells. The data for each existing generator is applied within that spatial resolution. The specific electricity grid data that is provided to WIS:dom® includes: Heat rates for thermal generators, minimum loading for thermal generators, fuel costs for thermal generators, fixed O&M costs for all generators, non-fuel variable O&M costs for all generators, remaining capital costs for all generators, transmission topology for all voltages above 69 kV, estimated relicense costs for nuclear generators, repower costs for variable generators, the age and expected life of all existing generators, the power factor of all existing generators, the near-term generator interconnection queue, and existing demand by sector.

Input ID	Input Name	Existing	New
1	Heat Rate	All Current Thermal Data	NREL ATB 2017 Value
2	Minimum Load	All Current Thermal Data	Fleet Average
3	Power Factors	All Current Generator Data	Fleet Average
4	Fuel Costs	All Current Thermal Data For Multiplier	NREL ATB 2017 Value
5	Fixed O&M Costs	All Current Generator Data	NREL ATB 2017 Value
6	Non-fuel Variable O&M Costs	All Current Generator Data	NREL ATB 2017 Value
7	Capital Costs	All Current Generator Data	NREL ATB 2017 Value
8	Relicense / Repower Costs	All Existing Nuclear, Wind, and Solar Generators	45% For VRE, N/A For Nuclear
9	Discount Rates	Uses Same Rate as "New"	5.87% Real
10	Economic Lifetimes	All Current Generator Data	NREL ATB 2017 Value
11	Transmission Costs	Uses Same Cost As "New"	ABB / Blended Existing Costs
12	Transmission Topolgy	Current Above 69 kV Aggregated To Reduced Form	New Lines Allowed Within WIS:dom; constrained by user
13	Demand	Current Demand By Sector	Growth Estimates Provided By Sector By VCE
14	Weather / Power Data	N/A	One Year Of Hourly Power Data For Wind & Solar Over El
15	Policy & Regulations	Apply All Existing Policies & Regulations	Input As Constraints On Future Scenarios
16	Locational Multiplier	N/A	Black & Veach / NREL Public Data Combined By VCE

Figure W14: The most commonly used datasets and inputs for the WIS:dom® optimization model. Where it states NREL ATB 2017, the values have been updated to the NREL ATB 2019 for any new projects.

The cost assumptions for all new builds of generators, transmission and storage remain constant throughout the scenarios carried out within a study, unless specifically requested. However, the cost assumptions are changing within each scenario based upon the NREL ATB 2019 values. The NREL values were chosen to be reputable values; are used by RTOs in their modeling; give high granularity and are updated frequently. Figure W15 display an example of the cost assumptions used in WIS:dom® for new variable generators and storage. The storage values are not provided by NREL ATB, and so VCE® has provided these through internal study and resources.





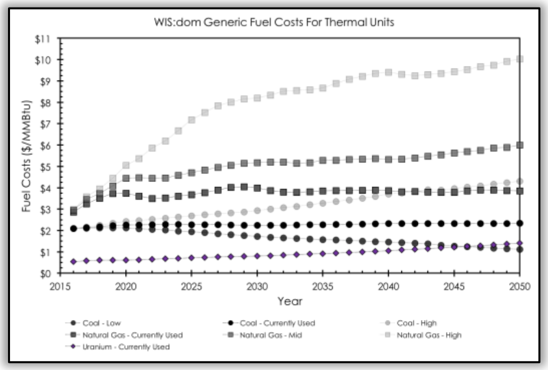
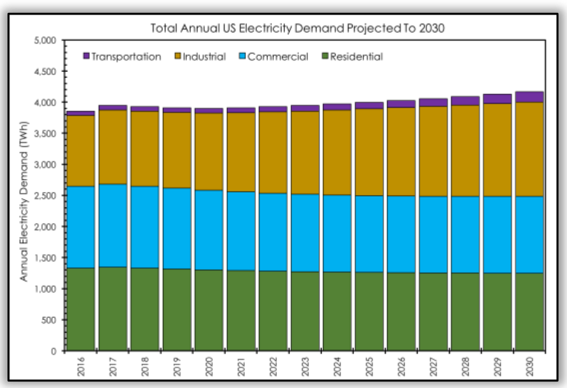


Figure W15: Example costs for weather-driven renewables (top left) and storage (top right) capacity expansion, and fuel costs (bottom). All inputs within WIS:dom® are customizable for specific localities. Multiple fuels costs are shown for coal and natural gas because of the high degree of uncertainty.

The WIS:dom® optimization model must supply electricity demand for each 5-minute interval for at least an entire year across the Western Interconnection, while retaining operating and planning reserves, and considering transmission power flow and associated losses. To do this, WIS:dom® requires load forecasts for the investment periods. In Figure W16, the annual demand profiles for the entire US is shown along with the aggregate hourly values. WIS:dom® has the load data input at a county level. The load/demand data is separated into the sectors of residential, commercial, industrial, and transportation. The sector breakdown facilitates Demand Side Management (DSM), Demand Response (DR), Electric Vehicle (EV), heat pump transitions to all be accounted for and estimated for flexibility and growth/reduction on the demand side. These demand side resources are calculated a priori and are given upper bounds within the model. The WIS:dom® optimization model will decide the level to actually utilize. This is important for Energy Efficiency (EE) because some reduction in EE might help drive investment in some areas, while more aggressive EE in another region might help control local cost spikes.



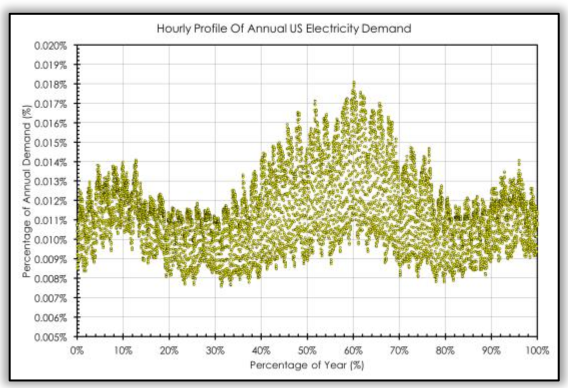


Figure W16: The estimated annual US electricity demand by year (left) and the hourly load profile as a percentage of annual demand (right). The hourly load profile is calculated for the weather data years used within a study, to correlate with weather-driven impacts.

The weather years used to provide the weather data and power inputs for the variable generation is taken to be 2013 to 2018 at 13-km hourly and at 3-km 5-minutely. These years were chosen for their inclusion of the most advance weather simulation physics, containing extreme events (hurricanes, tornadoes, floods, droughts), and a decadal history of climate change impacts. The 5-minute values for wind at 80 m, 100 m, 120 m, 140 m, and 160 m hub heights along with fixed solar PV tilted at (0º, 15º, 30º, 45º, and latitude, single axis tracking and dual axis tracking were computed for every site within the United States (potential VRE resource). For existing wind and solar sites, existing parameters were input into the power algorithm to overwrite the potential VRE resource. If WIS:dom® determines repowering a site is worthwhile, the potential VRE resource will replace the existing values when the repowering takes place; thus, providing the enhancement to the generation at that site. The siting constraints for the whole US is also calculated by VCE® using the latest and highest resolution land use datasets. The datasets allow WIS:dom® to have realistic bounds siting for the variable generation. Figure W17 displays the land use data set that is incorporated into WIS:dom® for siting constraints of renewables. Figure W18 shows the best wind resource siting by hub height and the optimal solar PV technology.

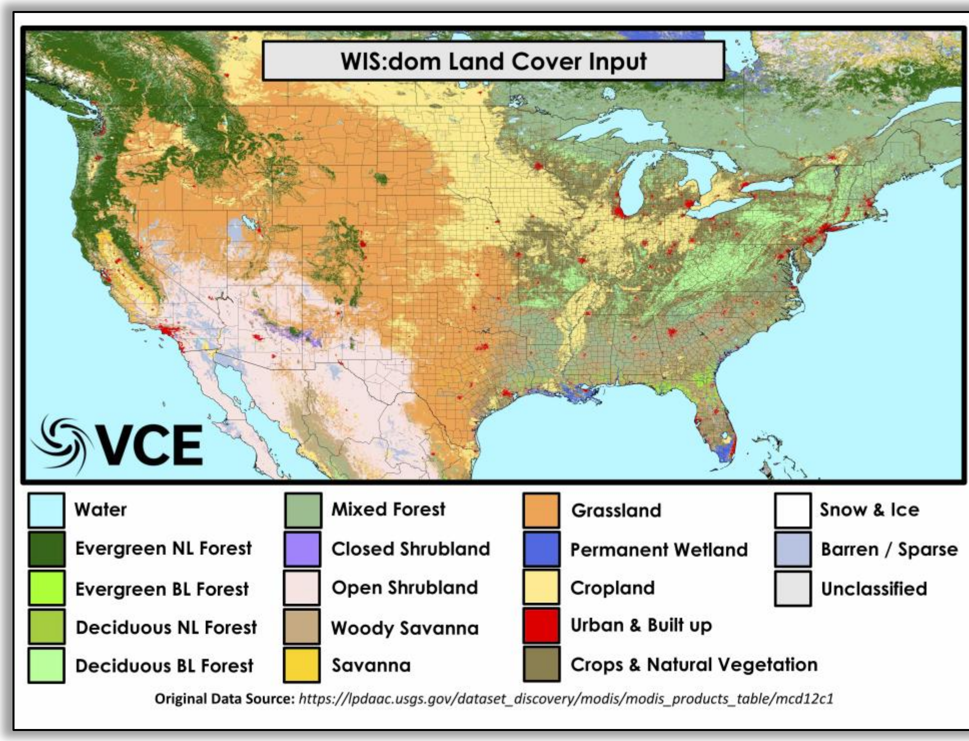


Figure W17: The land use dataset that is used within WIS:dom® to determine the appropriateness of locations for development of variable generation. Other layers are applied to the land use dataset, such as topographic, critical species, migration paths, etc.; however, the land use dataset has the largest impact on siting.

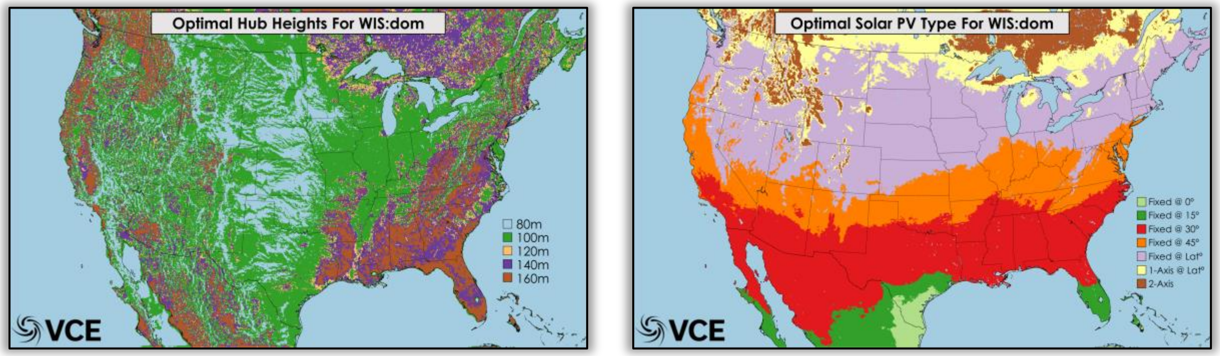


Figure W18: The optimal hub height for wind turbines (left) and the optimal solar technology (right).

Another assumption/input that WIS:dom® accounts for in its internal logic is the constraints on nuclear and hydroelectricity generation with regards to weather and refueling schedules. Hydroelectricity is heavily dependent on the weather, and nuclear has somewhat strict maintenance and refueling schedules. This manifests with the fleet of nuclear and hydroelectricity changing their capacities month by month. For WIS:dom®, VCE® determine the last 10 years of data for the nuclear fleet cycling due to maintenance and refueling and apply the average of those 10 years to the WECC fleet. For hydroelectricity, WIS:dom® is forced to release the same amount of water as was released in the weather years each month. The implication for hydroelectricity is that it can be more flexible to changing electricity grid mixes, but must retain steady water flow on a monthly basis as to not alter other uses for the water substantially. This is done because many hydropower plants are run-of-river and cannot store the water and others are used for many other purposes other than electricity generation. A final reason to deal with hydropower in this way is to take into account the changing weather patterns and how they influence the stream flows for the hydropower.

Using the demand data, shown in Figure W16, WIS:dom® assigns a value to each 5-minute interval for flexible demand while computing the optimal, least-cost resource mix. The two main areas for flexibility are EVs and DSM (that represents primarily space and water heating in residential and commercial sectors, along with a small portion of industrial DR). WIS:dom® has a cost assigned DSM and DR to be dispatched within the WIS:dom® market. The cost is to allow WIS:dom® recognize that there are implications costs to providing flexibility that need to be compensated for (beyond the simple arbitrage that would accompany early adoption of DSM and DR). The costs associated with DSM escalates over time, to represent the additional burden for the economy as more flexibility is demanded. The cost of DSM is inelastic and WIS:dom® can decide to use none, some, or all of the available flexibility. Further, related to these variables is the import and export capabilities of the US system to Canada and Mexico. The connections to Canada and Mexico are static in terms of capacity and cost to buy and sell, but the transactions are free variables within WIS:dom® to decide when to purchase power and when to sell power to these other countries.

At its core WIS:dom® is a combined capacity expansion and production cost model. It is, therefore, a synthesis model. WIS:dom® will constantly seek the lowest cost system(s) it is optimizing over; taking into account all the constraints and commitments built into the initialization. WIS:dom® for most studies is run in LP mode. This means that all variables are real number values; allowing more detailed inspection of the changes to the electricity grid composition. The branch of WIS:dom® that is used for projects that solve over the entire Western Interconnection. It solves for each of the regions that are in the WECC, while considering the transmission corridors between them, committed units for certain areas and other friction/inefficiencies. These can be relaxed with WIS:dom® selecting transmission corridors to invest in over investment periods. The user can constrain the amount of cooperation and transmission build out. Since WIS:dom® is an LP optimizer, if transmission is completely constrained between markets, each market will be solved separately.

The essential function for WIS:dom® is for it to minimizes its objective function, which is the sum of the total costs for each of the systems it is considering. The system costs include: capital repayments, fixed costs, variable costs, fuel costs, transmission costs, reserve payments, integration costs, retirement payments, and other social costs that are borne through policy. The minimization of the total system costs is under tension/pressure from the enforcement of constraints, which act to enforce reality on WIS:dom®, and will change the composition of the solution vector; typically increasing the total system costs. The main equations that WIS:dom® solves over are provided in Figure W19. The figure attempts to highlight the impact of each equation set.

Constraint ID	Equation Name	Equation Purpose	Impact Estimation
1	Total System(s) Cost Objective	To define the objective that is being minimized	**Critical** Other objectives may alter solutions significantly
2	Reliable Dispatch Constraint	Enforce WIS:dom meets demand in each region each hour without fail	**Critical** Strict enforcement of zero loss of load
3	Market Clearing Price Adjustment	Allowing WIS:dom to estimate the dispatch stack & attribute price vs cost	**Critical** Different market structures could impact deployment choices
4	DSM Balancing Constraint	Ensures that DSM providers can balance their demand	**High** Changing the description of DSM and costs could alter solutions
5	Transmission Power Flow Constraint	Produces the optimal power flow matrix and associated losses	**Critical** Transmission power flow significantly impacts dispatch and deployment
6	Transmission Capacity Constraint	Calculates the capacity of each transmission line	**Critical** Without this constraint, power flow could become artifically large
7	Planning Reserve Constraint	Ensure planning reserve margins are maintained	**High** Capacity credit for VREs can alter deployment decisions
8	Coal, NGCC, NGCT, Nuclear, Hydro, Geo Capacity Constraints	Maintain the capacity of generators above their peak production	**High** Without the constraints generations can be incredibly based on marginal costs alone
9	Storage Power & Energy Capacity Constraints	Complex equations & constraints to determine the utilization of storage	**Critical** Storage correctly modeled can change all investment decisions and dispatch
10	Coal, NGCC, NGCT, Nuclear, & Geo P_min Constraints	Constraints that force WIS:dom to adhere to P_min attributes for thermal generators	**Medium** P_min enforcement has lower impacts on decision
11	RPS & Emission Constraints	To enable WIS:dom to understand policy, regulatory and societal limitations	**Critical** When emissions enforced investment decisions are completely changed
12	Generator & Transmission Capacity Expansion Constraints	To require WIS:dom to keep investments in new generation & transmission to specific levels	**Low-Medium** Very tight enforcement could impact decisions, but realistic values do not substantial change solutions
13	Coal, NGCC, NGCT, Nuclear, & Geo Ramping Constraints	Describing the speed at which generators can alter their output for WIS:dom	**Medium** Faster ramping thermal generation is more favorable in lower emission scenarios, so this constraint impacts decisions in those cases
14	DER Deployment & Cost Constraints	Specifies to WIS:dom the amount of DERs to be constructed and/or cost to system of these assets	**Low** Has minimal impact on the overall system costs and investment decisions of utility scale generators
15	CIL & CEL Constraints	Describe the import & export limits between markets, countries, states, and interconnections	**Medium-High** Transmission expanding from existing lines & the addition of market impacts can dramatically alter decisions in some high emission reduction scenarios
16	Spatial Limitation Constraint	Allow WIS:dom to understand the space requirement for generators and competition for land use	**Medium** Without this constraint land use can be over used and over count the amount of generation in a location/site
17	Extraction Limits For VRE	Determines the limits to VRE extraction for nearby sites	**Medium** Impactful for wind siting considerations but much lower for solar PV siting
18	Nuclear & Hydro Dispatch Schedule	Informs WIS:dom that nuclear and hydro must conform to addition constraints regarding the water cycle, water temperature, and refuelling	**Low-Medium** Nuclear suffers a small amount due to offline times & hydro flexibility limited by constraint to assist with other VREs
19	Relicense / Repower Decision	Facilitates WIS:dom opting to relicense or repower an existing nuclear or VRE site	**Medium-High** Repowering can substantially improve existing sites at lower cost, while relicensing enable nuclear to remain within markets for longer
20	Load / Weather Forecast Error Estimator	Enables WIS:dom to detect regions with poor weather and/or load forecasts for consideration during investment decisions	**Low-Medium** Load & weather forecasts are small enough over EI markets that the invesments are not substantially altered. For WECC, the impact is much higher

Figure W19: The main equation sets that WIS:dom® computes and solves over during its optimization procedure. Not all equation sets are shown; only the most important are displayed.

The equations in Figure W19 are initialized for each of the investment periods (2018, 2020, 2025, 2030, 2040 and 2050). WIS:dom® solves for each investment period in chronological order. When WIS:dom® completes a solve for an investment period, all the data / solution vectors are stored and passed to the next investment period to allow conditions to be constrained based upon previous decisions. In that way, WIS:dom® is operating in "myopic mode"; that is previous investment decisions impact future ones, but future ones do not impact previous decisions. To complete an investment period, WIS:dom® must simultaneous: determine the generator capacity and siting, determine the transmission capacity and siting, determine the storage capacity and siting, compute retirement decisions, decide upon all the dispatch profiles for all the generation and transmission, compute the cost for each market region, incorporate the VRE dispatch based upon weather drivers, calculate the emissions produced at each site, and finally conform to every constraint imposed (without fail).

For focus regions in studies, WIS:dom® also includes a high detailed description of the transmission system. For example, in Colorado the full electrical transmission grid (to 69 kV), including substations, is represented explicitly within WIS:dom® (see Figure W20). Typically, the reduced form of transmission is used in scenarios that encompass large geographies to expediate the solution time and provide less specificity to individual lines.

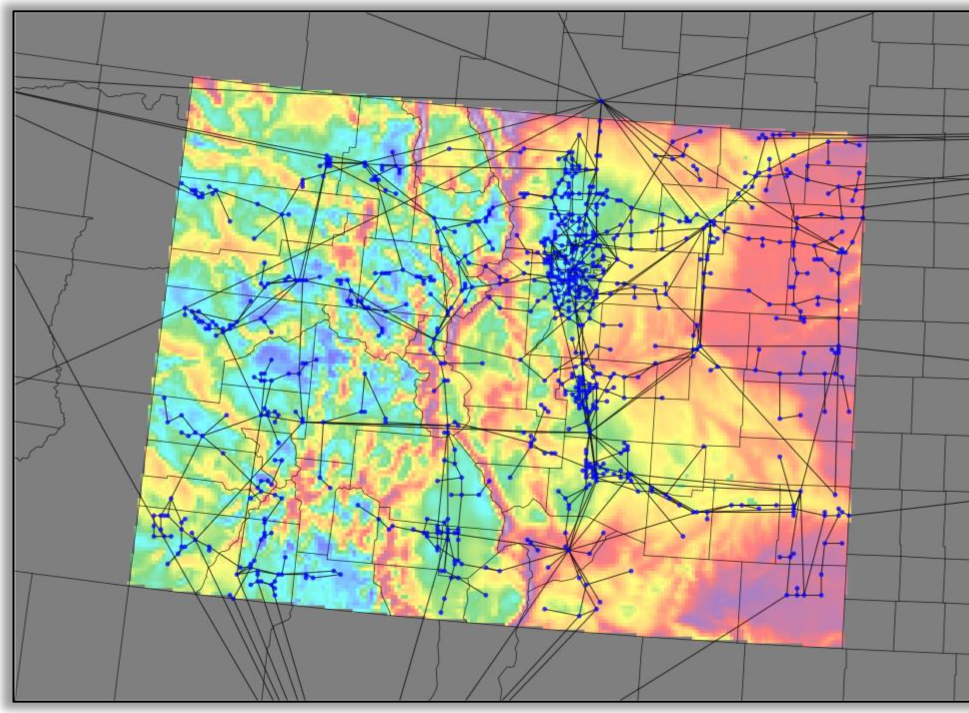


Figure W20: The transmission and substation infrastructure for Colorado at highest resolution (down to 69kV)