WECC

2040 Clean Energy Sensitivities Study

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January 28, 2022

Executive Summary

The purpose of this study assessment is to better understand the opportunities, challenges, uncertainties, and reliability implications associated with achieving a 100% clean energy future in the Western Interconnection (West) and to build upon what has been learned from previous scenario studies performed by WECC with the goal of ensuring future reliability in terms of:

- Resource adequacy and performance,
- The changing resource mix,
- Distribution system and customer load effects on the bulk power system (BPS).

This assessment examined the implications of achieving clean energy levels of 80%, 90%, and 100% for the West through a sensitivity analysis of the drivers trending toward clean energy. Over 200 simulations of various resource portfolio mixes at various highly electrified two-week seasonal heavy and light load conditions were simulated using a production cost model (PCM) tool. The purpose behind these simulations was to assess the sensitivities of simulation results to perturbations of underlying model parameters and to find optimal resource mixes at 80%, 90%, and 100% clean energy levels at various seasonal load levels. Full-year PCM simulations were then performed to further refine these resource mixes. The results of these simulations revealed the following:

1. Penetrations of variable Renewable Energy (VRE) resources, such as solar and wind, will need to significantly increase over the next 20 years to achieve a 100% clean energy future. Operational challenges will also significantly increase with these higher penetrations of VRE resources, especially in terms of ramping requirements.
2. A saturation is reached with the deployment of new battery energy storage systems (BESS) and VRE resources alone at 90% where the benefits of further deployments are greatly diminished, primarily due to the misalignment of energy production from VRE resources with hourly load demand. As a result, renewable energy curtailments increase over all hours of a day (primarily light load days) minimizing the opportunities for batteries to dispatch and resulting in negative locational marginal prices. Resource planning and operations must be carefully coordinated among the many entities in the Western Interconnection to arrive at a balanced resource portfolio mix that ensures a reliable BPS while minimizing operational challenges and market disruptions.
3. BESS will be a key component of achieving a 100% clean energy future. At clean energy levels above 90%, however, the benefits of BESS are diminished. The findings of this study suggest that BESS and VRE resources alone will not be enough to achieve a 100% clean energy future.
4. Other emerging clean and flexible (ECF) energy resource technologies that do not produce emissions were needed in addition to BESS to replace the lost resource flexibility that would otherwise be provided by displaced gas-fired resources. Because VRE output and customer loads vary significantly during any given day, and over the course of the year, and because

there are limitations on BESS performance, there is a need for other clean resource types with performance characteristic similar to that of gas-fired generation resources.

5. Increasing VRE resources may create transmission challenges. As VRE penetrations increase above 90%, the resulting changes in resource dispatches significantly change the inter-regional flows in the Western Interconnection. In some cases, the changed flows result in transmission utilizations in a range between 90% to 100% of their rated capacities.

The current trends toward clean energy are introducing dramatic changes to the BPS in the West. With these changes, the long-term energy future of the West is becoming less certain and less predictable. Uncertainty stems from the inability to compare future trends to past experience. Strategic foresight planning will be needed to manage uncertainty and envision plausible futures. Scenario planning is probably the most recognizable strategic foresight planning method in use. Scenario planning is a continuous learning process that aims to envision a range of plausible futures by identifying forces and trends and to change the way decision-makers look at the future to help them make informed decisions and steer a course toward the most desirable outcome. The recommendations in this report are made to inform decision-makers and planning processes of uncertainties and risks to the BPS in the West.

This study is Phase 1 in the study of scenarios developed by the Scenarios Work Group (SWG) focused on the sensitivities of drivers that trend toward a clean energy future. Phase 2, scheduled for 2022, will delve deeper into the scenarios, focusing more on the implications of technology, consumers, policy, and markets.

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Purpose

With few exceptions, most states and provinces within the Western Interconnection (the West) have announced ambitious clean energy plans. At the federal level, the Biden administration has laid out a bold climate agenda with a goal to reach net-zero carbon emissions by 2050 [1]. The Canadian provinces of Alberta and British Columbia have passed similar clean energy legislation [2] [3] as has the Mexican government [4]. Climate change and environmental issues have become a major social and political concern.

As the number of clean energy commitments and goals at federal, regional, state, and tribal levels of government continue to increase, it is essential that the opportunities, challenges, uncertainties, and reliability implications associated with achieving these commitments and goals be better understood.

WECC's mission is "To effectively and efficiently mitigate risks to the reliability and security of the Western Interconnection's Bulk Power System" [5]. There are many strategies that WECC uses to accomplish this. One method is scenario planning, which focuses on drivers of change and the implications that they may have on the long-term (20+ years) energy future. WECC and the Scenarios Work Group (SWG) craft scenarios concerning trending drivers of change as part of WECC's biennial study programs. The main themes of the 2040 Scenarios are:

1. The opportunities and challenges of achieving a 100% clean energy future.
2. The implications regarding policies and markets;
3. The implications regarding technology advances; and
4. The implications regarding consumer adoption of new technologies and service options.

The SWG recognized that, to effectively study Themes 2, 3, and 4, a sound understanding of the opportunities and challenges associated with Theme 1 must be obtained. The SWG decided that the study should be structured in two phases: 1) Phase 1: a clean energy sensitivities study to better understand the opportunities and challenges of achieving 80%, 90%, and 100% clean energy levels (this study), and 2) Phase 2: a scenarios study that builds upon the Phase 1 study.

This study presents findings from Phase 1 and is focused on sensitivities performed on 80%, 90%, and 100% clean energy levels in the West.

Key Assumptions

The following assumptions were made for this study:

- The study horizon was 2040. An examination of the yearly progression to the 2040 study horizon was not included.
- Electrification—and the resulting customer demands—will be increasing over the next 20 years. This will be caused by increased use of electric vehicles, electrification of other parts of the

transportation sector, and conversion of natural gas applications to electricity, such as space and water heating [6].

- A production cost model (PCM) tool was used to perform this study. While the analysis performed in this study was based solely on PCM results, a goal of this study is to inform other planning processes with different objectives, which may use different planning tools, of issues that may warrant further detailed study based on the findings of this study.
- This study focused on the BPS in the West. To the extent possible, modeling proxies were used to represent aspects of the distribution power system (DPS) that may influence the study results (e.g., rooftop solar, demand-side management).
- The study was performed from an inter-regional perspective focusing on the interconnections between planning subregions within the West as shown in Figure 1.
- In the context of a 2040 planning horizon, it is assumed that subregional planning groups and local Balancing Authorities (BA) will plan for the necessary transmission reinforcements within their respective subregions (e.g., CA/MX, Northwest, Southwest). A goal of this study is to inform subregional and BA planners of findings that may be influential from a subregional standpoint and worthy of their consideration.

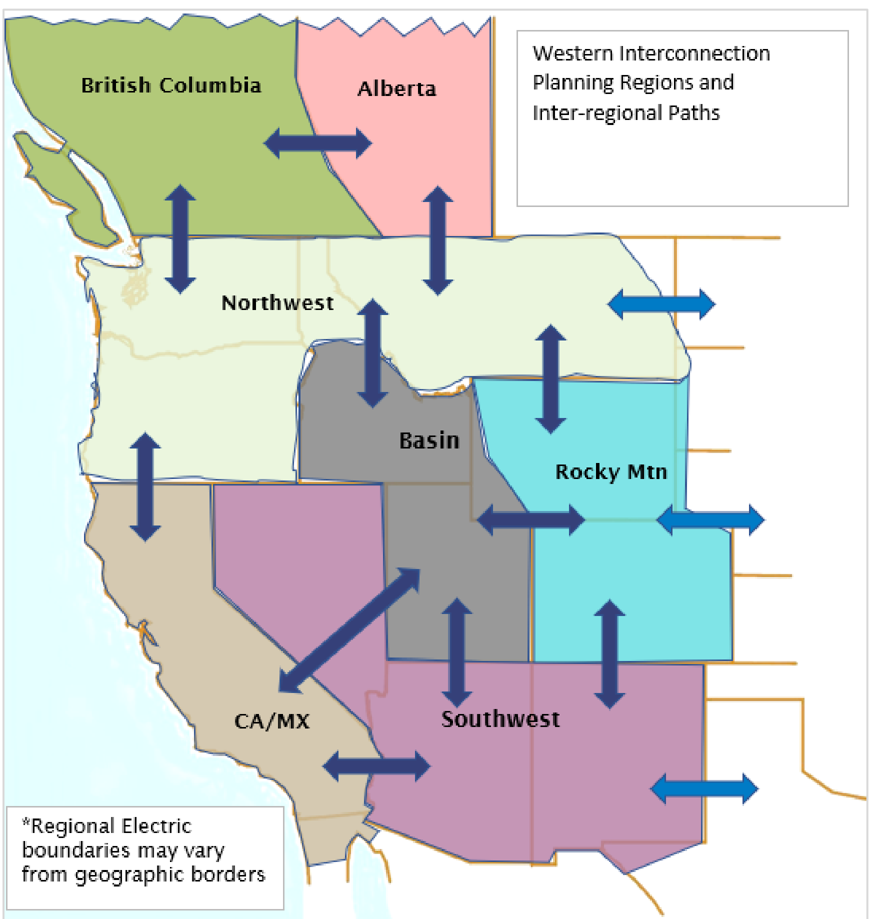


Figure 1: Planning regions and inter-regional paths in the West

Input Data

The 2030 Anchor Data Set (ADS) is the foundation upon which the 2040 Clean Energy Sensitivity Cases were built. The following changes were made to the 2030 ADS to adapt it to a 2040 study horizon at various levels of clean energy:

- The load models used in this study were derived from the demand-side load models used in the National Renewable Energy Laboratory (NREL) Electrification Futures Study, specifically, the high consumer adoption and rapid advancement of electrification technologies for 2040 [6].
- Transmission and existing generation resources modeled within the 2030 ADS.
- The generation models in the 2030 ADS were augmented with new candidate generation resource additions that were derived from the NREL Annual Technology Baseline (ATB) for 2040 and were aggregated at state and province levels. Distribution factors were used to distribute the generation dispatch from these aggregates to bus nodes proportional to their load share within the state [7]. New candidate generation resources that were added consisted of biopower, geothermal, combined cycle gas, gas turbines, distributed generation, rooftop and utility-scale photovoltaic (PV) solar, concentrated solar power (CSP), onshore and offshore wind, DPS and BPS battery storage, storage from electric vehicles, and a modeling proxy for clean and flexible resources with performance characteristics similar to gas-fired generation that may emerge in the future.
- New battery storage was modeled as 12-hour.
- The energy production potential for new renewable candidate resource additions were derived from renewable technical potential supply curves obtained from NREL [8].
- An additional resource type was added as a proxy to represent emerging clean and flexible (ECF) resource types that do not produce emissions that can replace lost resource flexibility that would otherwise be provided by displaced gas-fired resources. These ECF resources were modeled to have performance characteristics similar to that of gas-fired resources (e.g., ramping, regulation, and inertia requirements).
- Fixed and variable operating and maintenance (O&M) costs for 2040 from the WECC Generator Capital Cost Tool [9].
- Fuel costs for 2040 were obtained from the Annual Energy Outlook 2021 [10].
- Carbon costs were set at $100/ton based on a consensus among SWG members.
- Ramping rates were the same as those already modeled in the 2030 ADS.

Approach

Method

One goal of this study was to find resource portfolio mixes in which energy supply was optimally balanced with demand at 80%, 90%, and 100% clean energy levels while enforcing security constraints (e.g., transmission line ratings) and minimizing operating costs and curtailments. Solar and wind resources have the most renewable potential in the West and were the primary sources for candidate additions of variable renewable energy (VRE) resources. BESS were included in the study to help align VRE resource dispatches with load and to provide resource flexibility.

VRE resources were modeled in the study as price takers, meaning that they are always committed. Fixed hourly shapes were used to model the dispatch of VRE resources since their dispatch is dependent on weather. The hourly dispatch modeled by these VRE shapes were derived from historic locational wind and solar potential and the energy conversion characteristics of the VRE resources being modeled obtained from NREL [8].

Since VRE resource are treated as price takers in a PCM, their mix had to be iteratively adjusted outside of the PCM using sensitivity simulations until optimally balanced resource portfolio mixes at the desired clean energy levels were obtained. To get these balanced resource portfolio mixes, the following steps were performed.

1. Start with a clean energy portfolio that most closely represents one of the desired clean energy levels. The starting portfolio mix was derived from the NREL low renewable energy cost and battery cost standard scenario [11].
2. Run the portfolio using the PCM over a 14-day seasonal heavy load period and note the clean energy level.
3. Adjust the available capacities of the candidate renewable resources and repeat Step 2 until the desired clean energy level is reached.
4. Run the resource mix from Step 3 for heavy and light load conditions for each season of the year and note the clean energy levels.
5. Adjust the available capacities of the candidate renewable resources and repeat Step 4 until an optimally balanced mix at the desired clean energy level is reached for all seasonal load levels.
6. Run the portfolio for a full-year simulation and note the clean energy level.
7. Adjust the available capacities of the candidate renewable resources and repeat Step 6 until an optimally balanced mix at the desired clean energy level is reached for a full-year simulation.
8. Run additional sensitivity simulations on the resource portfolios based on earlier findings (e.g., DPS load shifting, increases and decreases in ECF resources).

Study Limitations

The following are limitations to the assumptions, methods, models, and data used to perform these studies:

- Only two variations of high electrification load levels were examined in the sensitivities: 1) no resource flexibility from electric vehicle storage, 2) resource flexibility available from electric vehicle storage. [6]

- A production cost model (PCM) was the primary tool used in the study. On average, it would take the PCM a day to complete an hourly simulation for a full year. In this regard, it was not practical to run numerous full-year simulations. Instead, sensitivities simulating different 12-day seasonal heavy and light load conditions were performed as first passes to find balanced resource portfolio mixes at different clean energy levels. Full-year simulations were then run on these first-pass portfolio mixes to further refine the resource balances.
- PCM tools are designed to represent and simulate current market structures and operational practices of the BPS. Market structures and operational practices will likely have to adapt to the challenges and uncertainties introduced by high electrification and high renewable penetrations to achieve a 100% clean energy future. PCM tools will also have to be adapted to represent any changes to market structures. The PCM used in this study was GridView. The results of this study are constrained to the design constructs of GridView based on current market structures and operational practices that are common in the West and across the U.S. It does not represent possible adaptive future market structure strategies that may manifest. In this regard, the findings of this study may be overly conservative in that new structures and practices may emerge that may enhance operational flexibility.
- Not all clean energy technologies were explicitly modeled as new candidate resource additions in the study. Only the more prevalently deployed, such VRE, BESS, biopower, geothermal, and nuclear resources were explicitly modeled as new candidate resource additions. ECF candidate resources were added as a proxy to provide resource flexibility at higher clean energy levels that would otherwise be provided by displaced gas-fired resources.
- No attempt was made to optimally site candidate resource additions to explicitly represent optimal points of interconnection, nor to avoid possible congestion. Candidate resource additions were modeled as aggregate resources at state and province levels, and their generation capacities were distributed to the Balancing Authority (BA) modeled in the PCM using distribution factors proportional to the load share of each BA to that of the total state or province. The PCM logic further distributed the BA aggregate generation to bus nodes in the BA using bus load distribution factors. While this method does not provide an optimum siting of new generation resources, it does provide a degree of optimality in the distribution of new aggregate generation.
- While transmission congestion was modeled as a constraint in the PCM, transmission expansion alternatives were not co-optimized with resource additions.
- The treatment of clean energy alternatives on the DPS was limited due to a lack of accurate representations of DPS alternatives. DPS alternatives that were modeled included distributed generation (DG).

Tool Limitations

Finding an optimal portfolio mix of resources at various clean energy levels is not easy, especially given the analytical tools available today. The two tools often used to perform the type of analysis in this study are PCMs and resource capital expansion models (RCEM).

PCM tools are designed to represent real-world, day-ahead commitment and hourly dispatch of resources while minimizing production cost and enforcing security constraints. PCM tools are not designed to find an optimal portfolio mix (e.g., optimal resource expansion) at various clean energy levels. RCEM tools are designed to minimize investment costs while finding optimal resource portfolio mixes subject to a set of underlying assumptions, goals, and constraints. RCEM tools are not, however, designed to simulate the day-ahead commitment and hourly dispatch of resources. A portfolio mix created by an RCEM is what is often presented to a PCM. While RCEM tools and PCM tools are very useful stand-alone tools, they have their limitations. The generation resource capital expansion ensembles created by RCEM tools are often used to construct PCM cases for study from a production cost standpoint. Results from RCEM tools are not as quantitative as those from PCM tools in that RCEM tools usually simulate conditions at seasonal heavy and light load granularities, whereas PCM tools simulate conditions at hourly granularities. because of this, an iterative process of using RCEM and PCM tools in combination is sometimes used in which results from the PCM are fed back into the inputs of a RCEM to arrive at more refined results from both tools. While there are useful benefits in using RCEM tools and PCM tools in combination, a drawback is that it doesn't yield a co-optimized solution and is time consuming if an iterative approach is used.

Another challenge is that of co-optimizing a transmission capital expansion model (TCEM) with RCEM tools and PCM tools. TCEM tools are designed to minimize investment costs while finding optimal transmission expansion plans subject to a set of underlying assumptions, goals, and constraints. As with RCEM tools, while TCEM tools are useful stand-alone tools, their solutions are not co-optimized with RCEM tools or PCM tools. Tools that co-optimize generation and transmission expansions are needed. In this study, there were occurrences of unserved load at the 100% clean energy level due to congestions. A tool that can optimally locate new generation resources and quantify the trade-offs between generation resource expansions and transmission expansions through co-optimization will greatly improve the analytical capabilities of assessing the challenges and opportunities of achieving a 100% clean energy future. To this end, WECC has been collaborating with Dr. Benjamin Hobbs of Johns Hopkins University to support his work in the development of the Johns Hopkins Stochastic Multi-Stage Integrated Network Expansion (JHSMINE) tool [12].

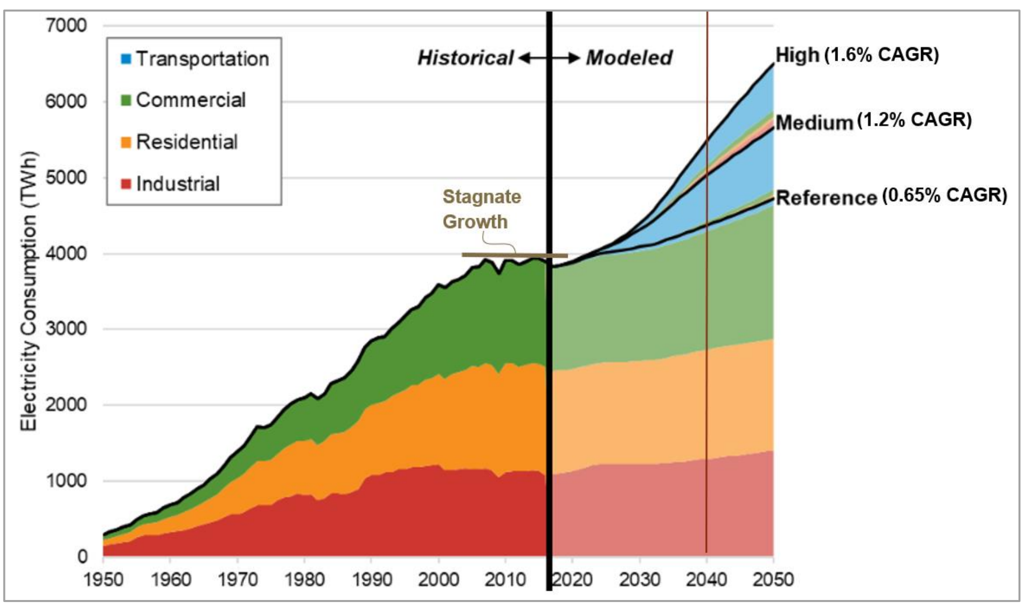
Findings and Conclusions

While it is feasible to achieve a 100% clean energy future, there are still many challenges and uncertainties that need to be better understood and resolved. Over 200 14-day diurnal and six full-year sensitivity simulations were performed and analyzed to better understand the promise of achieving 80%, 90% and 100% clean energy levels, to uncover hidden challenges, and to explore possible solutions to address those challenges.

The primary tool used in the study was a PCM and a primary goal of the sensitivities was to find optimal resource portfolio mixes at 80%, 90%, and 100% clean energy levels in which unserved load, curtailments, and CO_2 emissions were minimized and in which there were no security violations (e.g., overloaded transmission lines).

The Electrification Challenge

By 2040, the demand growth for electricity has the potential to increase significantly as seen in the NREL EFS [6]. According to the EFS, the compound annual growth rate (CAGR) could be as high as 1.6% for the high electrification case (high consumer adoption, rapid technology advancement) as compared to a fairly stagnant growth rate over the last decade as depicted in Figure 2 from the EFS study. As Figure 2 shows, most electrification growth is expected to come from the transportation sector. The transportation sector currently accounts for less than 1% of electricity demand but accounts for nearly 30% of total energy consumption in the U.S. [6]. Widespread adoption of electric vehicles and a transition toward clean energy will greatly transform the energy requirements of the BPS in the West. These CAGRs may be conservative estimates since current trends toward vehicle electrification have rapidly increased since 2018 when the EFS demand-side study was published. The EFS high electrification demand-side load model was used in this study and was viewed by the SWG to be more likely than the more conservative EFS demand-side models given current trends toward electrification. The SWG viewed it as being a better test to uncover the challenges that may be encountered as the BPS transitions toward higher levels of clean energy.



[6]

Figure 2: EFS—Electricity consumption growth potential

Most of the electrification load growth demand is concentrated around evening peak periods leading to more exaggerated diurnal load demand shapes. The gaps between load at peak demand hours and at light demand hours are more pronounced in the 2040 cases with high electrification as compared to that of the 2030 ADS. With additional charging demands from BESS, these gaps become even more pronounced as shown in Figure 3, in which served load (demand minus unserved load) is compared with and without charging for the 2030 ADS and the 2040 clean energy cases.

As Figure 3 shows, the difference between load demand and load demand plus charging is negligible for the 2030 ADS case since there is little storage in the 2030 ADS relative to load. Conversely, there is a significant difference for the 2040 cases since a great deal of storage was modeled, increasing the amount of additional generation resources required for charging by as much as 25% (275,000 MW) over the 2040 load demand (220,000 MW).

While there are no occurrences of unserved load in the 80% clean energy case, there are occurrences in the 100% clean energy case. As Figure 3 reveals, the occurrences of unserved load coincide at shoulder hours (as shown by the dashed vertical light blue and orange lines) in which there is not enough resource flexibility to satisfy the increased ramping requirements of increased electrification, further exacerbated by increases in resource variability from VRE additions, charging demand from BESS additions, and displacements of gas-fired generation that would otherwise supply resource flexibility. It is important to note that unserved load occurs both as load ramps up and ramps down due primarily to the misalignment of VRE hourly dispatch with load demand and transmission congestion.

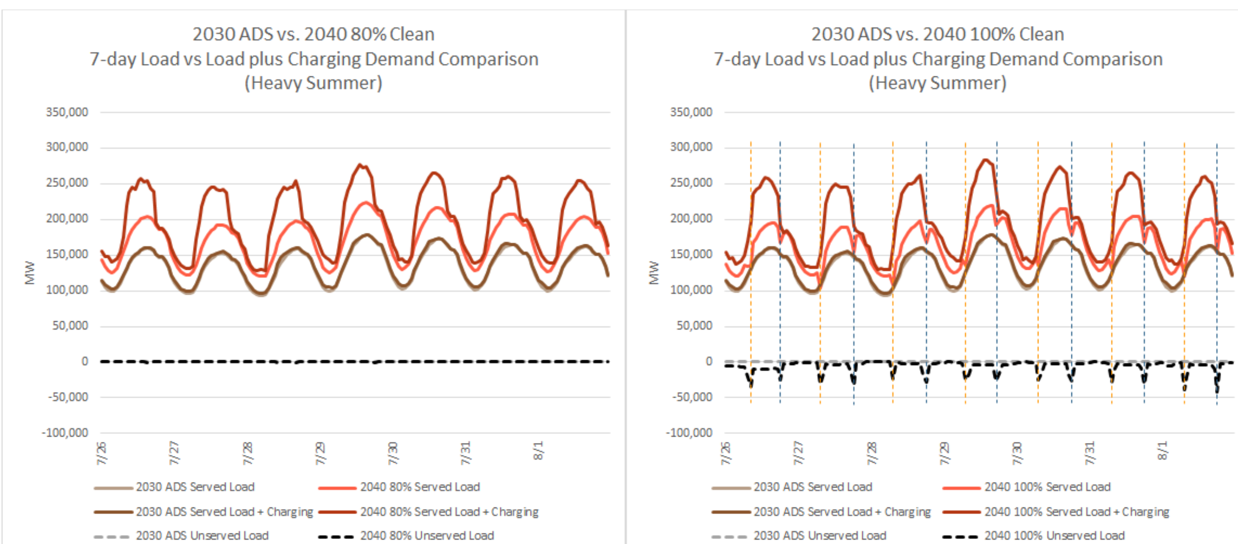


Figure 3: 2030 vs. 2040 load vs. load plus charging comparison

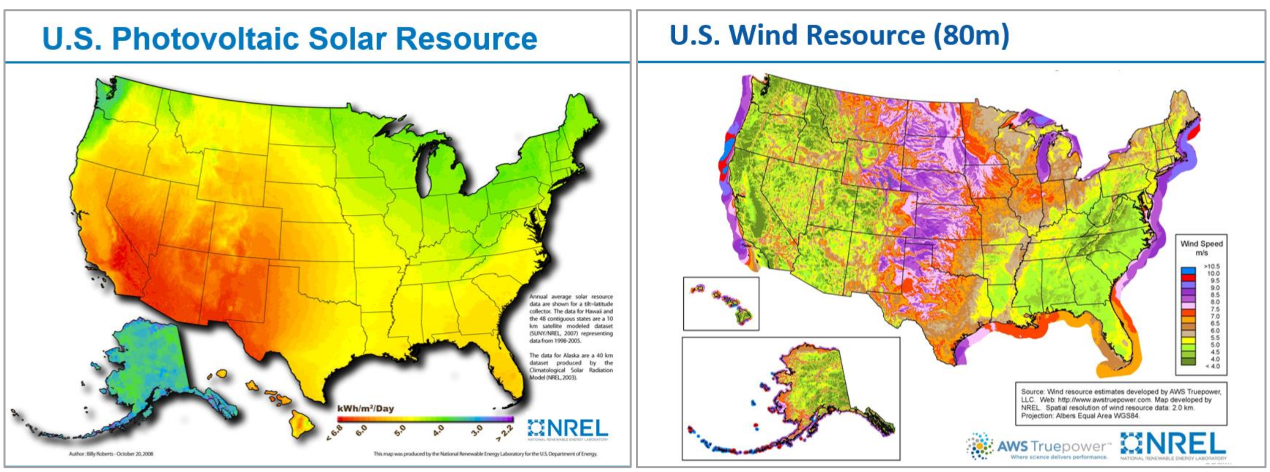
VRE Resources—Benefits and Challenges

The West has abundant renewable energy potential, especially from solar and wind. The annual energy potential from solar is estimated by NREL to be roughly 400,000 TWh (69,000 GW capacity) and over

15,000 TWh (4,600 GW capacity) for wind [8]. These energy potentials in the West are astounding, especially when compared to the annual system load energy requirement for the ADS of roughly 33 TWh (178 GW peak load) and 40 TWh (220 GW peak load) for the 2040 Clean Energy Sensitivities. Another advantage of the renewable energy potential in the west is its geographic diversity. With geographic diversity there is less dependence on one location for renewable energy supply and less risk should weather conditions limit the energy production from any given location if renewable energy production from other areas are not similarly affected.

Solar offers the greatest renewable energy potential in the West, as these numbers suggest and as depicted in Figure 4. While the renewable potential from wind is much less than that from solar, it is still abundant when compared to the expected load requirements. The energy potential from offshore wind is especially promising.

Another important benefit offered by renewable energy resources in the West is geographic diversity. The renewable potential in the West is spread across a large geographic area which helps to minimize the variability of VRE resources at a system level. For instance, if energy production from solar in California were to drop-off because of weather changes, energy production from solar and wind in the rest of the West may still be nominal and so the net effect is much less than if renewable energy production in the West were concentrated in a much smaller geographic footprint.



[8]

Figure 4: U.S. solar and wind resource potential

Despite having so much renewable energy potential in the West, there are challenges to overcome to take advantage of this potential:

- Solar and wind are examples of VRE resources because their energy production is dependent on weather conditions. Current market structures in the West treat VRE resources as price takers because they will always make money because their operating costs are usually less than their average LMP unless congestion or curtailments drive their LMP negative. With few exceptions, VRE resources are always committed and their dispatch depends on weather. Their effective load-carrying capabilities (ELCC) are low, however, since their weather-dependent hourly dispatch is variable, hard to predict, and not aligned well with hourly peak demand. This variability makes the operation of the BPS more challenging at high penetrations of VRE resources.

- Resource flexibility is currently provided to the BPS primarily by gas-fired resources. In the approach to a 100% clean energy level, gas-fired resources will be displaced, and resource variability will increase with higher penetrations of VRE resources such as wind and solar. Lost resource flexibility that would otherwise be provided by gas-fired resources will have to be replaced by some other clean energy source, especially as resource variability and ramping requirements increase due to higher penetrations of VRE resources. Resource flexibility will be a cornerstone to achieving a 100% clean energy future.
- There VRE resources in the West currently offer little resource flexibility when fully dispatched. VRE resources can, however, provide resource flexibility if they maintain a level of headroom in which some of their energy production capability is held in reserve, but at a lost opportunity cost. Without incentives or specific requirements, resource flexibility provided by VRE resources will be unreliable.
- Hourly energy production patterns of VRE resources do not align well with hourly load demand patterns, which results in daily periods in which there may be excesses or deficits of generation relative to hourly load demand. In particular, the sharp rises and falls in energy production from solar greatly increase the need for additional resource flexibility.
- At a 100% clean energy level, transmission constraints became an issue, primarily on transmission paths exporting energy from regions rich in VRE potential to areas poor in VRE potential. While this study did not address the challenge of interconnecting VRE resources to the BPS on a subregional level, the SWG felt that it was an important consideration to note since it takes many years to for new transmission to be planned, sited, approved, and built.

The Net Demand Ramp Dilemma

Because energy production from VRE resources does not align with load demand patterns, the risk of unserved load and curtailments increases with their use. The risks can be better understood by the use of a net demand ramp chart. This chart shows the timing imbalance between hourly demand with and without offset dispatch adjustments from VRE resources. The chart is constructed by subtracting the hourly dispatch of VRE resources from hourly demand. The resulting adjusted demand must be served by resources other than VRE. Figure 5 compares heavy summer load levels and light autumn load levels for the 2030 ADS and the 2040 sensitivity cases at 80%, 90%, and 100% clean energy levels using net demand ramp charts.

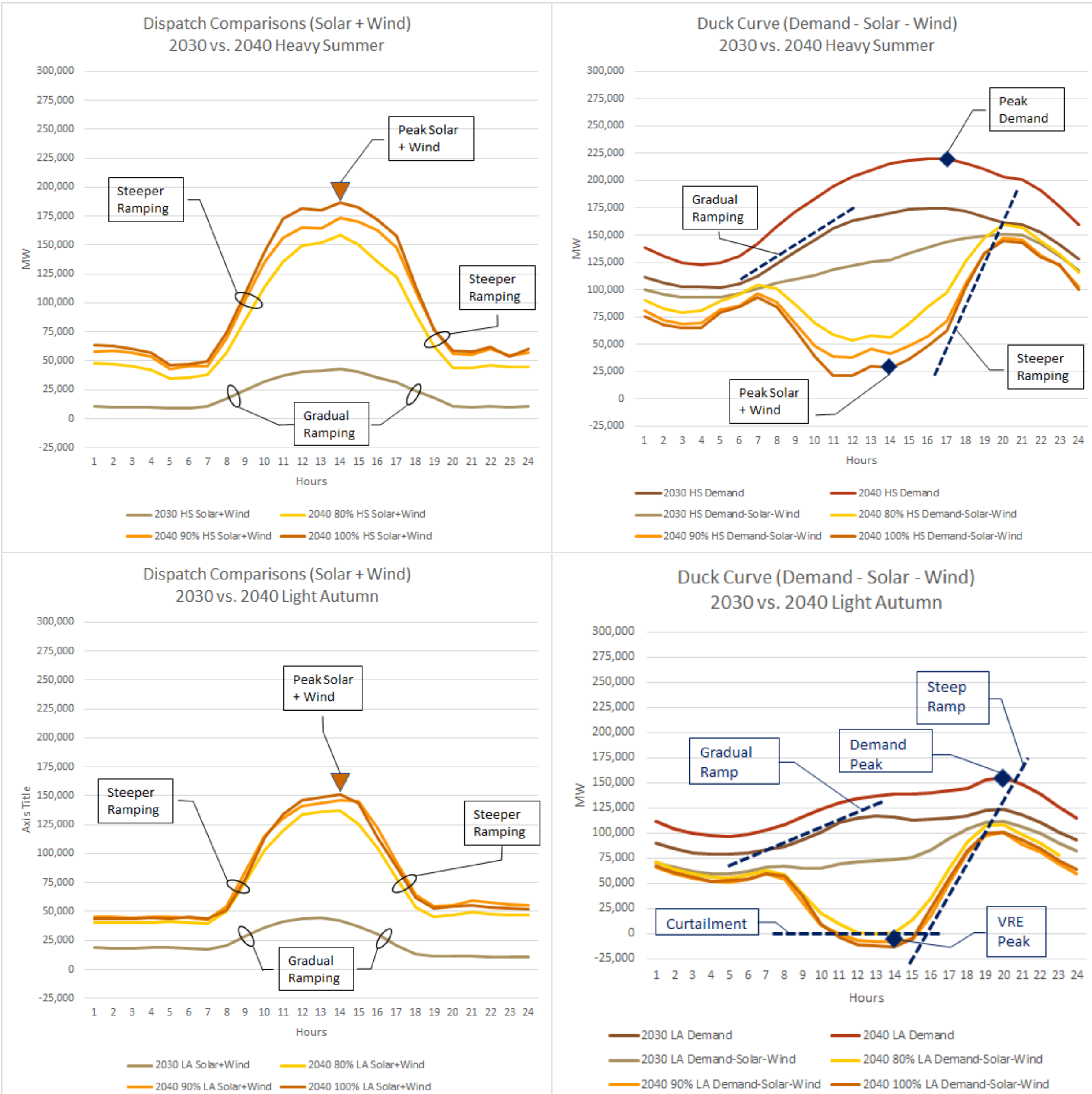


Figure 5: 2030 vs. 2040 net demand ramp comparisons

These charts reveal many risks and observations:

- The risk of excess generation and curtailment is greater during seasonal light load conditions than heavy load conditions for a number of reasons. Peak generation capacities from VRE resources in the 2040 clean energy cases range between 159 GW and 187 GW during heavy summer, and range between 92 GW and 106 GW for light autumn, while peak generation capacity from VRE resources in the 2030 ADS case range between 43 GW and 45 GW for light autumn and heavy summer, respectively. The maximum dispatch of VRE resources as a percentage of the total resource stack for the 2030 ADS ranges from 36% to 25% for light autumn and heavy summer, respectively, while that for the 2040 clean energy cases ranges from

97% to 85%. These percentages are much higher at light autumn than at heavy summer. The reason for this is that the drop in the light autumn load requirement relative to that of heavy summer is proportionally much greater than the differences between the energy production from VRE resources at heavy summer and light autumn.

- An optimally balanced VRE resource portfolio must have adequate resource flexibility to perform well at all seasonal load levels, which is not a trivial proposition and often more constrained by seasonal light load levels than by seasonal heavy load levels. Without specific rules that limit this percentage of VRE resources in the resource stack, operational challenges at seasonal light load levels may be more difficult than at heavy load levels. Compared to the changes in load between light autumn and heavy summer, the changes in energy production from VRE resources are small. During light autumn, there are fewer non-VRE resources that need to be committed and dispatch beyond the price-taking VRE resources that are always committed and dispatched. The result is that the percentages of VRE resources committed and dispatched to that of the total resource stack will be higher at light load levels than at heavy load levels, unless specific rules are in place to commit non-VRE resources for essential reliability services like resource flexibility.
- The hourly misalignment between energy production from VRE resource and load demand will require storage as a complementary resource to wind and especially to solar to shift hourly power supply to better align with hourly demand. In the absence of adequate storage, it will not be feasible for VRE resources to efficiently serve load unless hourly demand were to shift three to six hours in alignment with VRE resources, or if excessive curtailments were allowed, or both. During heavy summer, VRE resources peak at 2:00 p.m. MDT, while load demand peaks at 5:00 p.m. This represents a three-hour difference in peak alignments between VRE resources versus load demand at heavy summer. During light autumn conditions, VRE resources also peak at 2:00 p.m., while load peaks at 8:00 p.m. This represents a six-hour difference in peak alignments between VRE resources and load demand during light autumn conditions. This further illustrates that the risk of curtailment is greater in seasonal light load levels because the misalignment is greater.
- With increases in VRE resources, the duck bellies of the 2040 clean energy cases increase, as does the risk of curtailments and the number of hours that are exposed to that risk. VRE resources provide little value during periods of excess generation. Since VRE resources are usually committed and dispatched as price takers, their dispatch is not available for regulation to balance energy supply with demand. During periods of excess generation where the capabilities of regulating resources (e.g., gas-fired) to balance energy supply and demand have been exhausted, negative LMPs occur when curtailments occur. VRE resources get curtailed when LMPs turn negative since the downward regulating limits of regulating resources have already been exhausted and the only option left to balance energy supply and demand is to curtail VRE resources. This condition is illustrated by the duck curve where at the belly of the

duck there is abundant generation when hourly load demand is low. While the belly of the duck curve for the 2030 ADS looks trim, the bellies of the duck curves for the 2040 clean energy cases look overweight due to excess wind and solar generation at low load demand hours.

- At higher levels of wind and solar, the ramping and regulation requirements significantly increase as well, primarily during the shoulder hours when load and generation go up and down. As Figure 5 shows, the maximum ramping requirement for the ADS is roughly 10,000 MWh, while the maximum ramping requirements for the 2040 sensitivity cases are roughly 25,000 MWh. As more VRE resources are added, the resource variability and ramping requirements increase dramatically while fossil-fired resources that provide resource flexibility (primarily gas-fired) are displaced. When unserved load occurred in the sensitivity simulations, it usually occurred during the shoulder hours when ramping requirements were most challenging, particularly the shoulder hours when solar would abruptly drop off and peak demand would remain high.

The Promise and Challenges of Battery Storage

Storage will be required to compensate for the misalignment of hourly dispatches from VRE resources and hourly demand. BESS seem to be the most prevalent of the new energy storage systems being deployed, but other storage technologies such as compressed air energy storage (CAES) are also being deployed, and other, newer storage technologies are also emerging (see Technologies Advancement in the Appendix). For this study, new candidate storage resource additions were modeled as 12-hour BESS.

The benefits of BESS include:

- The costs of BESS have decreased nearly 70% between 2015 and 2018 according to the U.S. Energy Information Administration [13]. This trend is expected to continue with technology advances and economies of scale [14].
- Energy shifting where BESS can recharge when energy production from solar is at its peak, when load is low, and when the risk of curtailment is at its highest. In this regard, BESS can minimize the risks of curtailments. BESS can be dispatched when solar drops off, when load is high, and when the risk of unserved energy is at its highest.
- BESS can replace some of the lost resource flexibility that would otherwise be provided by displaced gas-fired resources.
- BESS can provide operating reserves and ancillary services.
- BESS can offset the need for new transmission expansions through strategic siting.
- BESS can provide blackstart capabilities.

The challenges of BESS include:

- Generally of short duration, although promising research into long-duration BESS is underway.

- Charge diminishes over time.
- Generation capability diminishes by extreme cold weather conditions.
- Lack of rules and clarity about the use of BESS (e.g., reserves, inertia, reactive support).

Despite the synergies between BESS and solar, an operational limit was reached at clean energy levels above 90%, at which point resource additions consisted only of solar, wind, and BESS. This operational limit was due to several factors:

- At higher levels of clean energy in which additions of solar, wind, and BESS increase, thermal resources capable of providing resource flexibility, such as gas-fired, are displaced leaving only BESS to provide resource flexibility in the absence of another clean energy resource capable of supplying resource flexibility.
- Ramping requirements increase as more VRE resources are added.
- While more additions of BESS increase resource flexibility, they also increase the need for more VRE resources additions and, in the absence of some other clean energy resource type that can provide energy for BESS charging, further exacerbate the ramping requirements and the need for more resource flexibility. Because of this relational dynamic, the study suggests that additions of BESS alone will not be enough to meet the required resource flexibility at clean energy levels above 90%.

Curtailments also increase with increases in VRE resources, especially during seasonal light load levels due to several factors:

- At very high penetrations of VRE resources, the number of hours available to dispatch BESS diminishes to a point at which curtailments occurred at all hours of the day, especially at light load days.
- With curtailments occurring at all hours of the day, there are plenty of hours for BESS to be charged, but no hours to be dispatched. Under these conditions, very little charging of BESS took place after an initial charge, since the energy from an initial charge could not be dispatched, negating the need for future charging. As a result, the ability of BESS to minimize curtailments is negated.

VRE Resource Saturation

As the additions of solar, wind, and BESS were increased in the PCM progression from 80% to 100% clean energy levels, a saturation of VRE resources was reached at 90% clean energy level in which curtailments became excessive and occurred at all hours of the day. While there are plenty of hours that storage can be charged under these conditions, there are no hours that storage can be dispatched by the PCM results where only BESS and VRE resources were added to reach higher clean energy levels.

The progression from 80% to 90% clean energy levels in which saturation occurred (90% saturation case) is illustrated by the diurnal heavy summer dispatches presented in Figure 6. The last chart in

Figure 6 presents 7-day snapshot results in which ECF resources were introduced at a 90% clean energy level. With only 9% of ECF resources added to the 90% clean energy saturation case, curtailments were reduced from 54% to only 3%, which is within the 3% average annual curtailment rates for wind and solar in the U.S. and California recorded in 2019 [15] [16].

Figure 6: VRE resource saturation with high curtailments

Figure 6 also reveals that gas-fired generation is being dispatched at all hours of the day in response to congestion and ramping requirements despite curtailments occurring at all hours of the day as well for the 90% saturation case. This observation further illustrates the need for resource flexibility from gas-fired resources or some other non-charging resource type with similar performance characteristics as gas-fired generation resources. The high level of curtailments that occurred in the 90% saturation case were due to the occurrence of congestion at higher penetrations of VRE resources in addition to the hourly misalignment of VRE resources to load where the PCM is having to curtail VRE resources and dispatch gas-fired generation resources to where congestion is occurring. The average LMP for the saturation case was -$1.50/MWh. While this LMP is negative, there were other sensitivity cases at lower levels of clean energy and lower levels of curtailment, but with much lower LMPs (e.g., -$800/MWh). As curtailments went up, the average LMPs went down. As more congestion was encountered, the average LMPs would go up. At lower levels of VRE penetrations, curtailments are more influential in driving LMPs down because less congestion is occurring. At higher VRE penetrations, congestion becomes more influential in driving LMPs, acting as a counterbalance to curtailment.

When curtailments occur, LMPs become negative, diminishing the values of solar, wind, and BESS. In the 90% saturation case with solar, wind, and BESS resource additions only, curtailments and occurrences of unserved load were excessive, especially at light load conditions where fewer gas-fired resources were committed by the PCM.

There are three dashed lines in the charts presented in Figure 6, which represent curtailment, load demand, and load demand plus charging from storage, including from BESS and pumped hydro resources. The gap between the “Load + Charging” line and the “Load Demand” line represents the dispatch beyond serving load that is required for charging. As the progression toward a 90% clean energy level continues, and, while the load demand remains constant, the charging requirement increases as more BESS are added. As more BESS are added to reach a 90% clean energy level, an additional 80 GW of dispatch from VRE resources was required beyond the 220 GW of load demand to charge the BESS additions for a total dispatch requirement of 300 GW which is 122 GW more than the 178,000 GW load requirement of the 2030 ADS.

It would be intuitive to think if the amount of VRE resources is decreased and the amount of BESS is increased, the curtailments and the amount of gas-fired generation dispatched should decrease. A sensitivity case was created to test this hypothesis, and the result was that, while curtailments did go down, dispatch of gas-fired generation went up to meet the increased charging demand from BESS and to compensate for the reduction in wind and solar that would otherwise be available for charging. While the PCM discards excess VRE dispatch (curtailment) beyond what is needed to balance supply with load plus charging, it still had to dispatch gas-fired generation to meet the requirements of resource flexibility and congestion redispatch.

A reasonably small percentage of ECF resources in the resource stack will go a long way to mitigate challenges that VRE resources introduce at higher levels of clean energy, namely variability, misalignment with load, ramping requirements, and congestion. As Figure 6 shows, the addition of only 10% of ECF resources were required to reduce curtailments to 3% as opposed to 54% curtailments with no ECF. Adding ECF resources to the resource stack gives the PCM more resource flexibility to optimally dispatch the clean flex resources where and when they are needed and reduces the amount of solar, wind, and BESS required. With more resource flexibility and less resource variability, the PCM can better optimize the overall generation dispatch to minimize curtailments and congestion. With less VRE resources in the resource stack, the ramping requirements are less severe while ramping capabilities are increased by the adding ECF resources. With less BESS in the stack, the load plus charging requirement is less, reducing the total generation requirement, which also helps to reduce the risks of congestion.

The PCM logic is designed around current market structures and, if the current market structures were to be redesigned to accommodate the challenges uncovered by these sensitivity results, higher levels of clean energy may be achievable. That determination will require continued research and tool development.

Balancing the Portfolio Mix

The criterion for finding an optimally balanced resource portfolio mix for the clean energy cases is that supply is balanced with demand (no unserved load) over various time scales (e.g., hourly, daily, seasonal, heavy and light load levels) while enforcing security constraints (e.g., no line overloads) and minimizing production costs, excessive curtailments, and generation resource additions. Early in the process of running the sensitivity simulations, we discovered that there are many challenges to finding optimally balanced solutions that satisfied this criterion, and the degree of difficulty increases as the desired levels of clean energy increase. Some of the challenges of finding an optimally balanced resource portfolio mix at higher levels of clean energy are:

1. There are infinite combinations of generation resource portfolio mixes that could satisfy any desired clean energy level. The challenge, however, is to find an optimal mix that balances energy supply with demand while minimizing curtailments and unserved load. As shown in Figure 7, both resource portfolios achieve an 90% clean energy level. The sub-optimal portfolio has several disadvantages relative to the optimal case, including:
   - More generation resource additions are required than for the optimal portfolio;
   - More CO_2 is produced when dispatches from gas-fired generation increase to satisfy increased resource flexibility requirements from a poorly balance resource portfolio as depicted by the sub-optimal case;
   - More curtailments occur when the amounts of VRE resources in the portfolio mix is not well balanced with the diurnal load demand;
   - The ramping requirements are more challenging with excessive amounts of VRE and BESS resources, further increasing the risk of unserved load;
   - At higher levels of generation, the risk of congestion is greater; and
   - The investment cost will be more with an excessive amount resources in a poorly balanced resource portfolio.

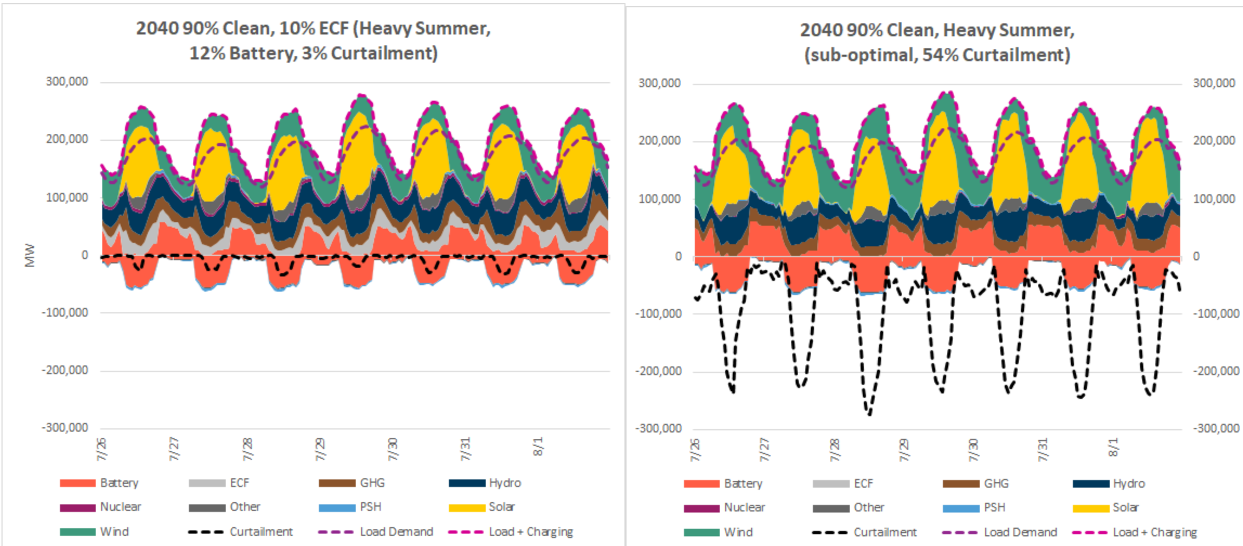


Figure 7: 2040 Optimal vs. sub-optimal portfolio balance (90% clean comparison)

2. Not surprisingly, in both portfolios depicted in Figure 7, when solar dispatch is highest, BESS are charging and when solar dispatch is lowest, BESS are being dispatched. Even more interesting is that dispatch from BESS seems to be greatest at shoulder hours when load demand is dropping off and picking up. This illustrates how the BESS are being dispatched by the PCM to meet the ramping and energy requirements that would otherwise be supplied by gas-fired generation resources.
3. The results of the study indicate that clean energy above 90% will not be achieved economically and efficiently without including additional ECF candidate resources. These ECF resources will need to have performance characteristics similar to those of displaced gas-fired generation resources (e.g., ramping, regulation, and inertia requirements). There are many promising clean energy technologies emerging that may provide the same performance characteristics as gas-fired generation resources. No one can predict what new clean energy technologies may emerge by 2040 or what their performance characteristics will be other than to assert that they will be needed to achieve high levels of clean energy. With the introduction of a new ECF resource type, a new constraint was added to the solution criterion to minimize the energy production from these ECF resources as much as possible for each of the target energy levels to determine the minimum amount of ECF resources required at each target. Figure 8 shows the percentage of ECF resources to total resource stack generation required to achieve balanced resource portfolio mixes for the 2040 clean energy cases.

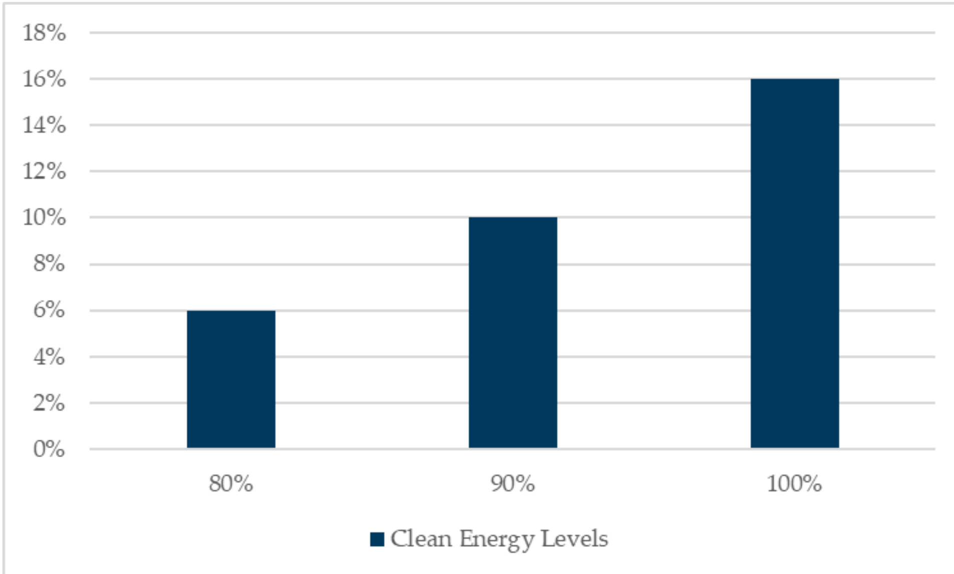
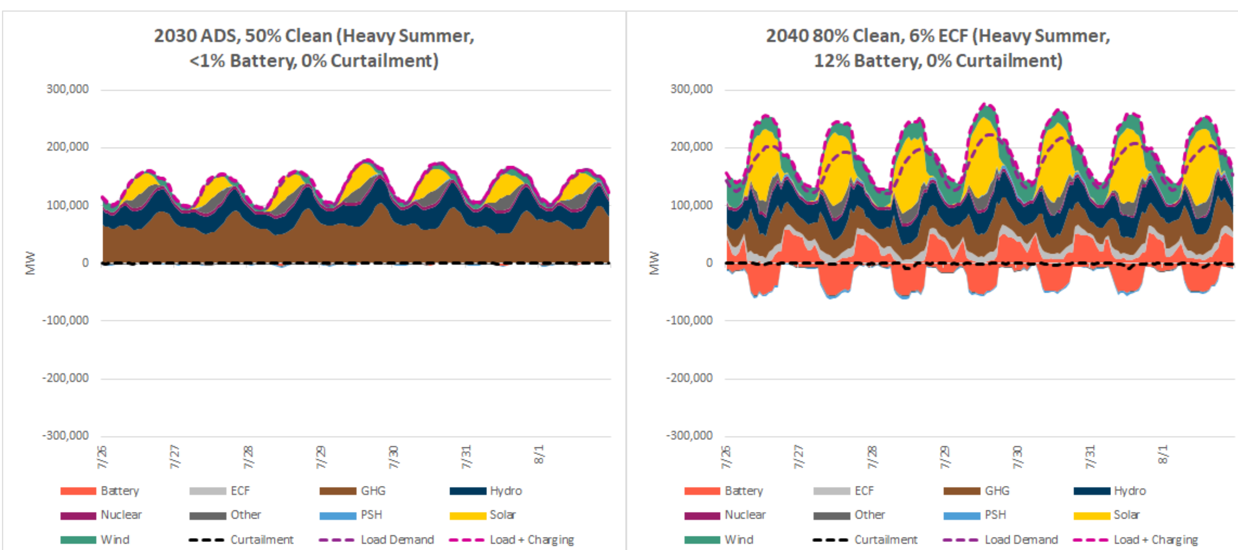


Figure 8: ECF percentages at clean energy levels

The challenge and complexities in the sensitivities to arrive at balanced resource portfolio mixes at various clean energy levels strongly suggests that coordination of planning efforts across research, policy, regulatory, market, industry, consumer, and environmental sectors will be essential to achieve these clean energy goals in an economic and equitable way that ensures the reliability of the West.

Case Comparisons

A progression of the diurnal dispatches for a heavy summer condition from the 2030 ADS to each of the 2040 clean energy levels by resource type. is shown in Figure 9.



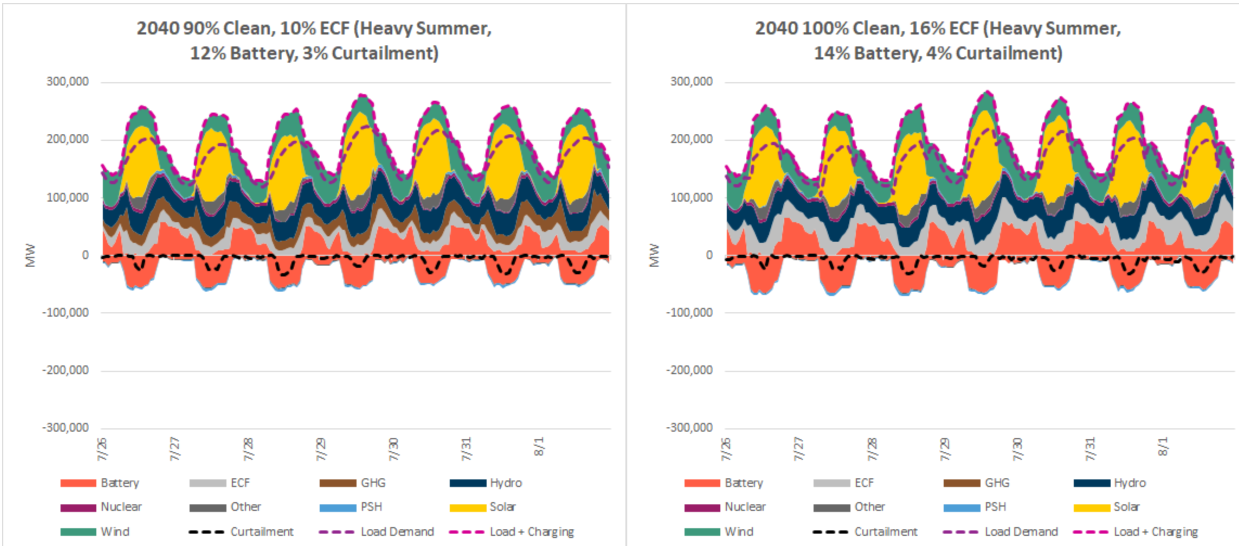


Figure 9: Clean energy progression comparison of diurnal dispatches

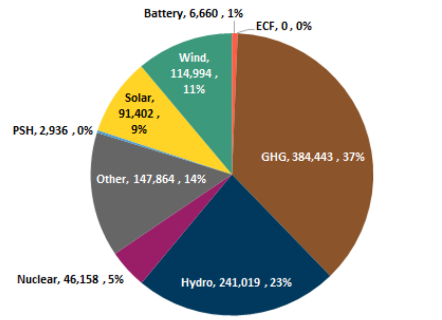
From the progression shown in Figure 9, the following is observed:

- Energy dispatch from VRE resources is misaligned from the hourly load requirement requiring BESS to be deployed to compensate for this misalignment by shifting energy from VRE resources as needed to balance hourly generation with load.
- The gap between light load hours and heavy load hours is much more pronounced in the 2040 clean energy cases than in the 2030 ADS case due to electrification and increased amounts of VRE resources additions. This gap greatly increases the ramping requirements during the shoulder hours. In the absence of adding more ECF resources, adding more batteries would require more VRE resources to be added which further exacerbates the ramping requirements.
- As additions of BESS were increased in the 2040 clean energy cases, the load plus charging peak MW load requirement approached 300,000 MW which is roughly 100,000 MW more than that of 2030 ADS.
- Charging of BESS is optimized by the PCM to charge when solar is highest and dispatch batteries when solar energy production drops off. BESS resource dispatch is highest during the shoulder hours of the day indicating that it is being used by the PCM to meet ramping requirements.
- Gas and ECF resources are being dispatched at all hours of the day by the PCM to help regulate the generation and load balance whereas the dispatch from solar and wind is variable according to fixed shapes representative of hourly solar and wind conditions. Solar and wind resources do not, in these simulations, provide regulation, although it's conceivable that they could at the risk of lost opportunity cost.

The system-level progressions of annual resource energy mixes and capacity mixes at various levels of clean energy from the 2030 ADS (50% clean energy level) to the 2040 clean energy cases (80%, 90%, and 100% clean energy levels) are shown in Figure 10.

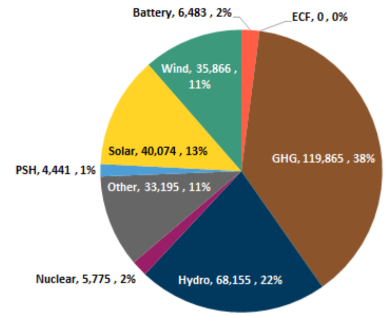
Energy (GWh)	Capacity (MW)

Energy Mix (GWh) by Gen Type – 2030 ADS, 50% Clean



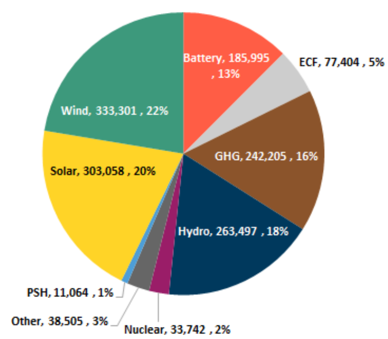
Total = 1,035,476 GWh

Capacity Mix (MW) by Gen Type – 2030 ADS, 50% Clean



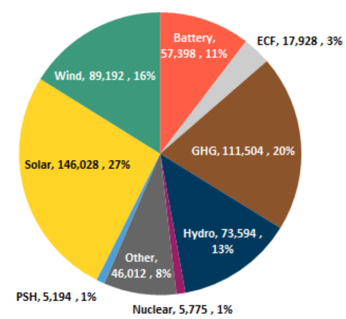
Total = 313,854 MW

Energy Mix (GWh) by Gen Type – 2040 80% Clean



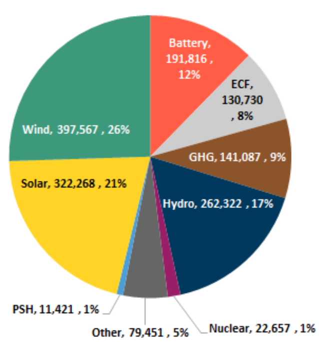
Total = 1,548,905 GWh

Capacity Mix (MW) by Gen Type – 2040 80% Clean



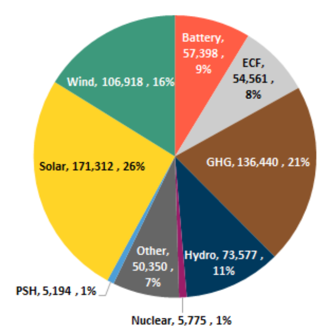
Total = 552,624 MW

Energy Mix (GWh) by Gen Type – 2040 90% Clean



Total = 1,559,318 GWh

Capacity Mix (MW) by Gen Type – 2040 90% Clean



WECC Total = 661,511 MW

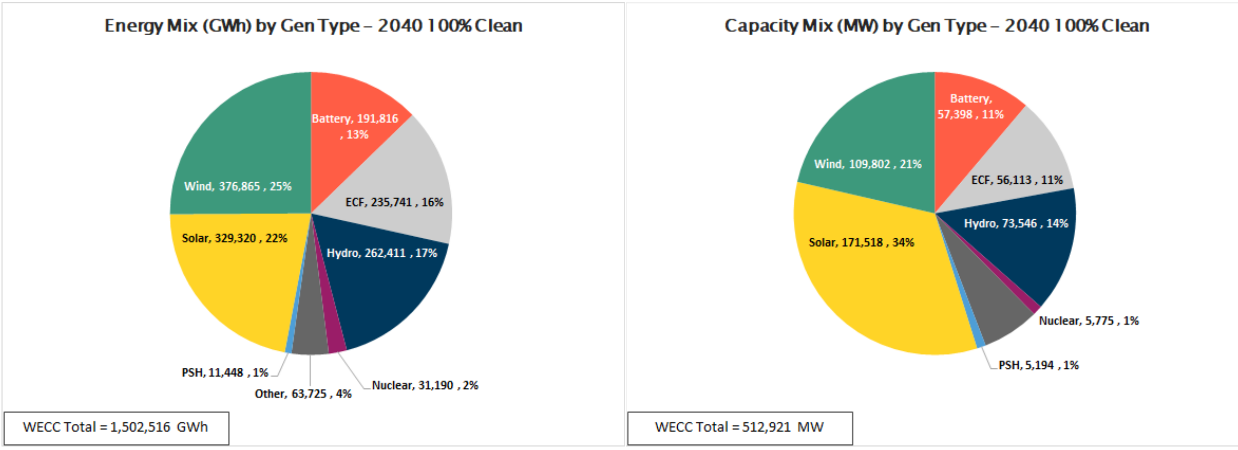


Figure 10: Clean energy progression comparison of system resource mix

The following is observed from Figure 10:

- The energy production in the 2040 clean energy cases was higher than that in the 2030 ADS case because load was higher, as was the charging requirement due to higher levels of BESS. While load demand in all the 2040 clean energy cases was the same, the net load plus charging requirements increase as more BESS are added.
- Energy production in each of the case results shown in Figure 10, is equal to load plus charging minus unserved load. Energy production at a 90% clean energy level was higher than at 80% clean energy level due to more BESS being added and no unserved load at either clean energy level. Energy production from a 100% clean energy level was less than both the 80% and 90% clean energy levels because significant congestion occurred resulting in unserved load reducing the total energy production.
- All CO_2-emitting resources were replaced in the 100% clean energy level by renewable resources. With that, higher levels of congestion occurred. Higher levels of congestion in the 100% clean energy level resulted in more unserved load and curtailments, primarily from wind, than what occurred in the 80% and 90% clean energy levels, resulting in less energy production as shown in Figure 11.

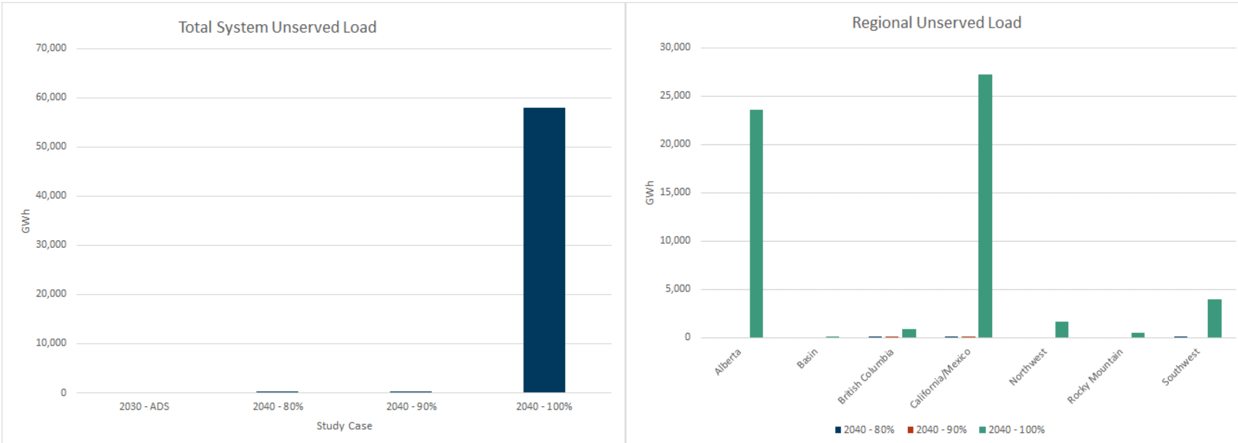


Figure 11: Unserved load comparison by clean energy levels

- Figure 11 shows that unserved load generally occurred in areas in which transmission interconnection capacity is relatively weak, and that the occurrence of unserved load was significant only in the 100% clean energy level. With optimized siting of new clean energy resources and transmission expansions, these results could improve, but collaborative coordination of planning efforts across all stakeholder groups and vested interests would be a challenge.
- All CO_2-emitting resources were entirely displaced in the 100% clean energy level. The lost resource flexibility that these displaced resources would otherwise have provided was replaced by BESS and ECF resources. The CO_2-emitting resources where being dispatched in the 80% and 90% clean energy levels for resource flexibility requirements rather than for energy resulting in very low capacity factors (CF), where a CF is a ratio of average energy production to maximum energy production capability. The CFs of the ECF resources were roughly 48% in the 100% clean energy level and 27% in the 90% clean energy level as compared to a 15% CF for CO_2-emitting resources in the 90% clean energy level. A modest increase in ECF capacity, along with a CF increase from 27% in the 90% clean energy level to 48% in the 100% clean energy level, was enough to replace the dispatch capacity from CO_2-emitting resources that were displaced, which led to a lower total resource portfolio capacity of 512,921 MW for the 100% clean energy level as compared to 620,872 MW for the 90% clean energy level.

Figure 12 provides a breakdown of generation resource type by clean energy level and a comparison of change relative to the 2030 ADS in terms of annual energy production.

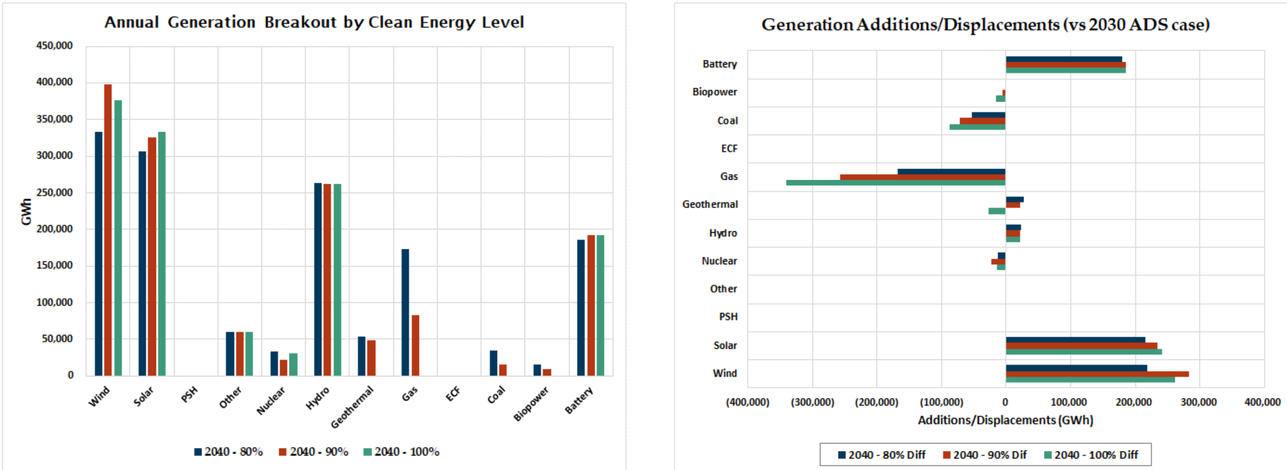
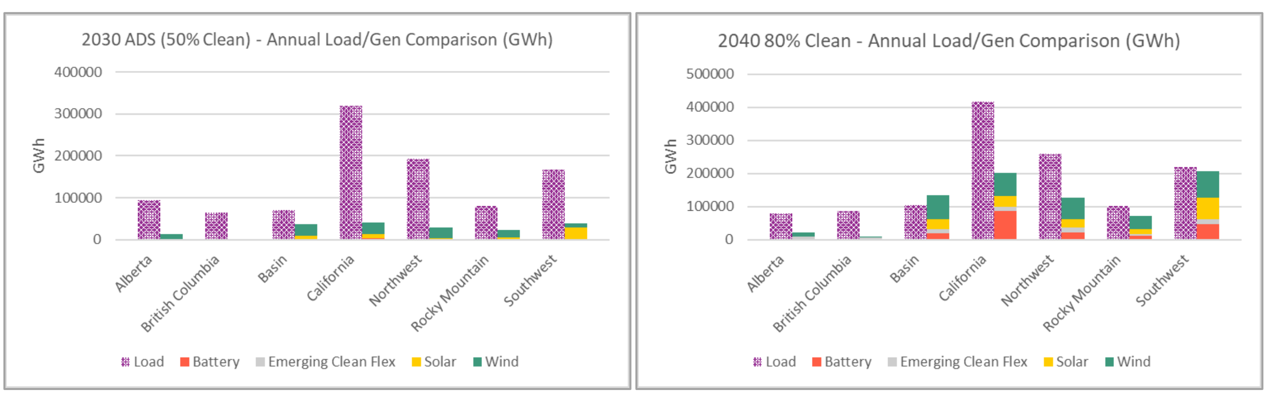


Figure 12: 2040 vs. 2030 annual generation by clean energy levels

As Figure 12 shows, most of the renewable energy comes from solar, wind, hydro, battery, and ECF resources. Most of the additions come from solar, wind, battery, and ECF resources. As discussed earlier, the additions of ECF resources increased non-linearly as the level of clean energy increased. Another surprising result was a slight decrease in energy production from nuclear, which suggests that nuclear units are also being dispatched to assist with downward resource flexibility. Energy production from wind is less for the 100% clean energy level relative to the 90% clean energy level because of curtailments from congestion.

Figure 13 shows the progression from the 2030 ADS to the 2040 clean energy cases of battery, ECF, solar, and wind by region. The focus of Figure 13 is on battery, ECF, solar, and wind renewable resource additions in the progression since they represented the primary renewable types added in the progression. As discussed in the Input Data section, the load requirements by state, in addition to renewable energy potential, were two of the main factors in the creation of the candidate resource portfolios by state.



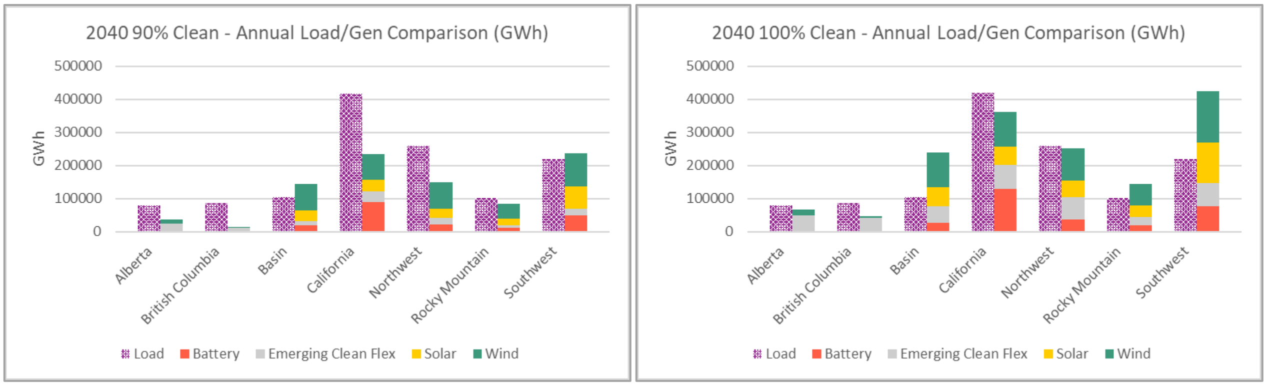


Figure 13: Clean energy progression comparison of annual renewable resource mix

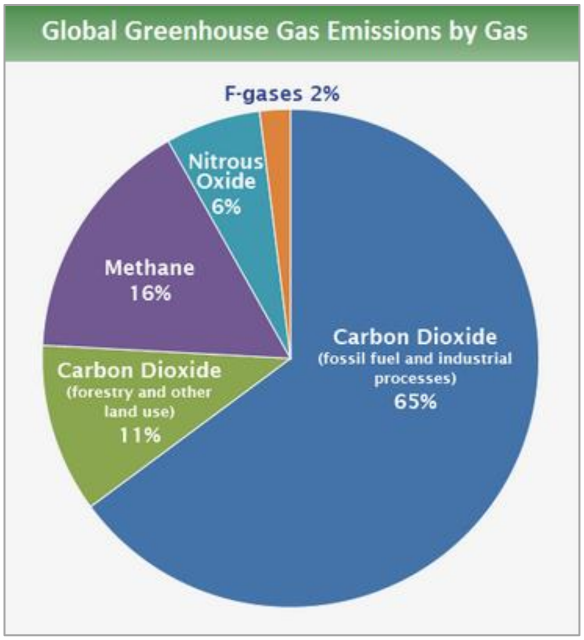
While load requirements and energy potentials were factors in determining how much new candidate renewable capacity to assign to each state, that capacity was only candidate capacity subject to the PCM commitment and dispatch goals and constraints.

The following observations from Figure 13 are noteworthy:

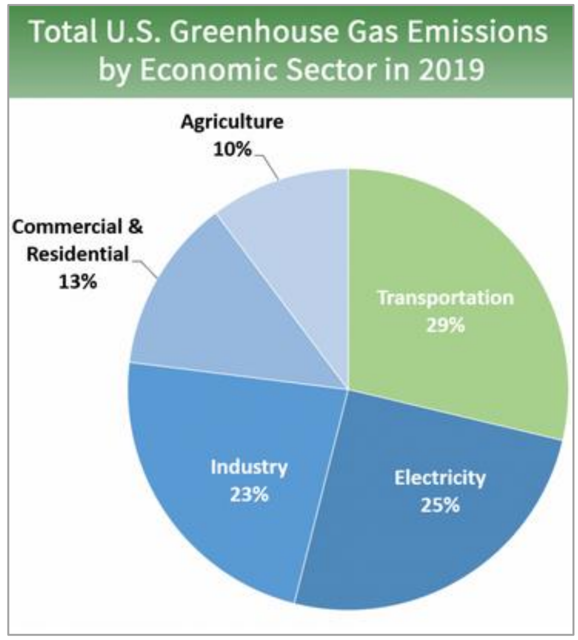
- Energy production from renewables steadily grows from a 50% clean energy level for the 2030 ADS to 80%, 90%, and 100% in the 2040 clean energy cases, with the biggest jump occurring between the 90% clean energy level and the 100% clean energy level. Much of the added renewables between the 90% clean energy level and the 100% clean energy level come from ECF resources.
- The PCM committed and dispatched a large share of BESS in California to meet resource flexibility and energy requirements. The load plus charging requirement will also be higher with more BESS deployed.
- The Southwest, Basin, and Rocky Mountain regions have an excess of renewable energy production relative to their load requirement.

CO_2 Emissions

Carbon dioxide makes up most of greenhouse gas case emissions [8] as shown in the first chart in Figure 14. According to the United States Environmental Protection Agency (EPA), 6,558 metric tons of CO_2 emissions were produced in 2019 [8]. As the second chart in Figure 14 shows, 25% of that comes from the electricity sector and 29% comes from the transportation sector. Given the accelerating trends toward the electrification of the transportation sector, there is great potential that much of the CO_2 emissions could be reduced if the electricity sector is able to meet the energy needs of a highly electrified transportation sector at higher levels of clean energy.



[17]



[18]

Figure 14: U.S. greenhouse gas emissions by gas and economic sector

CO_2 emissions are shown in Figure 15 for the 2030 ADS and each of the 2040 clean energy cases. The 2040 clean energy cases represent optimal mixes and the results shown in Figure 15 provide a good representation of how CO_2 emissions (tons CO_2/year) in the West might be reduced at higher levels of clean energy.

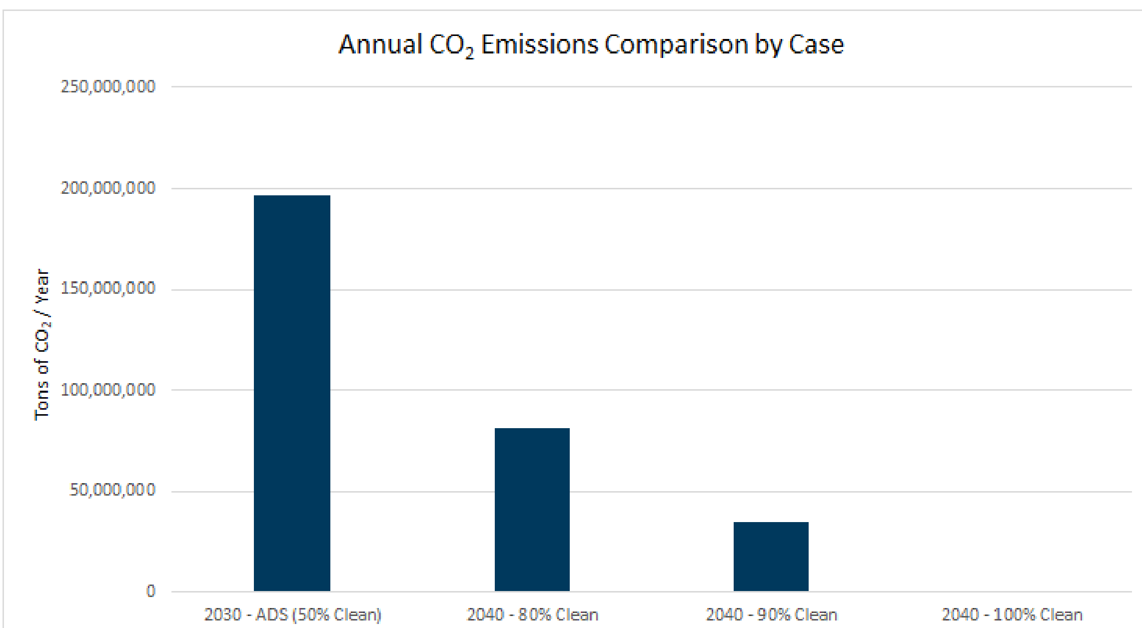


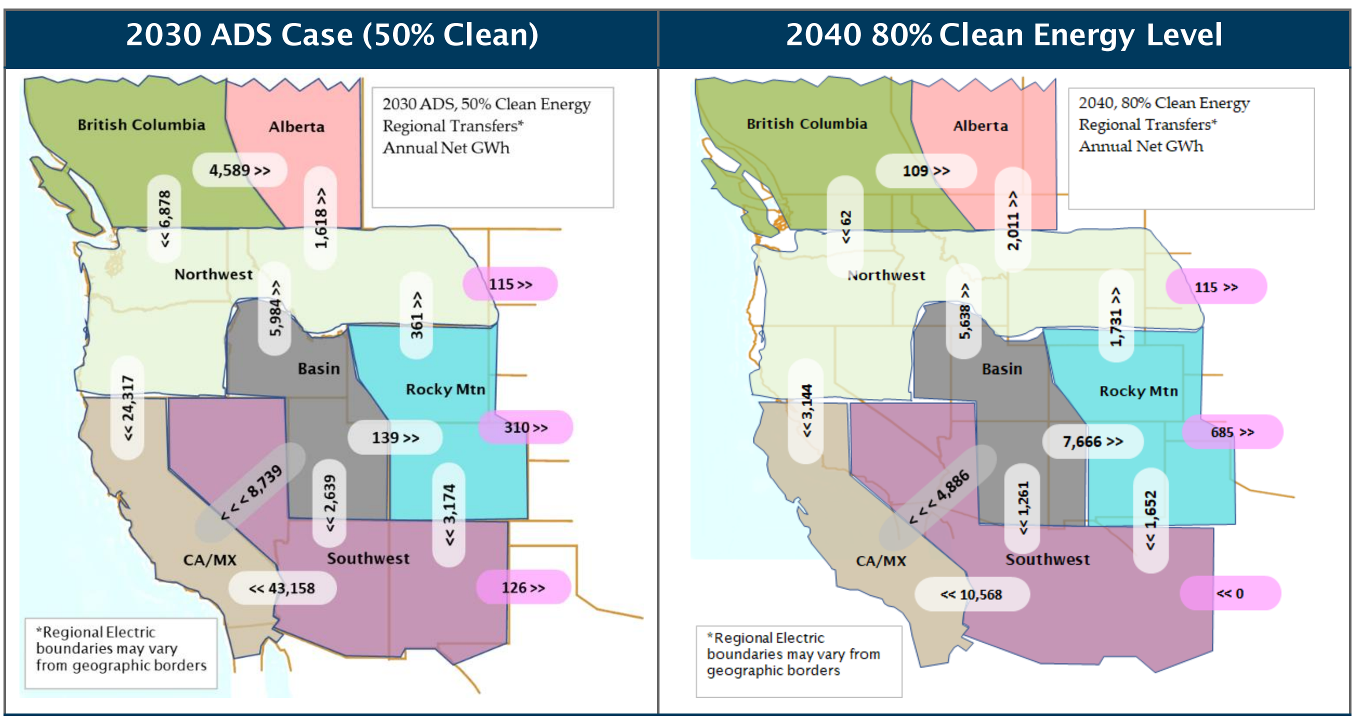
Figure 15: Annual CO_2 emissions by clean energy levels

CO_2 emissions can vary depending on how well-balanced the resource portfolio is, which is an important consideration when assessing reductions in emissions at higher levels of clean energy.

Transmission Inter-regional Interchanges and Path Utilizations

The progression of annual transmission energy transfers is shown in Figure 16. From Figure 16, we learn:

- Total imports into California in the 80% clean energy level scenario have reduced significantly (~75.6%) when compared to the ADS 2030 because of an instate increase of solar, wind, and BESS.
- Interchange energy imports into California increase for the 90% and 100% clean energy levels, primarily during evening shoulder hours.
- Imports into California and exports from the Basin increase from the 80% clean energy level scenario to the 90% clean energy level scenario as the portfolio mix transitions toward cleaner energy with more fossil fuel generation resources in California and the Southwest being displaced.
- In the 100% clean energy level scenario, in which all fossil fuel generation resources are displaced, imports into California roughly double with the Southwest, Basin, Northwest, and British Columbia regions becoming net exporters, while the California and Alberta regions become net importers, and the Rocky Mountain region becomes roughly net neutral.



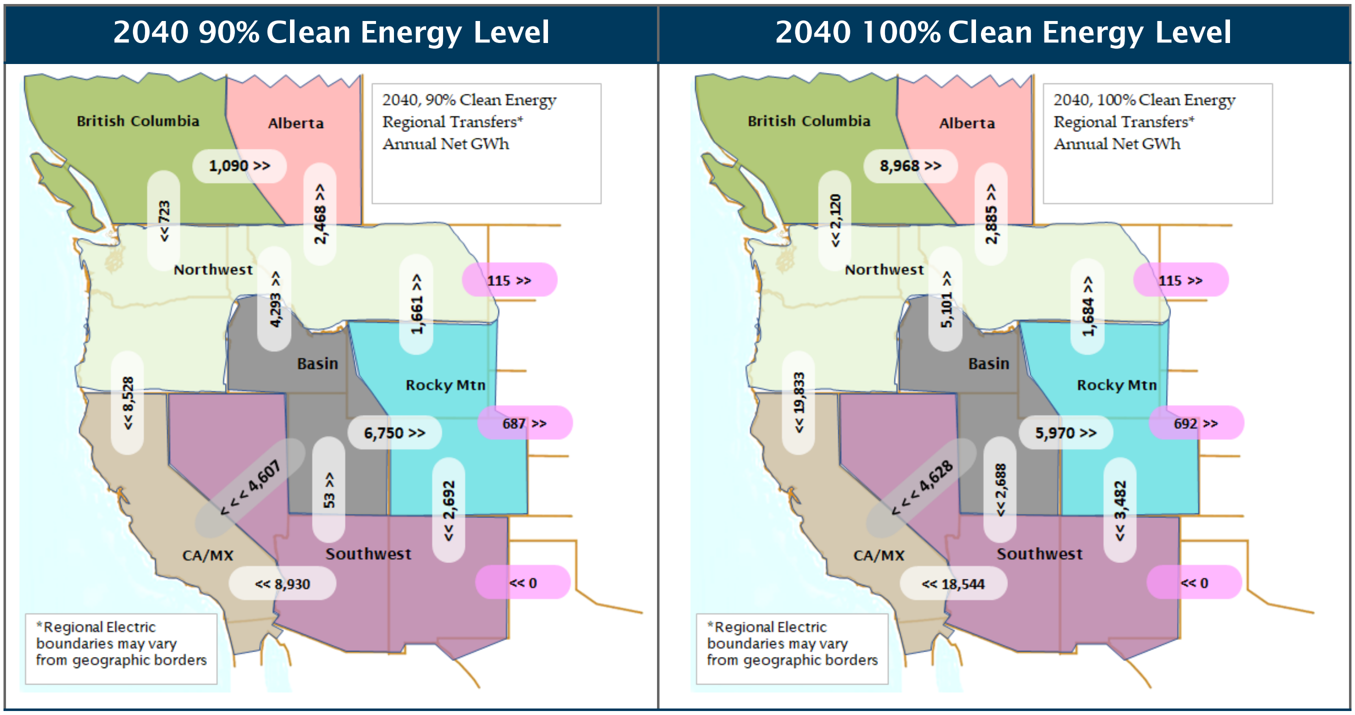


Figure 16: Clean energy progression comparison of annual regional interchanges

Figure 17 further illustrates how the imports and path utilizations into California change in the progression to higher levels of clean energy.

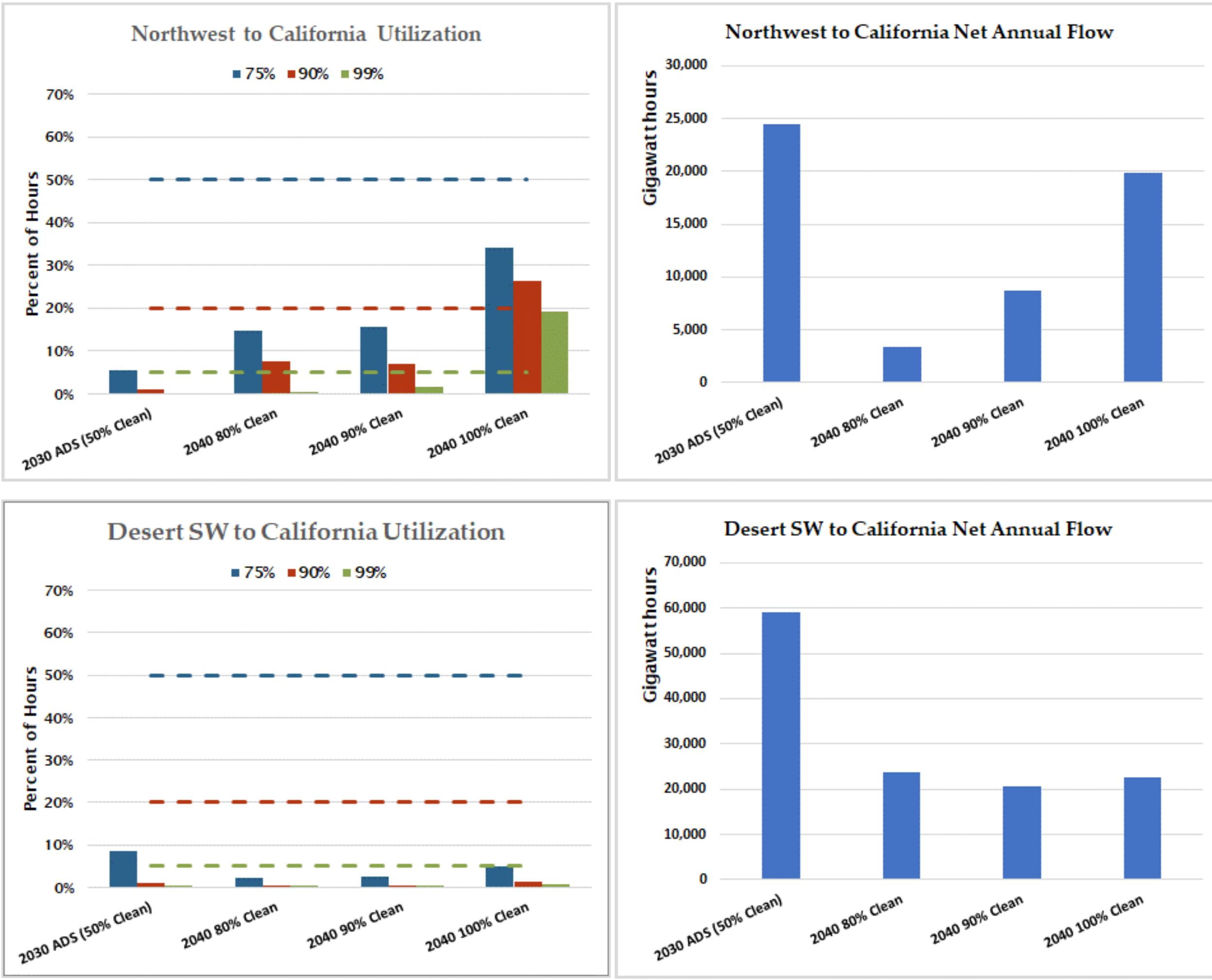


Figure 17: Comparison of imports into California by clean energy level

As Figure 17 shows that, while the total annual energy (GWh) transfers on all major transfer paths into California reduced significantly when compared to the ADS 2030 case, the number of hours in which the paths are being used at 90% and 95% of their rated capacity has increased. This means, that higher path utilization is taking place during the shoulder hours when ramping requirements become more severe at higher levels of clean energy.

Clean Distribution Power System Strategies

There are a lot of changes taking place on the DPS that are occurring due to the trends toward electrification and clean energy. While the focus of this study is on the BPS, the changes occurring on the DPS are driving much of the changes that are, and are expected to, take place on the BPS. While an in-depth analysis of the changes in the DPS is beyond the scope of this study, cursory efforts were made to model some of these DPS changes in the study:

- Adopting the NREL demand-side load scenarios from the Electrification Futures study as discussed in the Input Data section. The NREL demand-side load scenarios were created by

NREL by a bottom-up approach, using component models consisting of residential, commercial, industrial, and transportation end-use sectors with sufficient temporal, geographic, and end-use resolution to enable detailed analyses of current patterns and future projections of end-use load [6].

- Explicitly modeling—
  - Rooftop solar [6];
  - The contribution of electric vehicles to resource flexibility [8]; and
  - Battery storage on the DPS [8]

  at the BPS level with a proxy based on supply curve data from NREL representing energy production potential.
- Modeling other DPS strategies, such as demand-side management and load shifting, by using a load factor adjustment that smooths load by 10% while maintaining the same annual energy consumption level.

Other than the electric vehicle resource flexibility and load factor adjustment proxies, the rest of the DPS modeling components were already incorporated into default 2040 clean energy cases. After finding optimally balanced resource portfolios for the 2040 clean energy cases, more sensitivities were run to examine how additional clean energy measures on the DPS will affect the BPS. The result of including electric vehicle resource flexibility and a 10% improvement in load factor was roughly a 3% improvement in clean energy levels, but this also resulted in increased curtailments, especially at low load conditions. One of the implications of this is that collaborative coordination of planning efforts between the DPS and BPS will be required to fully realize the clean energy benefits on both the DPS and the BPS. Implementing clean energy strategies on the BPS regardless of what takes place on the DPS will increase the challenge of finding the correct balance of clean energy resources and strategies (e.g., rates, incentives and policies to shift load on the system).

Because of time constraints, the study did not include sensitivities to find optimal portfolio mixes between the BPS and the DPS. The results, especially regarding curtailments, further emphasizes the challenges and complexity of finding an optimal balance and strategies at all levels of interaction, whether BPS, DPS, policy, market, consumer, industry, or other.

An important observation about increased integration between the BPS and the DPS is the BPS load profile becomes less severe in terms of differences between the diurnal peaks and valleys and ramping requirements. With increased integration between BPS and DPS, the optimal deployment strategy toward clean energy futures may be very different from what is revealed by this study and what is conventionally assumed. As the load profile with which the BPS is presented becomes smoother, the challenges decrease because strategies on the DPS are reducing the uncertainties that are presented to the BPS side of the equation. Further studies are warranted that explore how closer integration between the BPS and the DPS can reduce uncertainties of higher levels of clean energy.

Market and Rate Design

Increasing system and resource complexities are forcing substantial changes to grid management. The nation's electrical system has evolved to a fully integrated system that relies on being supplied by large-scale merchant generation. The displacement of conventional fossil generation as the primary source of energy supply, increased electrification demand, higher penetrations of VRE resources, and significant developments in community-scale and demand-side generation is introducing new and complex challenges to the operation of the BPS and the assurance of reliability. Many of these challenges are not yet fully understood and have yet to be resolved. Adaptive strategies across all parts of grid management will be required, not the least of which will be market and rate design.

Market Design

Current market structures are designed around fossil-fuel resources, with VRE resources being treated as price-takers. If fossil-fuel resources are displaced, the flexibility that they provide will need to be replaced by some other clean alternative. VRE resources can technically provide resource flexibility if energy production capability is held in reserve (headroom); this practice will be at lost opportunity cost. Other challenges that also need to be considered [18]are :

- **Scale and pace**: Adequate planning for rapid build-out of solar, wind, battery, and demand-side resources. Continued operation of existing nuclear and clean and flexible generators should be considered as a planning strategy.
- **Innovation**: Market entry by emerging low- and zero-carbon technologies (e.g., advanced nuclear, gas, or bioenergy with carbon capture, advanced geothermal).
- **Generation resource mix**: Finding the best combinations of these existing and new resources.
  - With low cost but variable wind and solar, complementarities among sources are much more important than with traditional firm and dispatchable generation.
  - Need ways to compensate back-up sources of firm energy to ensure resource adequacy (RA) in every hour.
  - Keeping total system costs as low as possible requires more attention than ever before to get the right mix of generation resources.
  - Market design to ensure resource flexibility.

Rate Design

As grid management becomes increasingly more complex, rate design takes on new significance. Rate structures should be designed with system reliability as a major goal and should also be designed to be efficient, economic, and equitable. In this context, one important question to ask is "How might rate design help shift load to improve load factor, and will it be equitable?" Rate design typically addresses demand use and does not usually respond to market price signals from the BPS. It could, however, be extended to aggregated service providers and microgrids in ways that are more closely integrated with the operation of the BPS.

It is fairly certain that current market structures and operational practices will need to adapt to the challenges and uncertainties introduced by high electrification and high renewable penetrations to reach a 100% clean energy level. Decision-makers must be informed of these challenges and uncertainties and their implications before they can develop effective strategies to adapt current market structures and operational practices to them.

Conclusions

Clean Energy Potential

The West has abundant, and geographically diverse, clean energy potential. While it is possible to achieve a 100% clean energy future, there are still challenges and uncertainties that must be better understood and resolved.

Balanced Resource Portfolio Mix

A balanced resource portfolio mix must meet the reliability needs at all seasonal load levels. The risks of unserved load and curtailments increase as clean energy levels approach 100% with high penetrations of VRE resources.

A tool that can better bridge the gap between the objectives of resource capital expansion models (RCEM), transmission capital expansion models (TCEM), and production cost models (PCM) is needed to optimize and analyze future generation and transmission expansion needs in a more complete, effective, and efficient way.

Battery Resources

BESS will be a key component of reaching a 100% clean energy future. Storage must help compensate for the misalignment of hourly dispatches of VRE resources and hourly demand. it must also provide resource flexibility that will be lost as gas-fired generation resources are displaced.

While BESS could reduce curtailments and replace some of the lost resource flexibility, the benefits of BESS resource are diminished in the absence of another non-charging ECF resource at clean energy levels above 90%. Charging energy would then have to come from added VRE resources, which would further exacerbate the ramping requirements.

Distributed Power System

There are trends are occurring that will greatly affect the DPS. Trends that include increases in the use of:

- Electric vehicles;
- Rooftop solar;
- Distributed energy resources (DER) such as rooftop solar and BESS; and
- Micro-grids.

Because of these trends, the DPS can no longer be seen as just a predicted load pattern. The operational characteristics of the DPS and how it affects the BPS will be harder to predict and will make it harder to balance energy supply with demand.

ECF Energy Resources

The study suggests that, to effectively and economically achieve a 100% clean energy level, the West will need an ECF resource technology that does not depend on charging and has performance characteristics similar gas-fired generation resources.

Including a small percentage of ECF resources in the mix will go a long way toward mitigating many challenges that VRE resources introduce at higher levels of clean energy. The study suggests that those levels are:

- 6% ECF at 80% clean energy level,
- 10% ECF at 90% clean energy level,
- 16% ECF at 100% clean energy level.

VRE Resources

Penetrations of VRE resources will need to increase significantly over the next 20 years to achieve a 100% clean energy level. Unfortunately, operational challenges increase with higher levels of VRE. These challenges must be better understood and operational practices and planning strategies must adapt to these challenges.

Hourly energy production from VRE resources in the West does not align well with hourly load demand. This results in increased risks of unserved load and curtailments. BESS help to shift energy supply from VRE resources to more closely align with hourly loads.

At higher levels of VRE use, the ramping and regulation requirements significantly increase. The risk of unserved load is greater during the shoulder hours when ramping requirements are more challenging because of the addition of VRE resources and reduced ramping capabilities caused by the displacement of gas-fired resources.

At very high levels of VRE penetrations, the risk of curtailments will increase over all hours of the day (primarily light load days) resulting in negative LMPs. In this case, the opportunities for BESS to dispatch are negated unless dispatched into curtailment. If a BESS resource cannot dispatch, it cannot charge again after an initial charge, which negates its ability to offset curtailments. In essence, the value of BESS to the BPS is negated.

Achieving clean energy levels above 90% with additions of BESS and VRE resources alone may not be possible. As BESS additions increase, so must VRE resources to provide charging. As VRE additions increase, so does the severity of ramping requirements, especially during the shoulder hours of the day. The additional resource flexibility provided by BESS resource additions is not enough at 90% to compensate for the ramping capability that is lost with the displacement of gas-fired resources and the increased ramping requirements introduced by more VRE additions.

There are performance characteristics that synchronous resources provide that are essential to the reliable operation of the BPS. If synchronous resources are displaced by VRE resources, which are inverter-based, the challenges of maintaining these essential performance characteristics must be addressed and overcome in other ways, such as reserving energy production capability from VRE resources to provide resource flexibility.

Load Growth

The BPS in the West is becoming, and is expected to become, more electrified especially with the electrification of the transportation sector. Transportation accounts for about 30% of total energy consumption in the U.S. A significant trend has emerged toward the adoption of electric vehicles, not just on an average consumer basis, but on a commercial and industrial basis. The electrification of transportation represents a huge demand on the electric energy sector. This increased demand, in parallel with trends toward cleaner electricity, introduces reliability concerns, especially in terms of operational performance.

Most of the electrification load growth demand is concentrated in evening peak periods leading to more exaggerated diurnal load demand shapes. With high electrification, the gaps between load at peak demand hours and at light demand hours are more pronounced in the 2040 cases than in the 2030 ADS.

Market Design

Current market structures are designed around fossil fuel resources, with VRE resources being treated as price-takers. If fossil-fired resources are displaced, the resource flexibility they provide will need to be replaced by a clean alternative.

PCM tools are designed around current market structures common to the West and across the U.S. There are nuances in the study results suggesting that improvements in market design and operations could help to resolve some of the challenges to achieving a 100% clean energy future. Examples might include introduction of new ancillary service or capacity market options to encourage participation in resource flexibility.

Rate Design

Current rate structures are designed around conventional end-use needs and patterns. As end-use becomes more electrified, especially from the adoption of electric vehicles, grid management becomes increasingly more complex and rate design takes on new significance.

Rate design could play a key role in shifting load demand to improve load factor and to improve the misalignment between energy production from VRE resources and load demand.

Transmission Congestion

Increasing VRE resources may create transmission challenges at higher clean energy levels where the penetrations of BESS and VRE resources are higher. As VRE penetrations increase above 90%, the resulting changes in resource dispatch significantly change inter-regional flows in the Western Interconnection. In some cases, the changed flows increase transmission facility use from 90% to 100% of their rated capacities.

While transmission capability in the West seemed to be adequate at levels up to 90% clean energy, transmission congestion occurred resulting in unserved load, increased curtailments, and increased redispatch of resources. The occurrences of higher LMPs due to congestion also occurred, especially in areas in which transmission interconnection was weak relative to the rest of the BPS.

Recommendations

Clean Energy Potential

Continued studies and research are required to better understand known challenges and to uncover unknown challenges. Though there are no definitive reasons why a 100% clean energy future cannot be achieved, there are many challenges and uncertainties that still must be better understood and addressed before that goal can be achieved.

Coordinating planning efforts across research, policy, regulatory, market, industry, consumer, and environmental sectors will be essential to achieve these clean energy goals while still ensuring the reliability of the West. Decision-makers must be better informed of the challenges and uncertainties of achieving a 100% clean energy future and they should communicate and work together in their planning efforts.

Balanced Resource Portfolio Mix

Better tools and study methods are needed that bridge the gap between capital expansion (RCEM and TCEM) tools and PCM tools.

Better tools and study methods need to be developed that co-optimize BPS portfolio mixes with transmission expansion and DPS integration to uncover holistic strategies to achieve a 100% clean energy future and to identify the advantages and disadvantages of those strategies.

Strategies to coordinate planning efforts in a more collaboratively will need to be developed to effectively and economically achieve a balanced resource portfolio and to achieve a 100% clean energy future.

Battery Resources

The performance characteristics of BESS need to be studied further and models updated accordingly, especially in terms of charging requirements, dispatch optimization, and duration.

Strategies to develop hybrid BESS–VRE plants with increased resource flexibility need to be studied and modeled in future studies.

Long-duration storage options beyond 12 hours should be studied and modeled in future studies.

Distributed Power System

BPS and DPS planning and operations will need to be more closely integrated. Just as the BPS is undergoing change, so is the DPS. The DPS can no longer be seen simply as a load from a BPS perspective, especially in terms of high electrification and increased levels of distributed energy.

Further studies are warranted that explore how closer integration between the BPS and the DPS can reduce uncertainties of higher levels of clean energy.

ECF Energy Resources

Further study is needed of emerging clean technologies and strategies that provide the resource flexibility and performance characteristics of gas-fired generation resources as is the development of study models to adequately represent those technologies.

VRE Resources

Further studies are needed to explore strategies that will minimize the hourly misalignment of VRE resources to load demand. These may include ancillary services, reserves, and hybrid BESS-VRE plant designs.

Further study is needed of market strategies and technology advancements that enable the participation of VRE resources in ancillary services to provide resource flexibility.

The performance characteristics (e.g., resource flexibility, inertia, etc.) of inverter-based resources (IBR) need to be studied in greater detail. Study models representing IBRs and their performance characteristics need to improve (e.g., beyond a simple fixed dispatch representation).

Load Growth

Further studies are needed to explore load shifting and time-of-use strategies that will smooth the expected load profiles of a highly electrified future (e.g., increase load factor) and help to close the hourly misalignment gap between VRE resources and load demand.

Electrification beyond fuel switching needs to be studied and better understood.

Transmission Congestion

Optimal placement of new candidate generation resources to minimize transmission congestion should be studied in greater detail.

Tools that co-optimize generation and transmission expansion need to be further developed. A tool that can optimally locate new generation resources and quantify the trade-offs between generation expansion and transmission expansion through co-optimization will greatly improve the analytical capabilities of assessing the challenges and opportunities of achieving a 100% clean energy future.

Investment Planning

One of the biggest challenges to clean energy planning is the increasing need to better coordinate investment planning with operational planning. The degree of change in the energy sector, including the integration of an ever-expanding roster of technologies, comes with an unprecedented degree of investment uncertainty; failed investments and investment shifts due to changes in perceived risk can lead to increased investment uncertainties, adding to reliability challenges.

Market Design

Market structures and operational practices will need to increasingly refer and adapt to the challenges and uncertainties resulting from high electrification and high renewable penetration as clean energy levels continue to increase and ultimately reach 100%. Against these changes, markets must continue to prioritize reliability; greatly expanded technology types and distributed generation, along with changes in regulatory environments will necessitate elevated attention to reliability assurances to avoid system performance compromises. A better understanding of this significance will require further work in greater detail.

Further studies are needed to explore strategies to adapt current market structures and operational practices to a 100% clean energy future with high penetrations of VRE resources and highly electrified loads. These strategies should include an emphasis on assuring adequate resource flexibility and reserves.

Rate Design

Rate structures should be designed to be efficient, economic, and equitable and with system reliability as a major goal. In this context, one important question to ask is "How might rate design help shift load to improve load factor, and will it be equitable?" Further study is needed to explore answers to this question and to uncover other similar questions regarding rate design.

Next Steps

For WECC and the SWG, apply the knowledge learned from this study to Phase 2 of the 2040 Scenario studies in which the main themes related to policies, markets, technology advancements, and consumer adoption are examined in greater detail.

For WECC, investigate new tools that can be incorporated into WECC's planning processes.

For WECC, investigate new ECF technologies that may address the risks identified in this study.

Contributors

WECC would like to thank the following contributors who have invested valuable time and energy in this effort:

- The members of the Scenarios Work Group (SWG), led by Amy Mignella and Rafael Molano, for the time they committed to this effort and the subject matter expertise, feedback, guidance, and suggested edits that they provided.
- Quantum Planning Group, led by Gerald Harris and Richard Marrs for helping to guide the scenario planning process, tracking trends, and providing feedback and guidance with the study.
- WECC staff colleagues who helped with this study in various ways. Special thanks to Byron Woertz and Saad Malik for their guidance and perspective, to Bharath Ketineni and Stan Holland for their assistance with running simulations and charting data, to Chad Coleman for his technical writing reviews, and to Kirha Quick for her assistance with project management.
- A special thanks to Kaitlin Highstreet and Paul Rudnicki, Schultz Fellowship students from Stanford University. The "Technology Advancement" section of the appendix was largely based on their research as interns at WECC.
- The National Renewable Energy Laboratory and other national labs for the research and data they provide to the public, which were used in this study.

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Appendix

Technologies Advancement

There are many new emerging technologies that could play a significant role in achieving a 100% clean energy future. In this regard, advances are being made in the areas of demand response, storage, hydrogen, nuclear [19], and inverter technologies.

A generation resource technology type was introduced into the modeling of new candidate resource in the sensitivity cases. This was used as a proxy representing possible clean and flexible resources that may emerge with the same performance characteristic of gas-fired generation resources to overcome the challenges of VRE saturation at 90% clean energy levels and above.

This proxy was not encompassing of all emerging clean technologies and strategies that may further the advancement toward a clean energy future. The key takeaway is that further investigation of emerging clean technologies and strategies is warranted as is the development of study models to adequately represent these emerging technologies.

Demand Response

Demand response is a critical, multi-faceted tool that could be important in managing extreme events and reducing the capital costs of building new generation resources in the future. In some ways, demand response is better developed than other technologies in this list, as the various types of demand response have been implemented for large commercial and industrial customers for decades. However, its potential magnitude at the residential level, its optimal contractual form, and its reliability in crucial stress tests remain to be seen [19].

Demand response is as any mechanism by which the load profile of an end-user is changed in response to the needs of the power system, often by means of an incentive in the form of an immediate payment or a more advantageous rate structure. Demand response can be designed in many ways, limited only by the imagination and skill of utilities or regulators in designing customer contracts or incentive programs. Due to this broad range of possibilities, it is useful to classify it in different ways for conceptual simplicity [19].

Storage

Storage resources can minimize the misalignment of hourly energy production to hourly load demand by shifting energy supplied by VRE resources. Storage is any technology in which energy generated during low load demand periods can be stored and later released during high load demand periods. The main forms of storage used today are pumped storage hydropower (PSH), which can hold energy for about 12 hours, and lithium-ion batteries (LIB), which can economically hold energy for four to six hours [20]. Many more storage technologies are under various stages of development in four categories:

1. Flow batteries—store energy in liquid electrolytes, which is theoretically more easily scalable than traditional lithium-ion batteries;
2. Mechanical energy storage—includes compressed air energy storage (CAES) and flywheel technology;
3. Chemical energy storage—includes generation of hydrogen or other chemicals for future combustion; and
4. Thermal energy storage—store electricity as heat in molten salt, ceramics, or other forms [19].

Several factors go into determining the time scale of storage: the achievable rates of charge and discharge; the charging and discharging efficiencies; any losses during storage; and the value of energy arbitrage or capacity payments compared to the initial cost of the technology, its operating costs, and its lifetime. In general, technologies that have a relatively higher ratio of power costs to energy costs, such as hydrogen or CAES, are better suited for longer-duration storage, while technologies for which the energy costs scale more quickly, like LIBs and most batteries, are better for short-duration storage [21]. Storage is often classified by the number of hours it takes to fully charge or discharge the storage, which depends on the power (rate of charge) and energy (total potential storage) of the installation [19].

Hydrogen

Hydrogen is an emerging technology that is generating interest due to its potential on both the demand and supply sides. It is an energy carrier and is included in many projections of a clean energy future [19].

Hydrogen gas may be produced as an industrial byproduct or through a chemical process called electrolysis. In industry, it is primarily produced by natural gas steam reforming, which is when high-temperature steam is combined with natural gas. It can also be produced through biomass gasification or biomass-derived liquid reforming. The hydrogen produced in these manners, termed “grey hydrogen,” produces CO_2 emissions from the natural gas or other feedstocks. When techniques such as carbon capture and storage (CCS) are used to reduce CO_2 emissions of hydrogen production, the hydrogen is then referred to as “blue hydrogen,” which is often cited as a possible pathway to use existing natural gas infrastructure while decarbonizing energy production. However, this is subject to some debate, as a recent study indicates that the carbon dioxide emissions reductions are not substantial enough to merit the investment in CCS [19].

Nuclear

Nuclear reactor technologies have existed since the 1950s. These are typically large-scale, base load projects, generating an average of 1,100 MW per reactor. Electricity generated is carbon-free, but not waste- or risk-free. Nuclear energy faces challenges with public opinion because of accidents in the past and the high capital costs associated with building plants. While approximately 20% of electricity is currently generated by nuclear power, new large-scale projects are less common, with just two under construction in the United States. This lack of large projects, combined with the need for carbon-free base load generation, has prompted the private sector to develop smaller-scale nuclear reactors with safety, resource flexibility, and cost in mind [19].

There are about 25 advanced nuclear reactor designs in various stages of development using a variety of reactor technologies. Advanced modular water-cooled reactors may be the most familiar sounding because water-cooled reactors are well established and have been used in large-scale projects for many years. Companies working on these light-water small modular reactors (SMR) argue that smaller-scale reactors with this technology may be approved and commercialized more quickly. Liquid metal and molten salt reactors claim higher safe operating temperatures due to the coolant properties, but do not have that precedent of technology approval. Gas-cooled reactors are more common in smaller, more specialized settings [19].

There are three main categories of reactor size:

1. Microreactors—These are small-scale, producing under 20 MW of electricity, and may be used for specialized loads or when it's not an option to connect transmission lines to the reactors. They can usually fit on a flatbed truck and are mobile and deployable.
2. Small modular reactors (SMR)—These are the more familiar size and are flexible. They can be scaled up or down by changing and connecting the number of units, but a single reactor typically produces between 20 and 300 MW of electricity.
3. Full-size reactors—These generate over 300 MW of electricity. Full-size reactors help address needs for carbon-free base load [19].

Inverter-based Resource

Inverter-based resources (IBR), such as solar, wind, and BESS, produce direct current (DC) power and rely on power electronic devices called inverters to convert their DC power to alternating current (AC) power at the proper frequency and in phase with the BPS before that power can be delivered to the BPS. The BPS at 80%, 90%, and 100% clean energy levels will be dominated by IBRs, while most synchronous resources will be displaced. There are performance characteristics that synchronous resources provide that are essential to the reliable operation of the BPS. If synchronous resources are displaced by IBRs, then challenges with maintaining these essential performance characteristics will need to be addressed and overcome through technology advancement and other strategies. Some challenges to address:

- Inertia or rotational inertia, which is the kinetic energy that the rotor of a synchronous generator stores by virtue of its mass and rotation. This inertia is essential to the reliable operation of the BPS today because it helps to maintain frequency stability by providing frequency-responsive reserves in the event of a disturbance such as the loss of a large generator. Most synchronous resources are fired by fossil fuel. If these synchronous resources are displaced by IBRs, then the inertia that they would otherwise provide will have to come from some alternative source. Inertia can be provided by IBRs by operating IBRs at reduced output to reserve some of their generation capability to meet frequency response needs. This strategy is often referred to as "synthetic inertia." While synthetic inertia is able to replace synchronous inertia, it does so at a lost-opportunity cost. Inverters would need to be designed to properly detect and respond to frequency excursions. In 2018, FERC issued Order 842, which requires that new utility-scale VRE resource plants have frequency response capabilities [22].

- Grid strength refers to how sensitive the BPS is to perturbations such as contingencies, changes in load, and switching of equipment in terms of voltage and frequency. The stronger the grid, the less sensitive it is to perturbations. Weak grids can pose a challenge to the connection of IBRs, especially when the performance characteristics from synchronous generation resources are lost to displacement. The majority of IBRs use a phase lock loop (PLL) system to synchronize to the BPS [23]. Using a PLL system, inverters attempt to modulate the phase and frequency of the power that they inject into the BPS to that which they detect at the BPS terminal bus to which they are connected. This type of operation is often referred to as "grid following," meaning the IBR follows the frequency and phase of the BPS that it detects at its terminal bus. Most IBRs rely on the voltage magnitude and angle at their terminals to be largely insensitive to grid perturbations for stable operation, including the current they themselves inject into their terminal bus. Accurate PLL functionality becomes very difficult with weak grids. Inverters need to be designed to ensure stability for weaker grids. PLL functionality is often considered proprietary by inverter manufacturers [23]. For this reason, transient stability models are often limited in their representation of inverters. In terms of voltage support, IBRs often rely on other external facilities to provide voltage support.
- Existing system protection equipment is designed to detect and respond to high current events, such as short-circuit faults, and trip circuits according to its protection schemes. While inertia from synchronous resources is able to produce high currents under fault conditions, IBRs are not able to produce currents beyond their operational rating [15]. In this regard, higher penetrations of IBRs may render current protection equipment and schemes ineffective. While installation of synchronous condensers can help with this problem, the cost to do so is high. Technology advances in IBR and protection equipment will be needed to support higher levels of IBR penetrations.

Federal and Western State Clean Energy Policy Summaries

Federal, state, province, and tribal policies are constantly changing with regard to clean energy. As of the completion of this study, the information and documented references in this section of the appendix are what were posted by the referenced sources. In WECC's opinion, the best and most current source of information regarding state clean energy policies is contained within the Database of State Incentives for Renewables & Efficiency (DSIRE) [24].

United States Federal

"President Biden has laid out the boldest climate agenda in our nation's history—one that will spur an equitable clean energy economy and cement America on a path to net-zero carbon emissions by 2050." [1]

On April 22, 2021, President Biden announced "a new target for the United States to achieve a 50–52% reduction from 2005 levels in economy-wide net greenhouse gas pollution in 2030—building on progress to-date and by positioning American workers and industry to tackle the climate crisis." [25]

The H.R. 3684—Infrastructure Investment and Jobs Act bill was introduced before the 117th Congress of the United States (2021-2022) on June 4, 2021 and includes provisions to address climate change, including strategies to reduce the climate change impacts of the surface transportation system and a vulnerability assessment to identify opportunities to enhance the resilience of the surface transportation system and ensure the efficient use of federal resources. [26].

On November 15, 2021 President Biden into law the Bipartisan Infrastructure Deal, the Infrastructure Investment and Jobs Act. [27]

Alberta

From *Renewable energy legislation and reporting* on alberta.ca [2]:

> The *Renewable Electricity Act* outlines Alberta's commitment to increasing the amount of green energy produced in the province, including a legislated target of 30% renewable electricity by 2030. To get there, the province plans to add 5,000 megawatts of renewable electricity through the Renewable Electricity Program (REP).

Arizona

From *Renewable Energy Standard & Tariff* on azcc.gov [28]:

> In 2006, the Arizona Corporation Commission approved the Renewable Energy Standard and Tariff (REST). These rules require that regulated electric utilities must generate 15% of their energy from renewable resources by 2025. Each year, Arizona's utility companies are required to file annual implementation plans describing how they will comply with the REST rules. The proposals include incentives for customers who install solar energy technologies for their own homes and businesses. The Commission's Renewable Energy Standards encourage utilities to use solar, wind, biomass, biogas, geothermal and other similar technologies to generate "clean" energy to power Arizona's future.

British Columbia

From *Energy Efficiency Policy & Regulations* on www2.gov.bc.ca [3]:

> The Clean Energy Act, including British Columbia's energy objectives to:
>
> - Take demand-side measures and conserve energy; and
> - Reduce BC Hydro's expected increase in demand by 66% through demand-side measures by 2020.
> - Reduce BC greenhouse gas emissions to 33% below 2007 levels by 2020 and to 80% by 2050.

California

From *SB 100 Joint Agency Report* on energy.ca.gov [29]:

> Senate Bill (SB) 100 established a landmark policy requiring that renewable energy and zero-carbon resources supply 100 percent of electric retail sales to end-use customers by 2045. It requires the California Energy Commission (CEC), California Public Utilities Commission (CPUC), and California Air Resources Board (CARB) to prepare a report.

Colorado

From *Climate and Energy* on energyoffice.colorado.gov [30]:

> To address Colorado's two largest sources of emissions—the power sector and transportation—the state is working to transition to 100% clean electricity generation by 2040 and rapidly expand the electrification of vehicles. In May 2019, Governor Polis unveiled the administration's *Roadmap to 100% Renewable Energy by 2040 and Bold Climate Action*. The roadmap details directions, policies, and actions Colorado is taking to ensure a clean energy future.

Idaho

While the state of Idaho, as of February 2021, has no renewable portfolio standard or voluntary renewable energy standard or target, it has a number of regulatory and incentive programs to promote renewable energy.

Idaho Power has set a goal to provide 100% clean energy by 2045. In addition to its hydropower facilities, which typically meet almost half its customers' energy demands, Idaho Power plans additional investments in solar, wind, and other clean sources [24].

Montana

While the state of Montana, as of February 2021, has no renewable portfolio standard or voluntary renewable energy standard or target, it has a number of regulatory and incentive programs to promote renewable energy.

Montana's current energy policy states that it is the policy of Montana to "promote energy efficiency, conservation, production, and consumption of a reliable and efficient mix of energy sources that represent the least social, environmental, and economic costs and the greatest long-term benefits to Montana citizens" [31]

Mexico

The official renewable energy target adopted by the Mexican government, which is reflected mainly in the General Climate Change Law (Ley General de Cambio Climático) and in the Energy Transition Law (Ley de Transición Energética), is to have 35% of total generation based on renewables or clean energy by 2024, however, it has already been recognized that this target will not be met [4].

New Mexico

From Increase Renewable Portfolio Standards Bill 2019 on 350newmexico.org [20]

> In the 2019 session, the New Mexico legislature passed the **Energy Transition Act**, a bill to **Increase New Mexico's Renewable Portfolio Standard (RPS)**. This mandated that electric utilities convert to clean renewable energy to achieve these targets … With this bill, New Mexico intends to be a national leader in solar, wind, and geothermal energy and to provide good jobs, clean air, and clean water…
>
> - Investor-owned Utilities: Increase the RPS to 50% clean energy like wind and solar by 2030 and 80% by 2040
> - Rural Electric Coops: Increase the RPS to 40% clean energy by 2030 and 80% by 2045
> - Cost Protections: Create caps on the price that utilities pay for clean energy
> - Reliability: Follow the national mandate that all public utilities and coops meet reliability and operational standards established by the North American Electric Reliability Corporation (NERC) and enforced by the Federal Energy Regulatory Commission (FERC)
> - Job Training: Require that new renewable energy projects employ qualified New Mexico apprentices, encouraging diversity and representation from disadvantaged communities.

Nevada

From *Renewable Portfolio Standard* on puc.nv.gov [32]:

> The percentage of renewable energy required by the RPS will increase at a scheduled rate until it reaches 50% in 2030.
>
> - 22% in 2020.
> - 24% in 2021.

- 29% in 2022 and 2023.
- 34% in 2024 through 2026.
- 42% in 2027 through 2029.
- 50% in 2030 and each year thereafter.

The 2019 Nevada Legislature determined that energy efficiency measures can be used to comply with up to 10% of the annual RPS requirement. Of that 10%, 50% must come from energy efficiency measures installed at residential customer service locations. For calendar year 2025 and each calendar year thereafter, no portion of that amount may be based on energy efficiency measures.

Oregon

From the *State of Oregon Newsroom* on Oregon.gov [21]:

> [Oregon House Bill 2021] requires retail electricity providers to reduce greenhouse gas emissions associated with electricity sold to Oregon consumers to 80 percent below baseline emissions levels by 2030, 90 percent below baseline emissions levels by 2035, and 100 percent below baseline emissions levels by 2040.

Utah

From *Renewable Portfolio Goal* on dsireusa.org [33]:

> Utah enacted *The Energy Resource and Carbon Emission Reduction Initiative* (S.B. 202) in March 2008. While this law contains some provisions similar to those found in renewable portfolio standards (RPS) adopted by other states, certain other provisions in S.B. 202 indicate that this law is more accurately described as a renewable portfolio goal (RPG). Specifically, the law requires that utilities only need to pursue renewable energy to the extent that it is "cost-effective" to do so. The guidelines for determining the cost-effectiveness of acquiring an energy source include an assessment of whether acquisition of the resource will result in the delivery of electricity at the lowest reasonable cost, as well as an assessment of long-term and short-term impacts, risks, reliability, financial impacts on the affected utility, and other factors determined by the Utah Public Service Commission (PSC). For electric co-ops, cost-effectiveness is determined using criteria established by the co-op's board of directors, and for municipal utilities it is determined using criteria established by the municipality's legislative body.
>
> Under S.B. 202—to the extent that it is cost-effective to do so—investor-owned utilities, municipal utilities, and electric co-ops must use eligible renewables to account for 20% of their 2025 adjusted retail electric sales.

Washington

From *Programs (WA)* on dsireusa.org [36]:

> The state of Washington has a variety of policies and programs to support the development of renewable energy and energy efficiency from both public and investor-owned utilities. As one of the top states for renewable energy generation, Washington has a great number of renewable energy resources, such as wind, hydro, and landfill gas. The extensive hydroelectric-based system helps the state to maintain a low-emission and clean electricity grid. The state government has launched programs, such as requiring public building energy efficiency and supporting the use of energy savings performance contracts, to improve energy efficiency. [34]

The state has mandatory targets for all electric utilities to eliminate coal-fired generation serving Washington customers by 2025; all electric utilities must be greenhouse gas neutral by 2030; and all electric utilities must generate 100% of their power from renewable or zero-carbon resources by 2045 [35] [36].

Wyoming

While the state of Wyoming, as of February 2021, has no renewable portfolio standard or voluntary renewable energy standard or target [24]. A Wyoming state law was passed that allocates $1.2 million to the governor's office for lawsuits against states with laws and regulations that impede Wyoming's ability to export coal or force the early closures of coal-fired plants in the state [37].